Influence of Diamond Coating on the Performance of a Cutting Tool

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Abstract: Machining processes are used in the metal industry for the manufacture of components used in most consumer goods, where each new technological development has significant economic and social repercussions. The performance of manufacturing processes is influenced by several aspects related to lubricants, machine tools, numerical control, among others, but those related to the cutting tools are the ones that most limit the progress of these technologies.

This research is developed around the influence of cutting tools on the overall performance of the turning process seeking to identify the influence that the application of a coating has in the lifetime of the cutting tool. Assays were carried out sweeping a wide range of operating conditions for two aluminum alloys used in the aircraft industry range. Wear on the face and output components of the cutting force were observed, the respective adjustment equations that allow to quantify the mechanisms under study were established.

Keywords: Cutting Tools, Wear, Lifetime, Cutting Force, Chip

1. Introduction

Machining is a technological process of shape change, through which is intended to obtain a part with a given geometry by removing unnecessary material to its final form. [1] In these processes, the material is removed by mechanical action, by means of a cutting tool that removes small chips of material. One of the limiting aspects of the production rate of the machining processes is related to the existence of problems in the mechanical interface between the work material and the cutting tool. In this interface, different physical phenomena occur, intrinsically connected with the way the cut takes place, affecting the quality of the finished piece, as well as the degradation rate of the cutting tool, known as wear. These phenomena are influenced by many different parameters, namely cutting parameters [1] which can be adjusted according to the needs of the process, so that the optimal machining conditions can be achieved.

This paper tries to analyze the performance of a specific set of turning cutting tools made out of hard metal, with and without coating, machining with two different aluminum alloys, AW7075-T6 and AW2030-T4. To conduct the studies, a large number of experimental tests were carried out, with the intention of obtaining an estimation of the lifetime of the cutting tools. It is also object of study in this paper, the influence that a coating and the work material have on the performance of the...
cutting tool and its durability. Besides studying the lifetime of the cutting tool was also performed an analysis of the relation between the cutting conditions and the characteristics of the chip.

2. State of the art

The lifetime of the cutting tool is determined by the amount of wear that it accumulates over time. Depending on the cutting parameters, the wear may develop more or less rapidly, leading to a longer or shorter life time, respectively [2]. Therefore, it is crucial to study the cutting parameters, so that we can reach a combination that leads to the desired life time. In general, the wear of a cutting tool depends on its geometry, working materials, cutting conditions (cutting speed, feed per revolution, and depth of cut), of tribological phenomena, such as the type of cutting fluid used, and the characteristics of the machine used [3].

The flank wear, represented by VB, and the crater wear, represented by KT, are the types of wear that most influence the performance of the tool. According to ISO 3685: 1993 [2], the Flank Wear is most commonly used to monitor the evolution of the wear of a tool. The criteria generally set to determine the lifetime of a tool is one of the follow:

a) The maximum size of the flank wear is equal to 0.6 mm if the flank wear is not regular along the cutting edge;
b) The average size of flank wear is equal to 0.3 mm if the wear is considered regular along the cutting edge;
c) Catastrophic Failure

All cutting parameters influence the evolution of tool wear and consequently their lifetime. However, according to several authors [2, 4, 5], the parameter that has more impact on how the wear develops is the cutting speed. As shown in Figure 2.1, to different cutting speeds, successively larger, the life of the tool is correspondingly reduced.

Figure 2.1 Evolution of flank wear for different cutting speeds [2].

The ability to predict the lifetime of a tool is obviously important in the management of resources. At the end of the century, XIX, FW Taylor devised about 30 000 tons of material [4] in order to collect information on the performance of cutting tools, with the purpose of establish the first prediction method over the time life of the same. The first Taylor’s life time equation only considerate the influence of cutting speed over the cutting tool time life. However, Taylor noticed that other parameters so as the feed and the cutting depth, also had influence in this phenomena. As a result of these discoveries, the Taylor equation was changed to the following:

\[ V_c, T_w, f_n, d_p = C \]

Where \( f_n \) is the feed per revolution, \( d_p \) is the depth of cut, and the exponents a and b are
determined from the cutting conditions. According to this information, the order of importance of the parameters are: cutting speed, feed per rev and depth of cut [6].

In order to evaluate the performance of a cutting tool, it is also needed to study the chip formation accordingly to different cutting parameters. Like the cutting tool’s life time, the chip formation is influenced by several parameters, although, it is the cutting depth and the feed that mostly affect this phenomena.

3. Experimental Setup
To conduct the study, it was necessary to perform a set of tests that comprised the development of an experimental apparatus, going from the cutting tool to the machines used to conduct the tests and to measure the wear and the cutting forces of the process.

