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Tool wear monitoring and prediction in micro milling process for medical applications. Experimental analysis and characterization of tool wear for titanium materials

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Abstract: The detection and prediction of tool wear within micro manufacturing processes is very important in order to develop automatic systems for the reduction of defects to zero. The "in process" precision measurements of the tool wear in micro milling are very challenging. In this work, we present a method for establishing a relationship between the cutting forces and the tool wear based on signal process analysis. The reference milling is used for the development of signal patterns for the tool wear under well-known conditions. In process the cutting force's signals show a strong correlation with the tool wear (Tool wear experimental function). Based on this dependence, the tool wear for the consecutive next work piece can be predicted. In the next step of these investigations wavelets will be used for the signal analysis in order to increase the sensitivity of the method.

1. Introduction

Miniaturised parts or features, in the dimension of a few millimetres to a few micrometres, are increasingly demanded e.g. in medical, transportation, environmental and communication industries. Besides the amount of products, there are also new requirements on the quality of micro components, such as high accuracy, three-dimensional (3D) geometries and a broader material pallet including metals [1].

This study is part of a research project supported by MIDEMMA – "Minimizing Defects in Micro-Manufacturing Applications" and it aims to carry out the analysis of tool wear in micro milling tools through the optical and sensors monitoring. The goal of this study is data acquisition as well as discovering the behaviour of determined process indicators and developing a pattern that can be used as implementation of intelligent failure prediction in micro milling tools. Finally, we developed a Tool Wear experimental function according with the Taylor's equation for Tool Life Expectancy.

Working in micro dimensions is a very complex task, not only due to the difficulty to fabricate parts and tools, but due to precision requirements involved. The micro-technology still needs improved accuracy when it is directed applied in medicine. One piece with minimal inaccuracy can cause discomfort to a patient, and thus be unsuitable for use.

This study was carried out with the tracking and monitoring of work life of a micro-milling tool. During the process, tool wear was observed by using optical equipment and it was possible to characterize the wear evolution. Eventually we developed the Tool Life Curve.

This experiment was performed using titanium workpieces. When employing machining titanium alloys, the cutting tool is subjected to severe mechanical and thermal shock, especially in a small area close to the cutting edge, resulting in great influence on wear and consequently the tool life. Flank wear, crater wear, nicking, chipping and breakage of the cutting edge are the predominant failure modes when machining titanium alloys, being caused by the combination of high temperature, high mechanical stress, high chemical affinity of titanium materials tools, etc. [1].

2. Experimental setup

This experiment aimed to measure, monitor and analyse the tool wear in the micro milling process using a Ti6Al4V workpiece with dimensions of 100x80x12 mm. The work was carried out using a 5 axis micro milling machine tool and an end mill tool with 1 mm of diameter, short cut length and long neck, MS2XLD0100N060, Figure 1. The temperature of the spindle has its own cooling system and the temperature is controlled and stabilized between 24-28 °C. The results were not updated by the temperature changes and no external cooling system for the micro milling process was used.

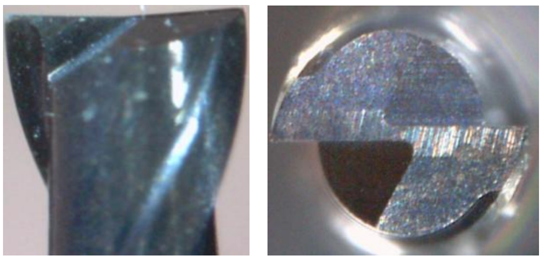

Figure 1 – Images of the used tool obtained with a simple digital microscope, with magnification 40

The pre-set parameters were established according to real parameters used in medical company for the micro manufacturing of dental prosthesis and maintained in all experiments in order to ensure the repeatability of the experiment, see Table 1. Described conditions are used during all experiments steps.

n (Spindle Speed)	22000 rpm
Vc (Cutting speed)	69 m/min
N° of teeth	2
fz (Feed per tooth)	0,01 mm/tooth
Vf (Tool Feed)	450 mm/min
Ae (With of cut/radial depth of cut)	0,5 mm
Ap(Depth of cut/axial depth of cut)	0,015 mm

Table 1 – Pre-set process parameters used in the experiments

2.1 Methodology

2.1.1 Description of micro milling process

In total 18.3 hours of manufacturing process and 252 meters of milling path on the titanium workpiece were performed. During the whole process the experiment was divided into 15 steps, see Table 2. Each step consists in face milling of two surfaces from the workpiece (100x80 mm) with the milling parameters settled, and every step had duration of 1.22 hours of milling with direct contact between the tool and the workpiece.

