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ANALYSIS OF TOOL WEAR IN GENERATION OF INDUSTRIAL GEAR TEETH

Cláudio Parreira Lopes
Durval Uchôas Braga
Frederico Ozanan Neves
Alex Sander Chaves da Silva
UFSJ - Universidade Federal de São João Del Rei - Praça Frei Orlando 170 - Centro - São João Del Rei - Minas Gerais - MG
CEP 36307-352
claudioufsj@gmail.com
durval@ufsj.edu.br
fred@ufsj.edu.br
achaves@ufsj.edu.br

Abstract. *Due to the versatility in production metalworking, CNC machines have been employed continuously replacing the conventional equipment in manufacturing processes. Proof of this is the growing demand for high -tech equipment that happens to a remarkable extent in most Brazilian companies, with consequent reduction of time and costs. Despite the high level of automation, it is often integrated devices for this equipment that are able to predict the optimum time for replacement of tools for wear and / or damage. In this sense, we ran a case study where through technical monitoring direct and indirect we´re able to evaluate the state of degradation of the tools in the gear milling industry. The results will then implement a sensor prototype monitoring to be installed on CNC machining centers. For the tests were used at different levels of tools, cutting speed and machining lengths. The main conclusion is that higher wear were observed when using low shear rate and greater cutting length, regardless of the type of tool used, and non intrusive techniques are important coupled to the reduction of subjective disposal of tools in the process of machining.*

Keywords: CNC, Milling, Wear / Faults, Gear Manufacturing, Monitoring.

1. INTRODUCTION

The milling process used in conventional gear manufacturing has been gradually replaced by alternative manufacturing computer-assisted performed on CNC machines. The tools used in the conventional process (milling module, cutter snail) have high levels of acquisition, being equally costly when they need regrinding and implementation of new coverage, when compared with interchangeable tools, lost in logistical requirements and technical requirements, and can quote complex geometry (which complicates its fixation on microscopes and profile projectors, interfering with the measurement of wear / damage), costs of machinery and tooling dedicated classes limited tools with respect to the machining of certain types of materials, among others.

Despite technological advances present in modern machine tools it is not completely possible to determine accurately the ideal time to exchange a worn tool in the machining process. Furthermore, there was heavy reliance on human factors to perform the interruption of the process which can create situations where new tools are discarded still in usable condition or worn tools are used when they should have been replaced. In this context, it is necessary to adopt technical criteria for monitoring the disposal of tools, especially when one takes into account the difficulties to manage large batches of manufacturing and machines working in cycles for continuous production. Normally, in these conditions monitoring techniques combined (direct and indirect techniques) show excellent results.

2. LITERATURE REVIEW

Several researchers (Davis, 2002; Diniz, Marcondes and Coppini, 2008; Ssandvik, 2005; Stoeterau, 2004; Trent, 2000; Youssef and El-Hofy, 2008) define the milling process as "material removal through a cylindrical tool with one or more cutting edges, where the axis of rotation of the tool is perpendicular to the feeding direction and the surfaces have created diverse forms; interrupted cutting with alternating contact between the tool and the work piece, creating cycles of strength, impact and thermal shock" and the greatest advantage is that the concept of the cited authors converge to a common sense.

In face milling (when the milling spindle is perpendicular to the work surface), the chip formation is influenced by the position angle χ_r (which is the angle between the tangent of the main cutting edge and forward direction), the cutting depth a_p (which contributes to the volume of material removed), the width of cut a_e (which is the distance transverse to the cut surface machining). The feed speed v_f (or also called table feed) is determined by the feed per tooth f_z (linear distance traveled by the tool) by turning the cutter (n) and the number of cutting edges or teeth in the process (z). The maximum thickness of the chip ($h_{máx.}$) depends on the sine of the contact angle φ and the feed per tooth f_z. When φ is 90º, the chip thickness is equal to the feed per tooth f_z.

The conventional milling has been replaced by alternative manufacturing on CNC machines. The advantage of the CNC process cites the reduction of time liabilities relating to the exchange of machines, with consequent reduction of setup times. Also permitted is the simulation time and the machining path, which is not possible in the conventional process. Advantageously, improved cutting strategies can be chosen to allow reduction of the machining time, as shown in "Fig. 1". Moreover, CNC machines allow high speed machining cutting, which is not always possible when using conventional machines.