The cutting tool, Figure 3.1, is produce by Palbit, made out of Cemented Carbide and it is design to operations of profiling, making possible to produce many different geometries with no tool changes.

Along the study, two different aluminum alloys were tested with the different cutting tools: AW7075-T6 and AW2030-T4. The Aluminum Zinc alloy AW7075 has the highest strength among all the alloys of aluminum. With the T6 temper, this alloy has a typical voltage transfer of 572 MPa, higher than many mild steels. Due to their high mechanical strength, AW7075 alloy is used in structures subjected to high stresses. Applications include aircraft fittings, gears and shafts, components for military artillery, components of pressure regulating valves and components for aerospace mechanisms [7]. Aluminum Copper Alloy AW2030 has high mechanical strength compared with soft aluminum, coupled with excellent machining properties that translate into good finishes. With the T4 temper, this alloy has a yield stress of 390 MPa typically. Due to its easy machinability combined with relatively high mechanical strength, this alloy is used in machining applications requiring high strength solutions such as the aviation industry, valve components, nuts and bolts [7].

The equipment used for measuring the wear over all trials, was a binocular loupe with 40x magnification capability, equipped with a microscopic sighting of a binocular lens and a table measuring coordinates, Figure 3.2 a). The table measuring coordinates Figure 3.2 b), has two electronic micrometers, which make motion in X and Y separately, with precision of 0.001 mm.

Figure 3.1 a) Cutting Tool GP0600E300-N02-NP, Palbit; b) Scheme of a profiling operation.

In addition to the study of the cemented carbide tool, a diamond coating was also tested, to determine the influence that this change cause on the performance of the cutting tool.
During all the tests carried out during the Study, was made a collection of the data from cutting forces involved during the process. For this purpose, a piezoelectric sensor dynamometer with three components (X, Y, Z) form Kistler was used, with reference KISTLER type 9121-3 toolholder component dynamometer. This sensor functions as a support bracket of the cutting tool, making the interface between the support and the CNC machine. The dynamometer consists of four three-component sensors set at high preloads between two metal plates. Each sensor comprises three pairs of quartz plates, each sensitive to a particular direction, X, Y and Z, Figure 3.3. The fourth sensor is mounted to isolated ground so as to eliminate problems loop. Cutting forces are thus measured virtually with no deviation.

To start the test, we tried to find an effective way to promote the wear of the cutting tool, reproducing the normal working conditions for this cutting tool, while it takes into account the effective management of available resources, so to maximize the number of possible trials carried out in accordance with the limitations of the process. ssim being, we opted for testing in longitudinal thinning, using only half the available cutting edge of the cutting tool, as illustrated schematically in Figure 3.4.

4. Results and Discussion

4.1 Chip Form – Chip-Breaker

In order to define the field of optimal use of the features of the chip-breaker from the cutting tool, there were a number of longitudinal passages longitudinal, where the cutting parameters like depth of cut and feed per revolution were varied. Then proceeded to collect chip formed in each of these combinations of parameters for future photographic record. With the collected photographs it was defined the diagram shown in
It should be noted that, unlike what happens with the tool life time, the cutting speed does not play a fundamental role in the chip form. Therefore, it was decided to use a speed of 1400 m/min for the entire diagram, because it is a high enough speed to be able to assess this topic enabling an economical management of the available material by optimizing the speed of the CNC machine.

Analyzing the diagram it appears that for feeds lower than 0.1 mm/rev, the chip breaker does not operate, leaving the chip-shaped ball, rolling up under its own. The same is true for small cutting depths, less than 0.25 mm. Thus, it follows that the chip breaker operates from these depth and feed values. In an attempt to determine the maximum use of puzzle chips, extended the diagram until feeds of 1 mm/rev and cutting depth of 3 mm. As can be seen from the diagram, the chip breaker continues to function with these cutting parameters. It is found that the chip remains out fragmented, despite the extremely high standards. For security reasons, it was decided not to proceed with the tests for higher values of cutting parameters, being the tested values sufficient for any kind of use of the cutting tool.

Since in this dissertation have been used two different work materials and two different coatings of the cutting tool, we tried to find out if changing these parameters have some effect in the chip form. To this end, we tested some combinations of depth and feed with different materials and coatings in order to compare the results obtained. It was determined that in one case as in the other, for Aluminum alloy AW7075 and AW2030-T6-T4, and the tools with substrate PH0910 - carbide; and coating SP3 –diamond coating, there are no appreciable difference in appearing to chip formation for the same cutting conditions.
where the tool was worn throughout its lifetime, the chip was greater at the end than at the beginning of test, Figure 4.3.

Figure 4.3 Chip Comparison between the begining a) and the end b) of the rehearsal.

