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ANALYSIS OF FLANK WEAR IN COATED TOOLS WITH DIFFERENT COVERAGES USED IN MILLING STAINLESS STEEL AISI 420

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Abstract. *For processing polymeric materials based on Chlorine, Fluorine and/or abrasive components the use of stainless steel for manufacturing die and mould has been applied in recent years. Stainless steel offers higher abrasive and corrosion resistance and increases the mould life. Milling operations are widely used to manufacturing these sorts of moulds. However, there still has a lack of knowledge about cutting parameters and cutting tools coatings to machine such materials. In this context, the current work aims to investigate 5 different coatings for the cutting tools, as CrN/AlTiCrN/AlCrN, AlCrN*, AlTiN, AlTiSiN e AlCrN** to milling stainless steel AISI 420. The flank wear of cutting tools were accessed along the two standards defined cutting lengths, to each coating of the tool. The results show the coating thickness and its coponents have a great influence on the tool wear along the cutting lenghts; it implicates cost, time and quality on the final part.*
Keywords*: Coatings; Wear Tool; Milling; Stainless Steel AISI 420.*

1. INTRODUCTION

The use of plastic products has grown exponentially in recent decades and this industry requires molds to manufacture such products. The mold industry represents a key position, affecting the cost, quality and lead-time for these products (Boujelbene *et al*., 2004, Souza *et al*., 2010, Lazoglu, 2003 and Ferreira *et al*., 2010). According to Kalss *et al*. (2006) the costs of cutting tool is not that representative. Reducing the cutting tool cost of about 30% represents only 1% in savings of total manufacturing costs. But, increasing by 20% the cutting parameters, it can save 15% of the total manufacturing costs. Therefore, to get such benefit the cutting tools, its coatings, together to cutting parameters must understand.

In this field of application, different materials such as martensitic stainless steel AISI 420 has been widely used. This material combines high strength, corrosion resistance and was developed specifically for the sector of polymer injection molds, with the need for injection of thermoplastic chlorinated and / or work or storage in humid environments (Villares Metals, 2008). According to Trent and Wright (2000), the stainless steels have poor machinability, due high tensile strength, high work hardening rate and high ductility, with a strong tendency to grip the surfaces of the tool during cutting. In some cases, it can cause damage to the cutting tool, with the breaking of the chip adhered. This characteristic of low machinability is caused by the composition required to submit high mechanical properties and corrosion. These factors explain the tendency to form built-up edge in cutting tool during machining of the traditional operations.

Vieira *et al*. (2010), mentions that during the machining operation the amount of heat generated is due to shear caused by the interaction between the tool, the chip and the part. Because of this, high temperatures can be observed at the interface chip/tool, which substantially influences the mode of chip formation, cutting forces and tool life. The chips removed during the cutting exert high pressure on the cutting edge. These pressures, when combined with high temperatures on the interface chip/tool cause the adherence of portions of chips in the tool. Furthermore, the low thermal conductivity of stainless steel contributes to the increased heat during cutting, getting larger amount of heat in part and in cutting tool than the amount of heat that is removed along with the chips (Lin, 2002 and Silva et al., 2007).

Materials with high-performance often lead to serious technical problems such as machining with low efficiency, high cutting tool wear, high production costs, among others (Yuefeng et al. 2010; Fox-Rabinovich et al., 2006).

The use of coated tools is essential to the current trends of machining for many reasons. The large heat generation in machining without cutting fluid (drilling) and high speed cutting (HSC) and, more recently, the drilling with high-speed demand cutting tools with a high resistance to heat or thermal insulation in the surface. This scenario favors the coating for cutting tools. So, today there are many options of coatings for specific applications (Santos *et al*., 2004). Research for better performance tools has focused the use of thin coatings applied to the substrate (base metal tool). The deposition of coatings aims to change the surface properties. Among the traits by means of coatings may be noted the optical, magnetic, electronic, chemical, mechanical strength and wear resistance (Hogmark *et al*., 2000). According to Musil (2000), the micro hardness of any coating is a mechanical property that influences the life of a cutting tool surface and the greater the hardness value, the greater will be the life of the coating applied to the tool.