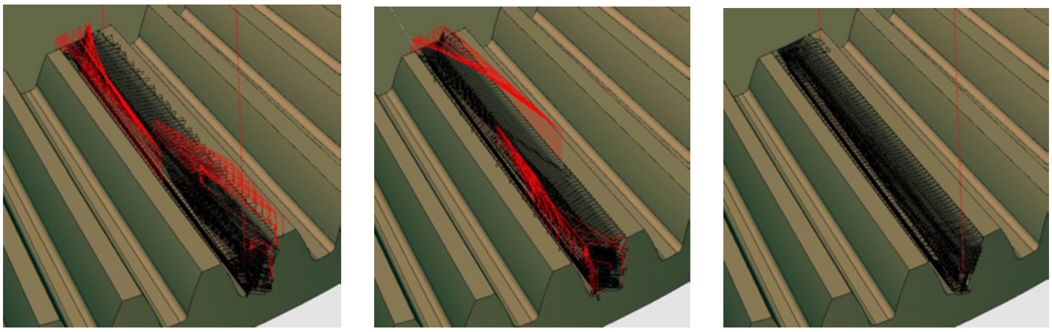

Figure 1. Different strategies in simulated machining CAM software.

According to Diniz, Coppini and Marcondes (2008), the milling operation, the cutting tools are subject to wear, defined as the continued loss and microscopic particles due to the cutting action and the remaining occurrences that do not have this characteristic are called faults. Several phenomena are responsible for wear and damage, but in the milling one can observe with greater frequency thermal damage due to the cooling cycle in interrupted cutting. When milling it is more common to find the flank wear, usually located on the main surface of the tool ($A\alpha$). This occurs due to high cutting speed and low feed per tooth f_z. On the exit surface crater wear can be seen, which occurs due to lack of coverage of the tool and the type of chip generated.

With regard to monitoring and control signals from the cutting process, Davis (2002) states that in the early work of machining fault detection depended exclusively on the human factor, and this dependence occurs until today. Modern machines work with rotations of 100.000 rpm and rapid advances of 500 mm / second, with no physical man to monitor these quantities subjectively. Aized (2010) states that currently there is no standard monitoring due to the large number of variables of the process and the many existing techniques. There is an obvious trend among researchers in the choice of methods for indirect and non-intrusive monitoring. The measurement of shear forces, for example, introduces limitations in the arrangement of the tool assembly and requires special care, especially with cutting fluid and chips from machining. Several authors (Bhattacharyya *et al.* 2008; Kovac, 2008; Li, Venuvinod and Chen, 2000; Norman, 2003) argue that monitoring via electrical current has good results , both in terms of acquisition, and from the point of view of costs for deployment.

The monitoring via electrical signals of the motor can be performed using Hall effect sensors. These sensors are current transformers (with an open or closed core) that vary its output voltage as a function of an applied magnetic field. They consist of two windings of coils (primary and secondary) wherein the ratio of the number of turns provides the current through the conductor. The main advantages of these sensors are that they are free of the problems with heat dissipation and are electrically isolated from the main circuit measurement. These sensor designs can be seen in "Fig. 2".

a) b)

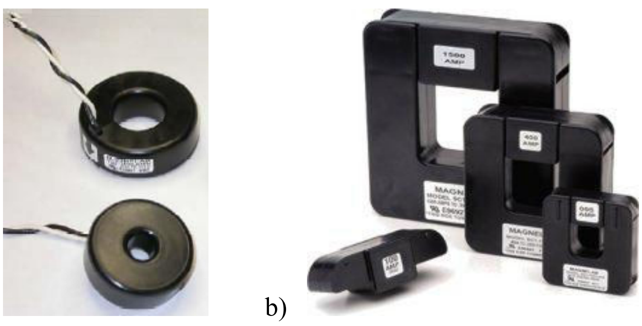

Figure 2. a) TC closed core; b) TC open core (Ni, 2013).

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3. MATERIALS AND METHODS

For the experiments, the equipment used was a machining center Travis M2000 brand, as shown in "Figure 3", with its set of tools in the machining process. The machine has the installed power of 15 kW spindle, rapid advancement in the XY axis of 18 meters / minute and the Z axis of 10 meters / minute, which features for fast magazine that holds up to 20 tools.

a) b)