The justification for the cause of this is that the development of flank wear along the cutting edge, changes the geometry of the tool, forming a new cutting edge, as seen in Figure 4.4. This change in geometry, results in a change in how the chip-breaker work, since its size is reduced. Thus, for small advances, less than 0.2 mm / rev, the change of the cutting edge geometry is enough for the chip-breaker to stop working correctly.

Figure 4.4 New cutting edge after some time of machining.

4.2 Influence of the coating.

To start the experimental trials, after all the development of the experimental apparatus is established, were chosen cutting parameters provided by Palbit, presented in Table 4.1. The objective of this trials is to get a time life of the cutting tool of 15 min. The first object of study was the uncoated cutting tool (with the reference PH0910) working with the aluminum alloy AW7075-T6. Then, the results obtained from these trials were to be compared with the ones from the coated tool.

Table 4.1 Parameters for the first rehearsals for Tool Not Coated (PH910) with Aluminum Series AW7075-T6

<table>
<thead>
<tr>
<th>Ensaios</th>
<th>Vc [m/min]</th>
<th>Ap [mm]</th>
<th>fn [mm/rot]</th>
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<tbody>
<tr>
<td>1</td>
<td>800</td>
<td>1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>2000</td>
<td>1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>2500</td>
<td>1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
<td>1.5</td>
<td>0.3</td>
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For the first set of trials, were used the values provided from Palbit. The results are presented on Figure 4.5. During the measurements performed, it was found that the evolution of flank wear is substantially homogeneous, with no significant regions where it progresses faster. Thus, it was decided that the criterion for end of life was to use the measurement of the average wear, VB, with the lifetime being set at the instant when the wear reached a dimension of 0.3 mm.

Figure 4.5 Graph of Lifespan vs Flank Wear in trials 1, 2 and 3, Legend of Chart: Name (Material; Speed Cutting; Cutting Depth; Feed)

As seen by the graph, the lifetime of the tool is much higher than required by the criterion defined by Palbit. Assays were performed for approximately 20 to 30 minutes period at
which they were interrupted, once that for this time of machining, the wear value was less than one third of the required one.

Accordingly to these results, it was decided to power up the parameters of the trials. In choosing the parameters it was taken into account the effective management of the available resources for their realization. Thus, it was decided to keep the cutting depth unchanged in all assays. This choice took into account the reduced influence that this parameter has on the life of the tool compared with the cutting speed and feed. The results obtained from the measurement of tool wear in trials 4, 5 and 6 are shown in the graph of Figure 4.6.

![Graph of Lifespan vs Flank Wear in trials 4, 5 and 6.](image)

The evolution of flank wear, VB, is quite similar to that experienced in previous tests, trend following a linear increase over the lifetime of the tool. With increasing cutting speeds, the life of the tool is approaching more and more of the desired results. In the case of Test No. 6 with a cutting speed of 2000 m/ min and feed 0.30 mm/rev, the lifespan of the tool is set at 16 minutes, so very close to the objective sought. From these tests it is also possible to evaluate the influence that the cutting speed and the feed have in the lifetime of the tool. With reference to the test No. 4, note that the lifetime of the tool is approximately 18 minutes. Comparing it to the test No. 5, where there was a 25% increase in the value of cutting speed from 2000 to 2500 m/min and feed remaining constant, we note that the lifetime tool decreased by 44% falling to 10 min. On the other hand, in Test No. 6 in which the cutting speed was kept constant while the feed per revolution was increased by 100%, from 0.15 to 0.30 mm/rev, the lifetime of the tool only decreased by 11 % to 16 minutes.

On Figure 4.3 is a comparison of the actual results, obtained experimentally, with Expanded Taylor’s equation. The expanded Taylor equation for this case is:

\[ V_c T^0.3796 = 5991.4 \]

With \( f_n = 0.15 \text{ mm} \) and \( a_p = 1.5 \text{ mm} \).

![Graph Cutting Speed vs Time Life; comparing feeds 0.15 and 0.3 mm / rev and Taylor's Equation](image)

Looking at the comparison of the graphs, it appears that the experimental results follow the trend of Expanded Taylor Equation, with closes values for higher speeds.

To determine the effect that the coating has on the tool life, the following tests were
performed with the cutting tool with diamond coating, Table 4.2

Table 4.2 Parameters for the rehearsals for Coated Tool (SP3) with Aluminum Series AW7075-T6

<table>
<thead>
<tr>
<th>Ensaio</th>
<th>Vc [m/min]</th>
<th>Ap [mm]</th>
<th>Fn [mm/rot]</th>
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<tbody>
<tr>
<td>1R</td>
<td>2600</td>
<td>1,5</td>
<td>0,15</td>
</tr>
<tr>
<td>2R</td>
<td>2900</td>
<td>1,5</td>
<td>0,15</td>
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The results obtained from the measurement of wear of the tools used in each experiment are presented in Figure 4.8 chart. The evolution of flank wear, VB, is quite similar to that experienced in previous tests, trend following a linear increase over the lifetime of the tool.