According to Shtansky *et al*. (2010), coatings with nanostructured films are the main feature for high life of a cutting tool. For tribological applications, these nanostructured films show superior performance under conditions of severe cutting and stamping, were also resistant to moisture, corrosive environments and high temperatures. The desired properties can be achieved in hard coatings based on carbides, borides and nitrides of transition metals by the complexity of alloys with other elements such as aluminum, chromium and silicon.

According Endrino *et al*. (2006), carbide tools are traditionally covered by two methods: chemical vapor deposition (CVD) and physical vapor deposition (PVD). Due to high temperature during the CVD process the carbide substrate can may lose some tenacity. The PVD process offers low temperature deposition and a cutting edge could be maintained more easily, which is very important for machining stainless steels. A series of PVD coatings have been used for machining of stainless steels and eventually the tool life can be significantly increased (Lin, 2002). Veprek and Veprek-Heijman (2008), reports that since the introduction of PVD coatings on machining tools coated with TiN to almost 30 years ago, many new hard coatings were developed to increase the speed machining, the life of coated tools and to improve the quality of machined surface. The advances in production technologies (increased cutting speed, feed rate, etc.) produced an exponential growth in marketing of PVD coatings for cutting tools and on the other hand, the technological advances in the technologies of coating (TiAlN, AlCrN and nanocomposite coatings) also allowed these advances in manufacturing technologies (Kalss *et al*., 2006).

New materials are the foundation for 21st century technology and the industry of nanomaterials is one of the priority areas of science and modern engineering (Shtansky *et al*, 2010). In surface engineering, the shape of multicomponent and nanostructured films with crystal size less than 100nm are an important and strong tendency to develop in the field of nanomaterials and nanotechnology. Another important characteristic of nanocomposite materials is that, unexpectedly, the high hardness is combined with high tenacity. These properties are very important for machining operations on hard materials and tough, especially in extreme conditions such as interrupted cutting, high-speed cutting and dry cutting operations (Faga *et al*., 2007).

According to Santos *et al*. (2004), the performance of a coated cutting tool depends largely on characteristics beyond the cladding material, which is a combination of physical and mechanical properties of the coating. Factors such as the geometry of the finishing tool, the structure of mono-layer or multi-layer, distribution of residual stresses, the coating thickness, chemical stability and adhesion to the substrate should also be considered.

The wear mechanism of cutting tools in general is the result of the load, friction and high temperature between the cutting edge and the workpiece (Kim *et al*., 2005). When higher cutting temperatures are reached, the tool tip can easily chip or crack. Thus, the wear mechanism in high-speed machining depends greatly on condition and the hardness of the cutting tool. Most of the coatings are available for industrial tools with multilayer coatings combining different materials included, transition metal nitrides, carbides, oxides, solid lubricants and many others. The layered structure also difficult the propagation of cracks in the coatings and is best achieved in coverage nanocomposites (Veprek and Veprek-Heijman, 2008).

Technological advances are rapidly growing for tools and machine tools, reaching high levels of excellence. However, the expected performance is only obtained with a complete adequacy of the process. Therefore, when choosing a cutting tool is essential to have knowledge of the properties of the material to be machined and the machine tool available (Zeilmann *et al*., 2010). Tool life is an important criterion for the selecting the material of the tool and is essential to consider the tool wear in machining difficult cutting materials. Unfortunately knowledge about the tool wear is not sufficient to predict the tool wear through calculations or simulations, because of the complexity of the problem. Thus, the wear of cutting tools is heavily studied by experiments, which in many cases are time consuming and expensive (Yuefeng *et al*., 2010).

In this context, this paper presents an study about the influences of the coating on cutting tools for milling stainless steel AISI 420. Five different coatings are evaluated and the evolution of the cutting tool wear (Vb) and surface roughness were analyzed.

2. EXPERIMENTAL PROCEDURE

This work investigates the flank wear of the cutting tools when milling AISI 420 stainless steel. The workpieces were previously tempered and hardened with 51 HRc.