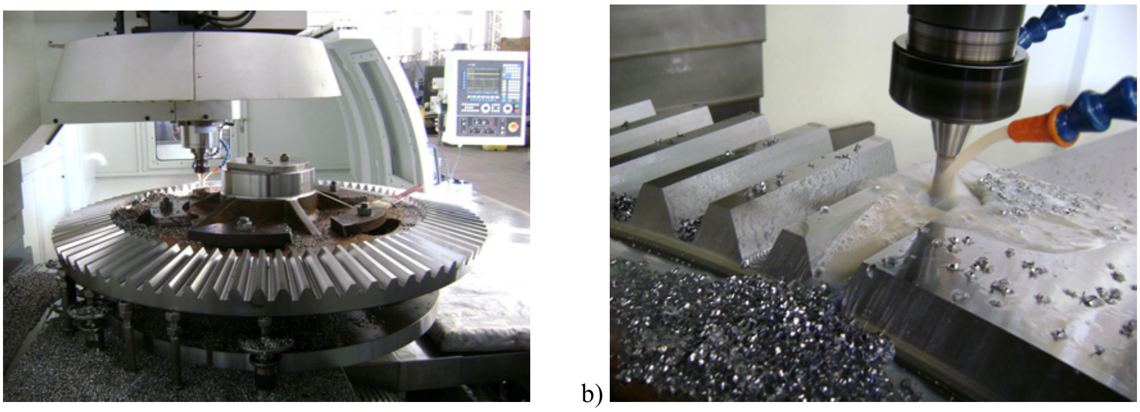

Figure 3. a) Machining Center Travis M2000; b) Installation of the tool.

The specimen used was a metal model with outer diameter of 1300 mm and overall height of 450 mm, cast steel ABNT 4140, displayed between 251-280 HB hardness after annealing and metallurgical structure composed predominantly martensite after heat treatment.

The independent variables were adopted in a two cutting tools (T1 and T2), the cutting speed (in three levels 80, 90 and 100% of catalog v_c) and the cut length into four levels (L1, L2, L3 and L4), as shown in "Tab. 1".

Table 1. Independent variables.

Controlling factor	Unit	Levels
Tool	-	2
Cutting speed (v_c)	m/min.	3
Cutting length	mm	4

The tools were hard metal, ISO Class P with a chipformer. The tool T1 is plated with titanium nitride (TiN) and the tool T2 plated with aluminum titanium nitride (AlTiN). In all trials remained constant cutting depth a_p and the value of 0,6 mm feed per tooth f_z, with 0,3 mm / tooth. The medium used for fixation of the tools was the model BAPZ300R101S12. Other information tools are shown in "Tab. 2" and "Fig. 4".

Table 2. Technical information tools T1 and T2.

Tool	Manufacturer	Identification code	r_ε (mm)	Le (mm)	Wi (mm)	Th (mm)
T1	MITSUBISHI	APMT 1135 PDER H4 F7030	1,6	11	6,35	3,5
T2	KENNAMETAL	XDHT 090316 PA 120	1,6	9	6,35	3,18

a) b)

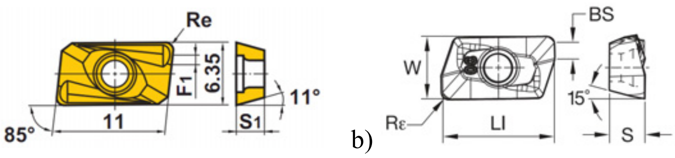

Figure 4. a) Tool T1 (Mitsubishi, 2012); b) Tool T2 (Kennametal, 2012).

The tests were conducted in four levels by the length cutting edge of the insert, this being equivalent to the material removed between two consecutive teeth, as shown in "Fig. 5".

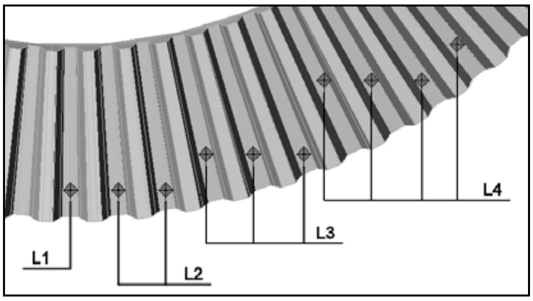

Figure 5. Determination of cut lengths.

For each test, three replicates were performed for a total of 2 x 4 x 3 x 3 = 72 tests. The execution order of the trials was randomized, ensuring that the variables studied and the experimental errors also present randomness. For each cut length, hardness measurements were performed in three positions of the gear tooth, measuring current and power and electrical measurement of wear, damage presented. In "Table 3" we specify the dependent variables of the experiment.

Table 3. Dependent variables.

Variable response	Variable type	Unit
Hardness	Quantitative	HB
Current	Quantitative	Ampere
Potency	Quantitative	Watt
Wear and / or damage	Quantitative	μm

To monitor the wear and or damage to the tools used an electron microscope Mitutoyo Model TM-500 with 60 times magnification and image processing software Motic Images Plus 2.0, as shown in "Fig. 6". The tools were fixed on the measuring table by a template. The handling of the tools on the table was performed through the ring micrometer digital coordinate axes in XY and Z axis and focus was regulated by manual control approach.