Milling Step	Accumulated Milling Time (hours)
00	0
01	1,22
02	2,44
03	3,66
04	4,88
05	6,10
06	7,32
07	8,54
08	9,76
09	10,98
10	12,20
11	13,42
12	14,64
13	15,86
14	17,08
15	18,30

Table 2 – Accumulated milling time per step

First the experimental geometry (as described above) has been milled two times into the “workpiece”; a reference line is milled into the reference line, (Figure 4). During the reference milling, sensors were measuring the cutting forces and the acoustic emission.

After this procedure, measurements on the top of the tool and the roughness of the references lines were performed and compared in order to find correlations between them. Within this experiment, temperature was not measured or controlled.

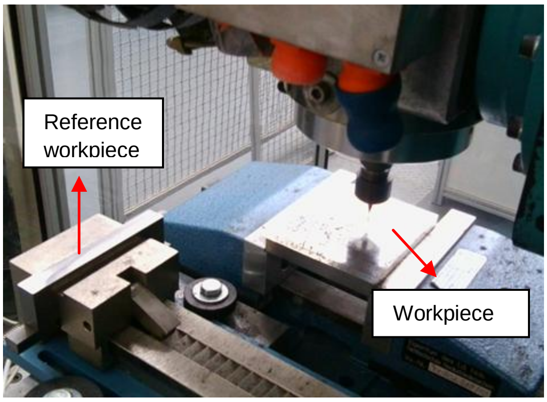

Figure 2 – Experimental set up of the milling zone with the work and reference piece

2.1.2 Tool wear measurements

As the axial wear was negligible small, we only measured the tool wear on the top of the tool by checking the cutting edges, see top Figure 3. For each of four surfaces milled on the workpiece, the tool was analysed using Microscope Macro Dynanoscope 5D. 21 measurements were performed on both cutting edges A and B. The wear was measured from the beginning of the wear region (M1) to the previous cutting edge position (M21). The distance between each measurement (M) was 20 micrometres, and with this methodology the two cutting edges were verified, see bottom Figure 3.

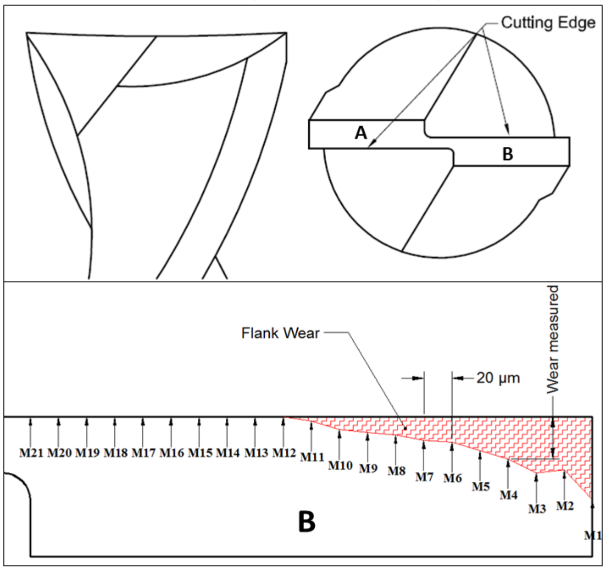

Figure 3 – Top: Model of tool and cutting edge, Bottom: Procedure of 21 wear measurements using standardised equipment (QuadraCheck 2000)

2.1.3 Reference lines measurements

All lines milled into the “Reference Workpiece” were analysed using the confocal Laser Scanning Microscope 700 in order to compare the behaviour of the lines according to the tool wear.