The experiments were conducted at PROMOLDE laboratory of the Educational Society of Santa Catarina (Sociesc). The machine used for machining is a vertical CNC machining center, model Feeler FV-600, controlled by Mitsubishi Meldas 500 CNC. The radial step corresponds to 75% of the diameter of the tool and the others cutting parameters were set as presented at Tab. 1. The machining experiments occurred without coaling, using only compressed air on the surface of the part to remove the excess chips generated.

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Table 1. Cutting parameters used in tests.

Cutting Speed	Cutting Depth	Cutting Width	Feed Per Cutting Edge
150 m/min	0.2 mm	6.0 mm	0.08 mm/edge

Solid carbide cutting tools with 8mm of diameter, 0.5 mm of edge radius with 4 cutting edges were used, as shown at Fig. 1a. The general properties of the coatings (A – E) used in this study were found in literature and collected in Tab. 2. Based on experiments preliminaries was identified that with a length of 26 meters machining were the first signs of wear and with 52 meters with more expressive wear, that even pledged to machining and which depending on the manufacturing process used may act as surface and generate dimensional errors.

Table 2. Coating properties.

	Composition	Micro hardness (HV)	Coating thickness (µm)	Coefficient of friction	Maximum use temperature (ºC)
A	AlTiSiN	3500	1 to 4	0,4	900
B	CrN/AlTiCrN/AlCrN	4500	1 to 5	0,35	1100
C	AlTiN	5000	1 to 4	0,15	1150
D	AlCrN*	3200	1 to 5	0,35	1100
E	AlCrN**	3200	1 to 5	0,35	1100

The cutting tools were fixed by a shrink fixing system in order to reduce vibrations during the machining process. To identify the level of attrition occurred in the cutting tool was used a stereoscopic microscope Olympus SZ 40, integrated with Image Pro Plus software. To identify the wear of the cutting tool a microscopic analysis was carried-out by amplifying 80 times. The wear was accessed along the machining by analyzing two machining lengths: i) 26.18 meters and ii) 52.36 meters. These lengths were established according to the number of passes of the tool on the test specimens (corresponding to 44 passes) and also by findings in a pre-test, where it was seen that to achieve a Vb of 0.8mm would be necessary a length of 52.36m of machining. The specimens had a cutting area with dimensions of 85x42mm, where the cutting occurred planar in the longitudinal direction as in Fig. (1b).

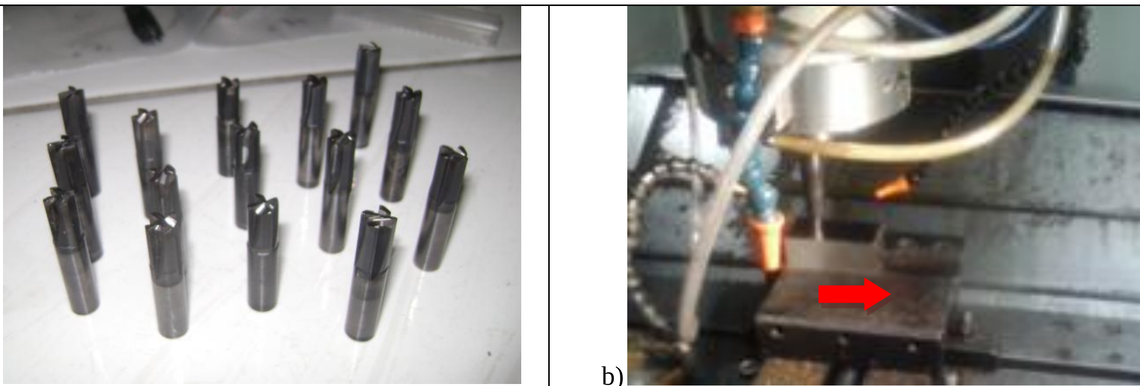

a) b)

Figure 1. (a) Cutters used in the experiments. (b) Sense of machining of the specimens.

A rugosimeter Mitutoyo SJ-201 P/4mn was used to determine the roughness of machined parts. An experimental design was conducted which employed an analysis of variance (ANOVA) containing a factor with five levels. The factor corresponds to the coating of cutting tool and the levels correspond to the types of coatings, designated A, B, C, D and E. To obtain reliable results, there were two replicates of each experimental procedure.