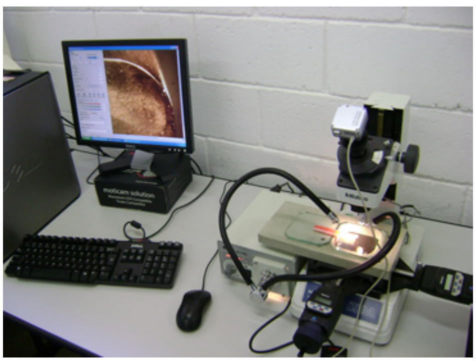

Figure 6. Measurement tools in digital microscope.

For qualitative analysis of wear / faults present in the tools was used a scanning electron microscope (MEV), model Hitachi TM-3000 with 300 times magnification and accelerating voltage of 15 kV. The tools were fixed on a sample holder as shown in "Fig. 7".

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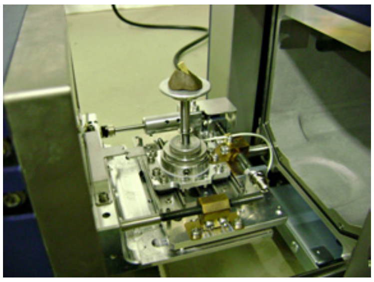

Figure 7. Fixing tool in scanning electron microscope.

The current signals and electrical power consumed in the power phase of the three-phase motor of the machine were collected in two ways. First we used a Yokogawa digital transducer Model 2480 D, and subsequently only for the signals of the electric current was used a digital acquisition card analog USB model 6008 from National Instruments.

To feed Transdig was used two Hall effect sensors, Model MSQ 30, Lukma manufacturer, with turns ratio of 60/5, able to perform readings between 0-5 amperes with approximation error of 5%. The model of current transformer and mounting scheme of digital transducer are shown in "Fig. 8".

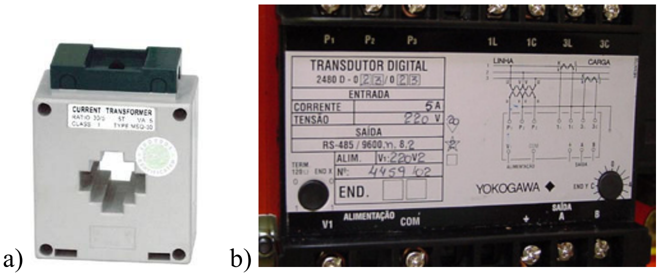

Figure 8. a) Current transformer (Lukma, 2012); b) Digital Transducer Yokogawa.

The electrical signals from the analog outputs of the transducer were connected to a digital conversion board AD brand ICP CON Self-Tuner Model 7520 RS-485 RS-232 and this to a computer via the USB port, using the software Transdig Enhanced 1.4.4 for data acquisition. The graphical display software was configured to read the signs of the electric current and power supply phases chosen. The experimental set acquisition can be seen in "Fig. 9".

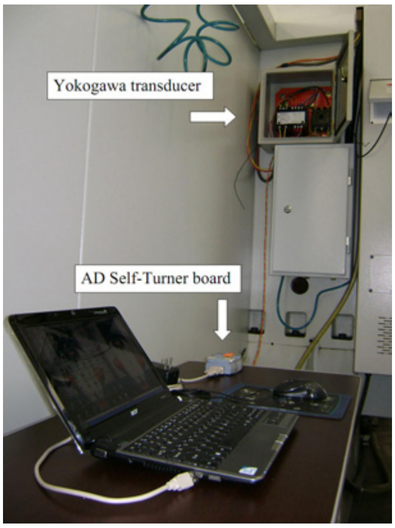

Figure 9. Mounting plate experimental AD Self-Turner and transducer Yokogawa.

In the second assembly was used the same current transformer whose analog outputs were connected to the input channels of the data acquisition card NI USB 6008, and the serial port of the computer where the signals were collected and stored through a virtual instrument (VI) software created in LabView 8.5. The sampling rate of the monitored signals was 120 Hz, with trigger set to five minutes interval.

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The hardness of the specimen was measured by a durometer manual Time Hardness Tester, Model TH 130 at three points located 25 mm in the end of the tooth profile machined. The trajectory of the cutting tool is determined by ISO programming language, generated with the help of software from CAM Fagor Automation. The profile drawing engaging the gear tooth was performed with the aid of CAD software, the ZWSOFT.