The thickness of the “Reference Workpiece” is 12.8 mm and the reference lines are milled using a feed rate of 450 mm per min and a milling depth of 15 µm. Milling one line takes 1.71 s and in total 15 lines were milled during this experiment. The development of reference lines is explained in Figure 4.

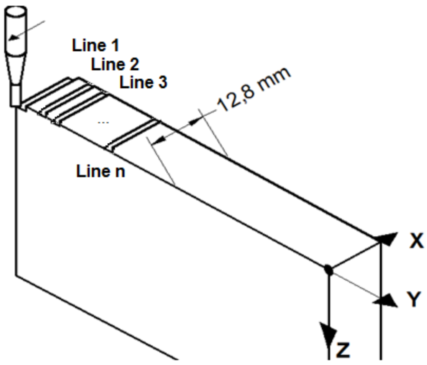

Figure 4 – “Reference Workpiece” model representation

We measured four parameters for every reference line: Line depth, line width, edge height and edge width, see Figure 5. To ensure a better representation, this procedure was repeated five times for each line and a mean value was used to represent this pattern.

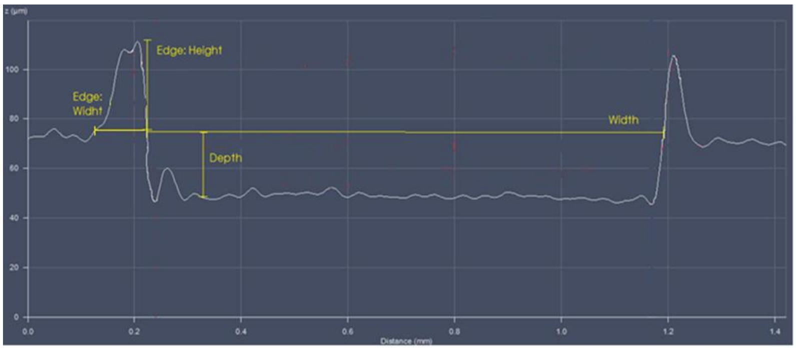

Figure 5 - Reference line measurements using the confocal laser scanning microscope 700

3. Results

3.1 Tool wear measurement

Table 3 shows the evolution of tool wear measured during every 2 steps.

Surface	04		08		12		16		20		24		28		30	
	EDGE		EDGE		EDGE		EDGE		EDGE		EDGE		EDGE		EDGE	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
M1	0,041	0,036	0,043	0,040	0,046	0,043	0,046	0,045	0,048	0,051	0,050	0,051	0,051	0,060	0,057	0,061
M2	0,033	0,032	0,035	0,036	0,036	0,039	0,040	0,040	0,042	0,043	0,045	0,043	0,048	0,050	0,051	0,052
M3	0,030	0,030	0,030	0,032	0,030	0,036	0,030	0,037	0,034	0,037	0,038	0,037	0,045	0,043	0,046	0,044
M4	0,025	0,026	0,026	0,026	0,027	0,028	0,030	0,032	0,031	0,034	0,034	0,034	0,040	0,039	0,047	0,040
M5	0,022	0,025	0,027	0,026	0,027	0,027	0,027	0,028	0,027	0,031	0,032	0,031	0,038	0,037	0,046	0,039
M6	0,017	0,017	0,024	0,020	0,021	0,024	0,024	0,028	0,025	0,028	0,030	0,029	0,037	0,030	0,041	0,036
M7	0,011	0,012	0,020	0,020	0,021	0,025	0,022	0,026	0,023	0,027	0,029	0,027	0,035	0,028	0,036	0,031
M8	0,003	0,013	0,015	0,020	0,020	0,019	0,021	0,020	0,023	0,020	0,025	0,020	0,027	0,023	0,030	0,025
M9	0,000	0,011	0,008	0,017	0,019	0,021	0,020	0,022	0,020	0,022	0,024	0,022	0,027	0,023	0,030	0,024
M10	0,000	0,000	0,006	0,014	0,018	0,020	0,019	0,022	0,019	0,023	0,023	0,021	0,025	0,020	0,028	0,023
M11	0,000	0,000	0,005	0,013	0,016	0,016	0,018	0,018	0,019	0,020	0,021	0,020	0,022	0,021	0,024	0,022
M12	0,000	0,000	0,000	0,007	0,012	0,012	0,016	0,017	0,019	0,020	0,020	0,019	0,021	0,021	0,024	0,021
M13	0,000	0,000	0,000	0,000	0,011	0,012	0,016	0,016	0,017	0,018	0,017	0,017	0,018	0,019	0,024	0,017
M14	0,000	0,000	0,000	0,000	0,007	0,008	0,012	0,012	0,014	0,016	0,016	0,016	0,016	0,012	0,019	0,015
M15	0,000	0,000	0,000	0,000	0,004	0,004	0,008	0,011	0,011	0,015	0,012	0,015	0,014	0,008	0,021	0,014
M16	0,000	0,000	0,000	0,000	0,003	0,000	0,003	0,004	0,006	0,010	0,004	0,010	0,005	0,005	0,009	0,009
M17	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,003	0,000	0,004	0,000	0,006	0,000	0,009	0,008
M18	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,003	0,000	0,006	0,003
M19	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
M20	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
M21	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ave.	0,009142		0,012142		0,015523		0,017381		0,018952		0,019904		0,021833		0,024571	