The tool wear was evaluated in each cutting edge by the value of flank wear (Vb). The values of Vb are given by the average value of the experiment and their replicas.

In parallel, an investigation was conducted on the properties of the coatings in this work, in order to compare research results with theoretical data. In the description of the manufacturers of coatings, there are two properties "interesting", the micro hardness and thickness of coatings.

In relation the thickness of the coating layer, there was an investigative procedure by the method of Calotest (Fig. 2a), which consists of applying an abrasive wear, concentrated in a region of the cutting tool and through software can be determine the thickness of the coatings. To carry out the wear, was maintained at 1000rpm rotation, for a time of 60 seconds by applying an abrasive paste, with 0.1 micron monocrystalline diamond grains. The microscope used for the analysis of this property was a stereoscopic microscope Olympus MX51 (Fig. 2b), integrated with software Eifeler QCP Analysis and the ball used for making wear has a diameter of 15 mm.

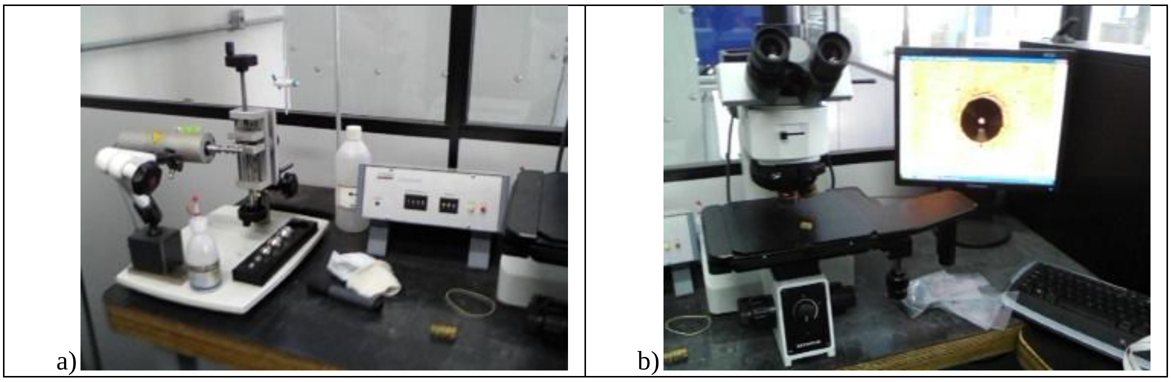


Figure 2. (a) Method of abrasive wear Calotest, (b) Stereoscopic microscope Olympus MX 51.

3. RESULTS AND DISCUSSION

When comparing the characteristics of five different coatings, there is a wide variation in the value of micro hardness, ranging from 3200 HV (coatings D and E) up to 5000 HV (coating C). There is an increase of 56% of the value, comparing the lower versus the upper. However, a study by Faga *et al*. (2007), he held a research on this approach and concludes that the theoretical value (catalog) of the hardness of a coating does not change considerably the value found experimentally. Thus, the theoretical value becomes acceptable and such investigative procedure is unnecessary.

The machining tests were conducted with all coatings of cutting tools, keeping all parameters unchanged in order to visualize the influence of the different layers of coating applied on cutting tools. Thus, the results of flank wear of cutting tools and machined surface roughness are the parameters adopted to classify the performance of different tool coatings.

By analyzing the characteristics of the coatings (Tab. 2), note that the thickness values are very vague (ranging from 1 to 4 m or 1 to 5mm). It was carried out tests to determine the real thickness of the coatings applied to cutting tools used in the experimental procedure.

The main results obtained by the experimental procedure are described in Tab. 3.

Table 3. Results of experimental procedures.

	Thickness measurement (µm)	Flank wear average (mm)		Roughness average Ra (µm)
		26.18m	52.36m	
A	2.97	0.067	0.386	0.098
B	3.29	0.092	0.776	0.149
C	3.3	0.142	0.899	0.224
D	2.31	0.089	0.409	0.146
E	2.01	0.078	0.384	0.102

The thickness of the coatings was measured by the method of Calotest for all coverages. In order to achieve greater reliability of the results of these tests, the test was conducted in three cutting tools for each coating used in experimental procedures machining. With the values of the thickness of the coating, it was possible to obtain an average value of each investment and generate an analysis among five facing employees, as Fig. 3.