4. RESULTS AND DISCUSSION

The first dependent variable studied in this work was the hardness. The measured values are compatible with the technical specifications of the manufacturer catalogs of tools with respect to the selection of the cutting parameters. Through a randomized factorial design through levels with fixed effects model and assuming a confidence level of 95%, it can be stated that the hardness values are equal and do not differ significantly in regards to the condition of tool wear. In "Table 4" shows the analysis of variance calculated.

Table 4. Analysis of variance for hardness in the gear teeth.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	815,944[a]	23	35,476	,571	,927
Intercept	5215373,389	1	5215373,389	83930,908	,000
Lc	101,389	3	33,796	,544	,655
vc	149,528	2	74,764	1,203	,309
Tool	16,056	1	16,056	,258	,614
Lc * vc	171,694	6	28,616	,461	,834
Lc * Tool	85,389	3	28,463	,458	,713
vc * Tool	88,528	2	44,264	,712	,496
Lc * vc * Tool	203,361	6	33,894	,545	,771
Error	2982,667	48	62,139		
Total	5219172,000	72			
Corrected Total	3798,611	71			

The second dependent variable was studied in this work wear. In "Table 5" shows the analysis of variance calculated. There was no major wear on the surface of ($A\alpha$) due to the fact the cutting depth (a_p) to be less than the radius of the tool tip (r_ε).

Table 5. Analysis of variance for the secondary surface wear.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	,220[a]	23	,010	15,370	,000
Intercept	1,120	1	1,120	1800,574	,000
Lc	,117	3	,039	62,944	,000
vc	,047	2	,023	37,790	,000
Tool	,001	1	,001	1,352	,251
Lc * vc	,039	6	,006	10,359	,000
Lc * Tool	,007	3	,002	3,943	,014
vc * Tool	,003	2	,002	2,742	,075
Lc * vc * Tool	,005	6	,001	1,381	,242
Error	,030	48	,001		
Total	1,369	72			
Corrected Total	,250	71			

Statistical analysis of variance (ANOVA) was calculated with respect to the wear measured. It is observed that the cutting speed and the cutting length, as well as their interaction, have an influence on the wear of the tools. Also, despite the type of tool used not showing significant differences in wear observed, have the same interaction with the cutting length, showing suffer influence.

Contrast analyzes for statistical cutting speeds observed that all interfere with tool wear, highlighting major cutting speeds, which produced lower levels of wear on tools. In the case of cut lengths used, it can be said that they directly affect the wear of the tools. However, in the case of the initial cut lengths (L1) and (L2), there were no significant differences in tool wear.

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From the analysis of the interaction between cutting speed and cut lengths, it can be said that there is significant influence, producing greater wear when machined with lower cutting speeds and higher cut lengths. Thus, in the case of milling of initial cut lengths (L1) and (L2) it is recommended to work with higher cutting speeds, given that the feed per tooth is constant, it is possible to produce parts with less machining time. Since the same behavior was also observed in the interaction between tools and cutting lengths suggested to select less costly tools in the initial cut (L1) and (L2). "Figure 10" is a graph of the average values of the wear of the tools depending on the length of cut and cutting speed studied.

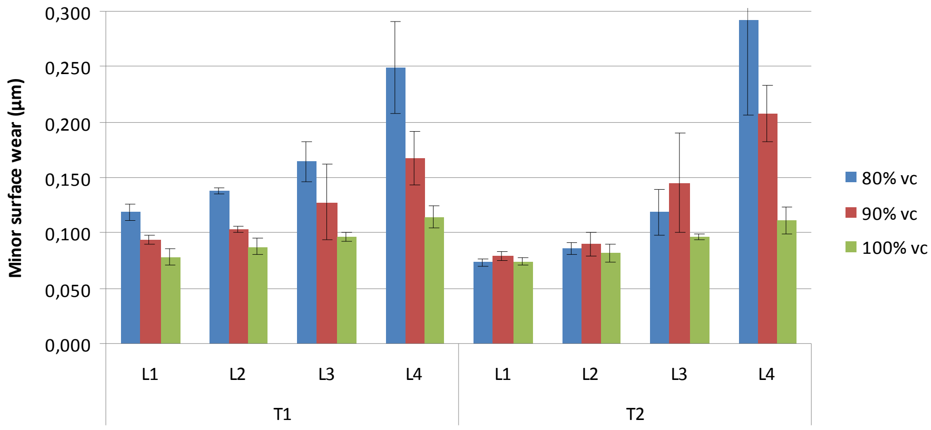


Figure 10. Average value of tool wear.

In "Figure 11" shows the secondary clearance surface for one of the tools T1 when used respectively, 80, 90 and 100% of shear with two lengths machined (L2) and four machined lengths (L4). In "Figure 12" shows the condition of the secondary area gap of one of the tools T2 when used respectively, 80, 90 and 100% of the cutting speed of two lengths machined (L2) and four lengths machined (L4).