![Figure 4.8 Graph of Lifespan vs Flank Wear for the coated (SP3) Cutting Tool.](image)

On Figure 4.9 is a comparison of the actual results, obtained experimentally, with Expanded Taylor’s equation, being for this case the following:

\[ V_c \cdot T_{p}^{0.3996} = 15 \ 835.8 \]

![Figure 4.9 Graph Cutting Speed vs Time Life; comparing feed 0.15 mm/rev and Taylor’s Equation](image)

Analyzing the graph, it appears that the real points coincide perfectly with the Expanded Taylor Equation. Having regard to the prediction given by the equation, it appears that the speed range leading to a life time of 15 minutes tool is between 4000 and 4500 m / min.

After analyzing the results collected from the trials to the coated tool, it was decided to compare them with the results of the uncoated tool. The graph in Figure 4.10 shows both the results with the respective predictions of Taylor. Thus it is easy to understand what the effects in terms of life time the coating promotes a cutting tool be changed without any process parameter. It is readily apparent what effect the coating has on the life of the cutting tool. In standard for the same combination of parameters, the lifetime of the coated tool is double to the corresponding uncoated one. Due to this fact, the range of velocities that lead to a life time of 15 minutes is about twice to the coated tool than for the uncoated one.
4.3 Influence of the Work Material

At this point we study the influence that the work material has on the lifetime of the cutting tool. The choice of parameters for this series of tests took into account all the information gathered in the tests previously performed, in order to achieve an efficient management of available material. Thus, due to the characteristics of the aluminum alloy AW2030-T4, that has resistant mechanical characteristics weaker than the AW7075-T6 alloy, it was decided to exclude the study of the coated tool, since the required amount of material to perform the tests would be too high for an effective study of the cutting tools.

Table 4.3 Parameters for the rehearsals for Uncoated Tool (PH0910) with Aluminum Series AW2030-T4

<table>
<thead>
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<th>Ensaio</th>
<th>Vc [m/min]</th>
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<td>1,5</td>
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The choice of these parameters intended to determine the changes caused in the life of the tool when the material changes. Thus, we opted for the choice of parameters such as cutting speed and feed per revolution, similar to the ones used in assays with material AW7075-T6 series. The results obtained from the measurement of tool wear in the trials are shown in the graph of Figure 4.7.

As with the previous tests, it was possible to measure only the initial minutes of each rehearsal, extrapolating the evolution of the wear over time to determine the expected lifetime for each tool. Analyzing the projected estimates for each test, it is concluded again that the cutting speed is the key parameter responsible for determining the lifetime of the tool. In the case of the first test, at a speed of 2000 m / min, feed of 0.15 mm / rev, the lifespan of the tool is approximately 54 minutes. Changing the shear rate in the second assay to 2300 m / min, which corresponds to a 15% increase in this parameter from the previous test and maintaining a constant feed value, it is found that the lifetime of the tool undergoes a decrease of 16.6% for 45 minutes. In terms of feed, the values are considerably different. With reference to the second test, it appears that an increase of 100% of the value, on the third assay, from 0:15 to 0.3 mm / rev, and maintaining a constant cutting speed, the lifetime of the tool undergoes a decrease of only 4.5% for 43 minutes. With these results, is confirmed once again the order of
importance of the cutting parameters affecting the lifetime of the cutting tool, being the most important the cutting speed, and the least, the feed.

In the graph of Figure 4.8 is the comparison performed in terms of lifetime of the tool and the cutting speed for the different aluminum alloys studied, AW7075-T4 and AW2030-T6. The Expanded Taylor Equation is:

\[ V_c \cdot T_p^{0.76657} = 42562 \]

Figure 4.12 Graph Cutting Speed vs Time Life. Comparison of aluminum alloys AW7075-T4 and AW2030-T6 with Uncoated Cutting Tool (PH910).

5. Conclusion

Throughout this dissertation several objectives were achieved throughout the process that took place over the months in which the study was conducted. The main objective was to study the performance of a cutting tool in turning its strands coated and uncoated, when machining two different aluminum alloys. It was also studied the phenomenon of chip formation, as well as the parameters that influence their formation. To achieve these objectives a series of essays that comprised the machining of more than 600 kg of material and about 15 cutting tools were conducted. With this paper, the author hopes that the results obtained have been useful for Palbit and consequently for all users of cutting tools studied over the same. All knowledge obtained was of great value to the experience of the author, a rare opportunity that the same thanks.

6. References