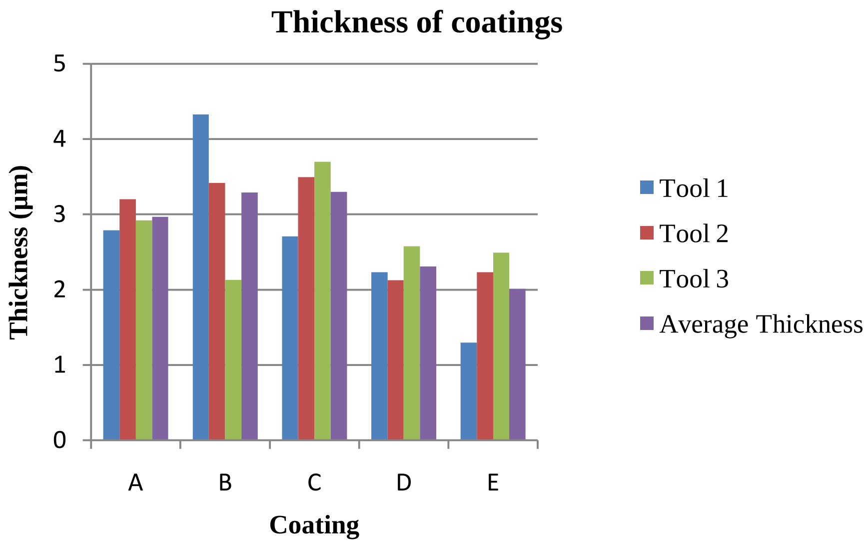
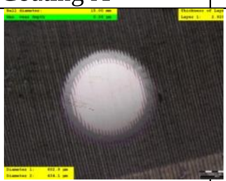
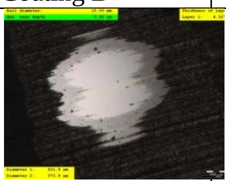
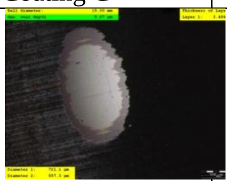
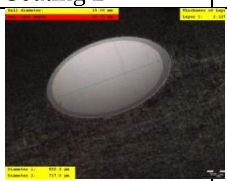


Figure 3. Average values of thickness of the coating of tools.

Table 4 presents the test results to determine the thickness of a sample of coatings.

Table 4. Images of the thickness of coatings deposited on the tools.

Coating A	Coating B	Coating C	Coating D	Coating E
 Thickness: 2.97 µm	 Thickness: 3.29 µm	 Thickness: 3.30 µm	 Thickness: 2.31 µm	 Thickness: 2.01 µm

The Fig. 3 and the Tab. 4 shows that there is a relative difference between the average thickness of the coatings, since reaching values of 2.01 µm for the coating E and to values of 3.29 µm for coating B and 3.30 µm for coating C. The average thickness of coatings D and E were very close showing a magnitude lower than other coatings, which may be related to the reason of monolayer coatings and belonging to the same manufacturer, which is distinct to that of other coatings. The coating B has triple layer and the latter is in the form of a gradient alloy AlCrN with Si_3N_4. The coating is nanostructured and nanocomposite, with a combination of Si_3N_4 and AlTiN.

Figure 4 shows the results obtained in experimental tests carried out. Based on the results, the wear of cutting tools and machining lengths of each tool were analyzed.