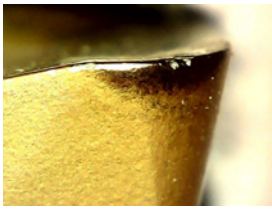
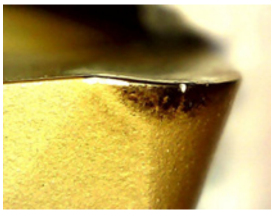
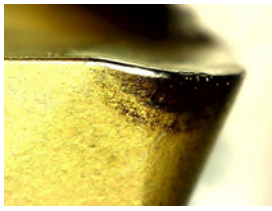
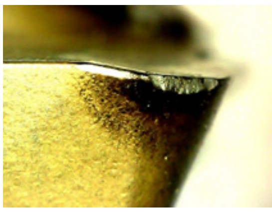
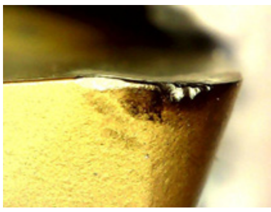
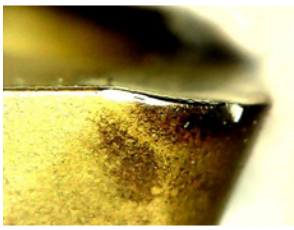
Length/v_c	80% v_c	90% v_c	100% v_c
L2			
L4			

Figure 11. Secondary area off tool T1.

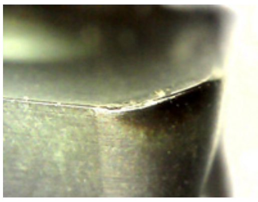
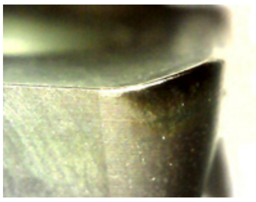
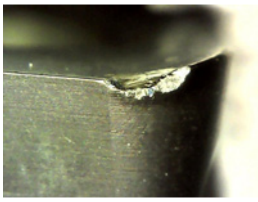
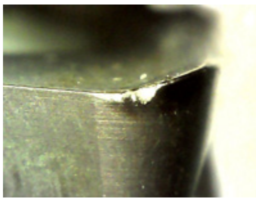
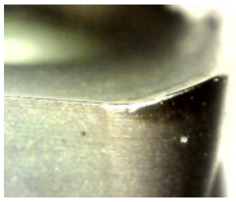
Length/v_c	80% v_c	90% v_c	100% v_c
L2			
L4			

Figure 12. Secondary area off tool T2.

The third dependent variable studied in this work was the motor current of the machine. In "Table 6" shows the analysis of variance calculated.

Table 6. Analysis of variance for electric current.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3,608[a]	23	,157	4,601	,000
Intercept	374,517	1	374,517	10982,776	,000
Lc	1,326	3	,442	12,960	,000
vc	,240	2	,120	3,515	,038
Tool	,444	1	,444	13,025	,001
Lc * vc	,188	6	,031	,918	,490
Lc * Tool	,367	3	,122	3,588	,020
vc * Tool	,368	2	,184	5,391	,008
Lc * vc * Tool	,676	6	,113	3,305	,008
Error	1,637	48	,034		
Total	379,763	72			
Corrected Total	5,245	71			

The current values were obtained from the electric current differences when the machine was without court action, or empty, and the machine in the machining process. Thus, the current value used for analysis of the results expressed exclusively the portion related to the machining process. The electrical output signals were monitored using the same methodology as current signals, as described in Materials and Methods, with similar behavior and showing correlation with results discussed below. It was observed that all levels of the independent variables influenced the current and power consumed in the tests, except for the interaction cutting speed and the cutting length.

In the contrast analysis cutting speeds, we found that lower velocities were more sensitive to the increase of the electric current when compared to higher cutting speeds, consistent with what was discussed in the case of wear variable, where the greatest erosion of the tools were found in lower values of shear.

While accepting the equality of the tools in the case of variable wear, it was noted to have the same interaction with the length of the cuts. There was an opposite behavior in the degree of wear from the length of the cut (L2), and showing differences in the cases with variable currents, it can be said that not all power consumed in the cutting is a consequence of tool wear, but it is also due to thermal cycling process, and the difference from degradation and fault coverage provided.

As noted in the dependent variable wear, there was a substantial constant increase in the current level after the machining of the second length cut. Thus, it is recommended as a preventive action an inspection of the tools when they are performing major cut lengths, considering that in this situation the electric current suffered greater interference of independent variables of the process. "Figure 13" represents the graph of values of electric current in function of the length of cut and cutting speed studied.