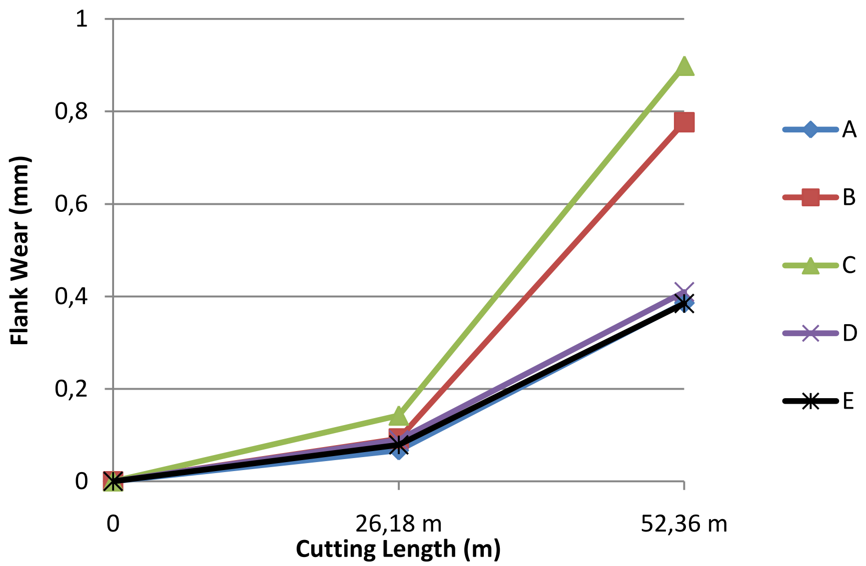


Figure 4. Evolution of flank wear with cutting length.

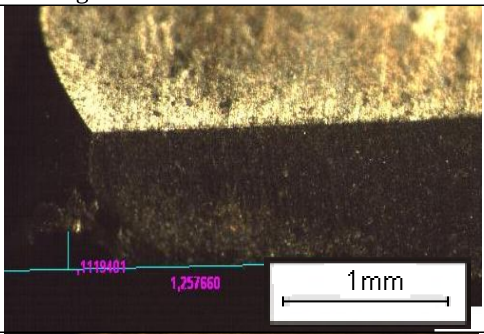
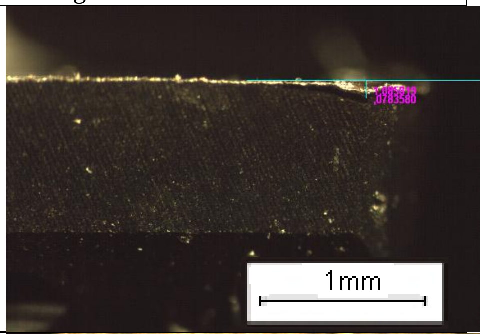
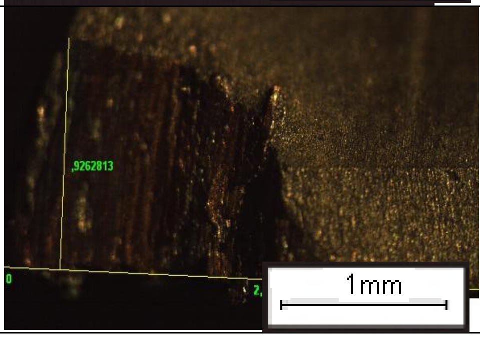
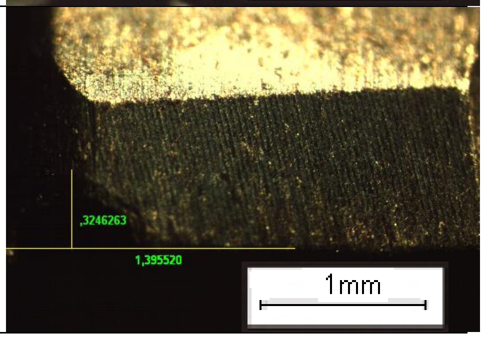
Figure 4 shows that for a length of 26.18 meters, the average flank wear of cutting tools were similar values for all coatings. In statistical analysis of these values, using the software Minitab version 15, was applied to obtain 95% of confidence level and realizes that the coatings A, B, C, D and E, for the length of machining of 26.18 meters, have common values within the range of corresponding confidence intervals, as in Fig. 5.

```
Level        ---------+---------+---------+---------+
A - 26,18m   (-*-)
A - 52,36m               (*-)
B - 26,18m    (-*-)
B - 52,36m                              (-*-)
C - 26,18m      (-*-)
C - 52,36m                                   (-*-)
D - 26,18m    (-*)
D - 52,36m               (-*-)
E - 26,18m   (-*-)
E - 52,36m              (-*-)
             ---------+---------+---------+---------+
                    0,25      0,50      0,75      1,00
```

Figure 5. Demonstration of graphics confidence intervals for all levels.

Already, for the length of machining of 52.36 meters, the behavior of Vb average and the confidence intervals are different. In Fig. 4 it is possible to notice a big difference in mean flank wear for the coatings tested. Observing Fig. 5, the confidence intervals are showed, for a confidence level of 95%, the coatings B and C had common values within their confidence intervals, but the coating A, D and E on the other hand, had their field well below the scale of development of wear (mm). Tab. 6 shows images of wear caused on tools C and E, which were facing more and less wear on the cutting edges, and also compared the cutting length of 26.18 m and 52.36 m machined.

Table 6. Images of the cutting tools after machining.

	Coating C	Coating E
Tools after 26.18 m of machining length		
Tools after 52.36 m of machining length		

As mentioned in Tab. 3, was also measured the roughness of machined surfaces after machining length of 52.36 meters. The parameter of the surface quality of the work was adopted for the Ra, which corresponds to the average value between the peaks and valleys of the surface in a long analysis, which for the experimental procedure was equivalent to 0.8 mm. Of the amounts collected in surface roughness was obtained for the average roughness of each coating tool used in the experiment, as Fig. 7.

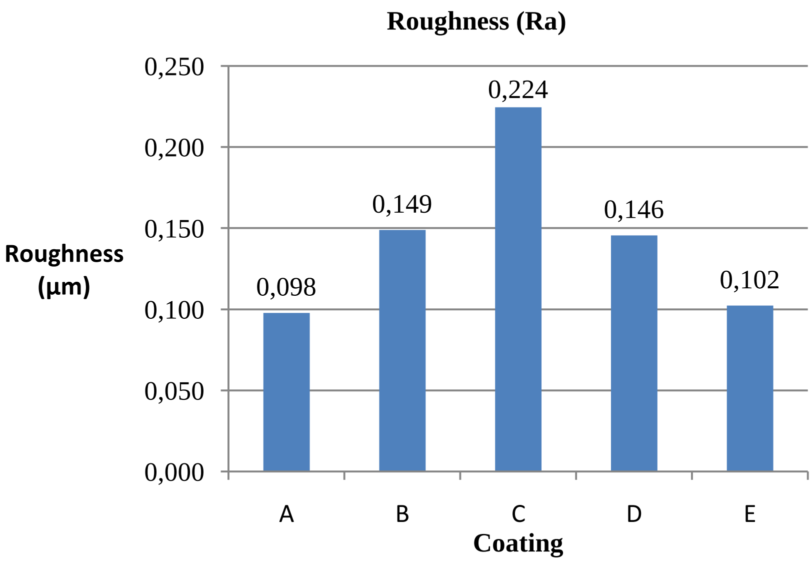


Figure 7. Ra roughness values for the machined surfaces.

Figure 7 shows the variation of roughness of machined surfaces with different tool coatings employed in this experiment. Collecting 9 points of the roughness according to each cutting tool, it was possible to determine the standard deviation for each situation as presented by Fig. 8.

```
Level     Mean    StDev   -+---------+---------+---------+--------
A      0,09778  0,02682   (------*------)
B      0,14889  0,04197            (------*------)
C      0,22444  0,10956                         (------*------)
D      0,14556  0,05747           (------*------)
E      0,10222  0,04177    (------*------)
                          -+---------+---------+---------+--------
                         0,060     0,120     0,180     0,240
```

Figure 8. Standard deviation of surface roughness with each coating tool.

Analyzing the roughness (Fig. 8) and the flank wear (Fig. 4) it is clear to note the relationship between both variables. The coating with the higher wear is also associated to the highest roughness value (coating C). The coatings A and E had the lower flank wear also had lower surface roughness Ra. Tab. 3 also establishing a relation between the tool wear, machined surface roughness and thickness of the coating, its noted that the thickness of the greater coating (C) showed also greater wear and better value for surface roughness, while that the thinner coating (E) had the lowest tool wear and the lowest value of surface roughness.