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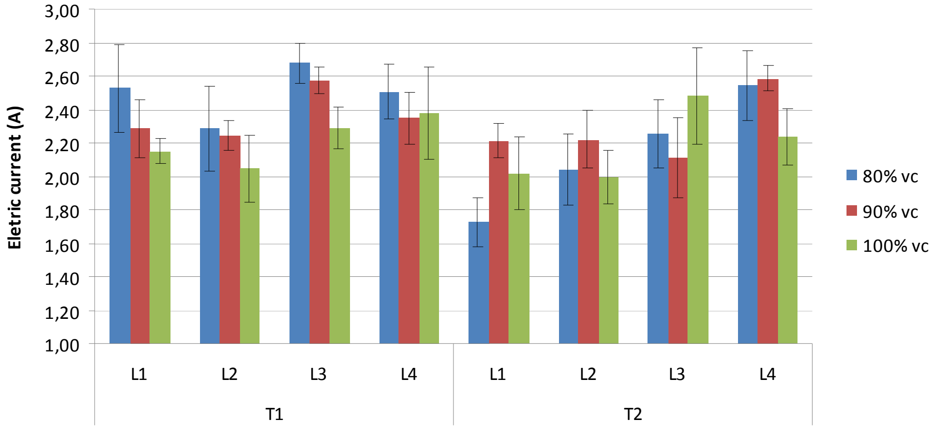

Figure 13. Average current for tools.

For tool T1, the largest average wear was observed in lower values of cutting speed, similar to what occurred in the behavior of the current monitored. For tool T2 it can be observed a large delta value of the electric current between the cutting length (L1) and cut length (L4), which occurred in a way more subtle in tool T1. This difference is related to the irregular behavior of the tool during machining T2, mainly depending on the type of coverage, which showed higher detachment as the cut lengths increased.

Tool T2 had higher electrical current trend with growth in higher cutting speeds, and this may be associated with the type of damage observed. In milling, when increase in the cutting speed is changed at the beginning of cutting, it is expected that damage decreases. However, as the feed per tooth in the tests was kept constant, increasing the cutting speed acted by promoting the occurrence of reverse faults, particularly chipping, as shown in qualitative analysis.

It is known that the milling process is cyclic, where the values of electric current tend to be alternating largely, as the cutting width is changed. Thus, the current behavior may have been influenced by the characteristics of the process, although in some cases it also depended on the state of degradation of the tool. There were two possible effects associated with increasing the electric current in this study in particular: the decrease in strength of the material due to the increased heat (which would facilitate cutting resulting in lower power consumed) and increased contact area between the worn surfaces and the workpiece (which would increase the coefficient of friction and power required to perform the actual cutting). In this case it was noted to have occurred influence the increase of the contact area between the tool and workpiece, as can be identified in the subsequent analysis of faults performed using the scanning electron microscope (MEV).

Knowing that higher cutting speeds have less influence on the wear / damage observed in the studied process, and subsequent lower values of current / electric power consumed, it is suggested to work with cutting speeds up to 100% of the values used in this work to ensure better operational efficiency of the tools.

Mechanical damage occurring during the milling process in this work was investigated at magnifications performed under MEV. The qualitative results of the analysis showed tools are consistent with the discussion previously performed, or when used 80, 90 and 100% of the cutting speed and the cutting length (L2) and (L4), it was observed that the tool T2 showed a higher degree of degradation compared to the tool T1 in larger cut lengths. In "Figure 14" shows the secondary cutting edge of the tool T1 and "Figure 15" shows the secondary cutting edge of the tool T2.