Thus, it is suggested that with greater coating thickness, the cutting tool loses some of the sharpening angle, a fact that reduces the cutting efficiency, the coating becomes a kind of curved. Thus, the cutting tool loses efficiency, increases the contact area between the tool and the workpiece, increasing the process temperature and the wear is generated on a larger scale.

Evaluating the properties of coatings, there are three possible factors for the evolution of tool wear, namely: i) the thickness of the coating, ii) its microhardness and iii) composition of the same. Note that the coatings B and C have the highest values of microhardness, which consequently makes them more fragile than the others. The intermittend wearing is a feature of the milling process. It is assumed that this fact, coupled with the greatest weakness of coatings B and C, may be responsible for micro chipping at the edges of the cutting tool, and in turn, responsible for increasing the amount of wear on the flank face of the tool, removing as much the coating as well as the base material of the tool. The micro chipping in the flank face of the tool edge can be observed by non-uniform wear profile, as illustrated by Tab. 6 (for coating C).

Putting the values of flank wear of cutting tools in ascending order, machined to 52 meters, together with the corresponding values of roughness, it was possible to draw the trend line of each variable, according to Fig. 9.

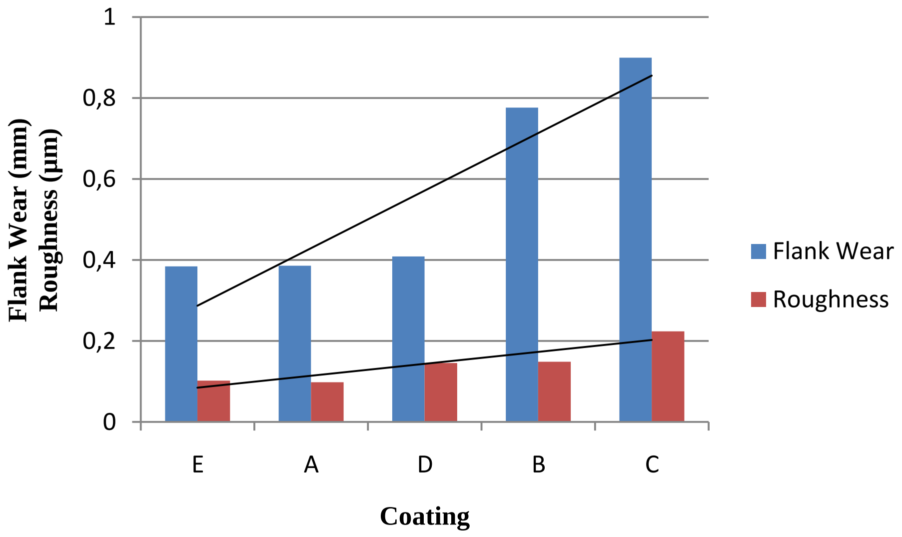


Figure 9. Effect of coating type on the flank wear and surface roughness of the machined material.

Figure 9 it is noted that the trend line growth of wear is more pronounced than the trend line of the roughness. You can also note that the higher the value of wear, the higher the roughness of machined surface.

4. CONCLUSION

The results show the cutting tool wear grows rapidly. It can be attributed to material`s properties, such as hardness, thermal conductivity, microstructure and other characteristics of these materials.

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It is noticed the cutting tool wear affect directly the machined surface roughness. Increasing the tool wear, the roughness get worst. The results are in a confidence level of 95%, since their common points within the confidence interval.

For the conditions employed in this experimental, the coatings A and E performed better than the other. The microhardness and the thickness of the coating C showed the highest values, whereas the coating E showed the lowest values.

The microhardness and the thickness of the coating C is 64% and 61% respectively, higher than the coating E. Comparing the flank wear and roughness of these two coatings, the results show that the tool wear and surface roughness machined with the coating C is 134% and 120%, respectively, higher than the coating E (52 meters machined).

Among the compositions of the coatings evaluated, the AlCrN showed good results when applied in a single layer (case E). This coating also had a lower microhardness. The results show that high coating thickness and high microhardness cannot be associated to the good machining performance.

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