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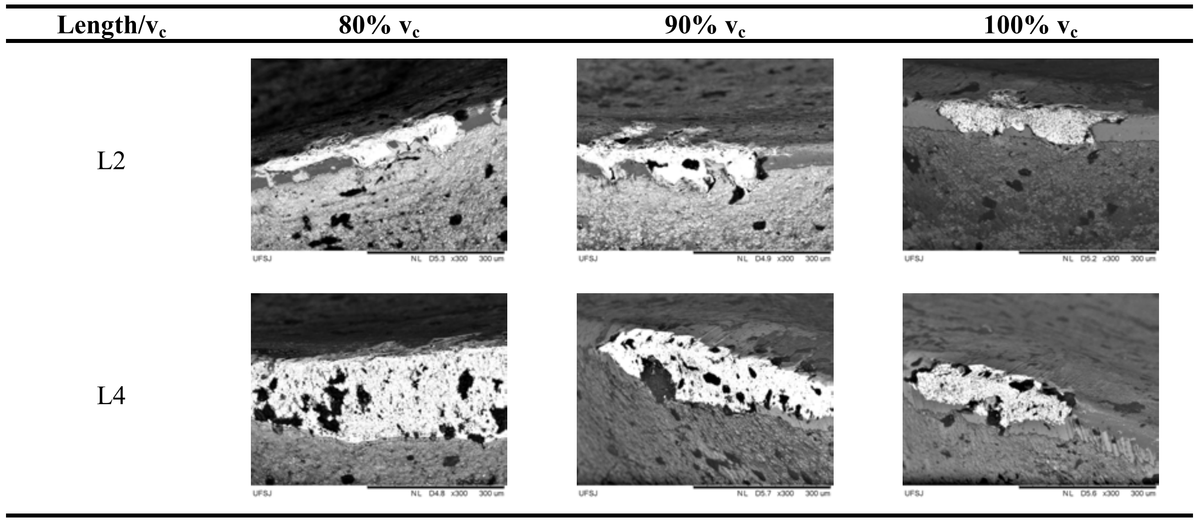

Figure 14. Secondary cutting edge of the tool T1.

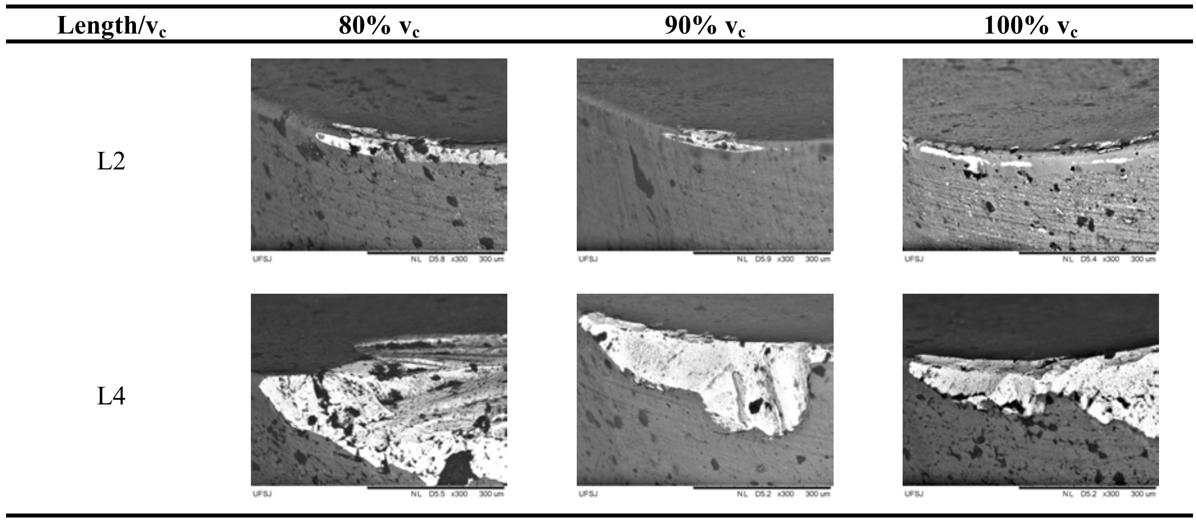

Figure 15. Secondary cutting edge of the tool T2.

As noted in "Figures 14 and 15" tool T1 showed higher detachment coverage at lower cutting speeds. This phenomenon was also noted in the tool T2 at lower cutting speeds, but with a gradient greater growth when compared to the tool T1. Thus, it is concluded that the qualitative manner of the state of degradation of the tool T2 is greater than tool T1, implying in definition in this test condition what is the end of the test tool life, in other words, after the machining of four lengths of cut (L4).

5. CONCLUSIONS

Analysis tools used in the generation of industrial gear teeth when using three different levels of shear rate and four levels of cut length concludes that:

- There is a dependency relationship between cutting speed and cutting length on the wear of the tools studied.
- The increased wear observed on the surface secondary to the gap of the tool occurred when we used the lowest level of cutting speed.
- The current and the electric power consumed by the motor of the machine showed similar behavior of growth and size as tool wear progressed.
- Higher levels of electrical current and wear were observed when there was an increase in cut lengths in the process.
- Despite having accepted the equality of the tools as for wear, qualitatively the tool T2 showed higher surface degradation secondary to the gap compared to the tool T1.
- The qualitative analysis of the wear performed using the MEV noted flank wear for half the tool life observed in (L2) followed by abrasion and chipping for the end of the tool life observed in (L4).

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