Table 3 - Tool wear measurements on cutting edge A and B (mm)

The edges A and B of the tool are depicted in Figure 6 and represent the evolution of wear during the micro milling process graphically. The darker area represents the Step 4 (after four surfaces milled) and the brighter area represents the latest milled face (after 30 surfaces milled).

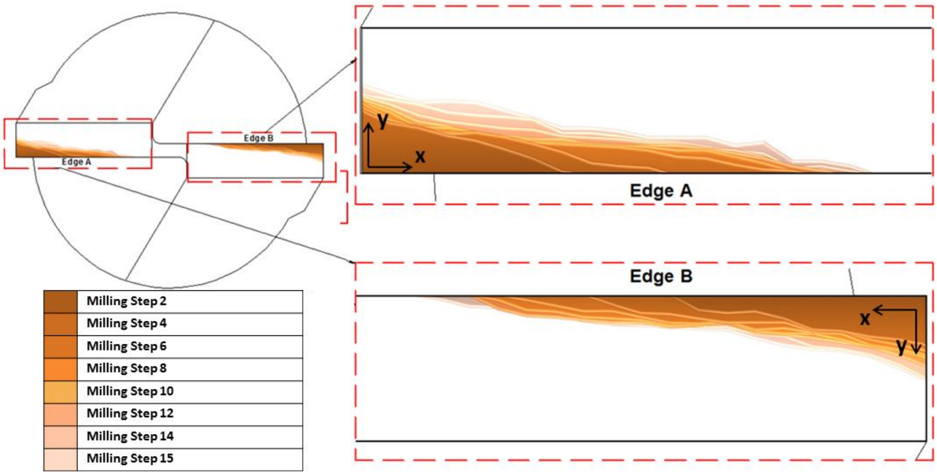

Figure 6 – Evolution of tool wear according to the number or milled surfaces

In every step of the evolution of wear we observed strongly increasing value of the wear in x axis direction and small increment in y axis.

3.2 Reference lines measurement

Since titanium is a poor conductor of heat with only 1/6 of the thermal conductivity compared to steel, the heat generated by the cutting process cannot dissipate quickly. [2] Therefore, most of the heat is concentrated at the workpiece cutting edge. Due to the heat generated in the initial deformation workpiece material in contact with the tool, thermal softening and consequent increasing of deformations on this area appear.

Titanium has a relatively low modulus of elasticity and high elastic limit of tensile strength. When subjected to cutting pressure, titanium elastically deforms almost twice as much as carbon steel. [1]

The images in Figure 7 show the reference lines milled on the reference workpiece. We observed the difference between the shapes of the lines that represent the evolution and consequence of the tool wear on the workpiece. The images shown in 3D served as reference for the measurements, for example, the image shown in Figure 5 is a frontal section view of this 3D model. In 2D images, in Figure 7, (bottom), it is possible to observe the variance of the surface stripe.

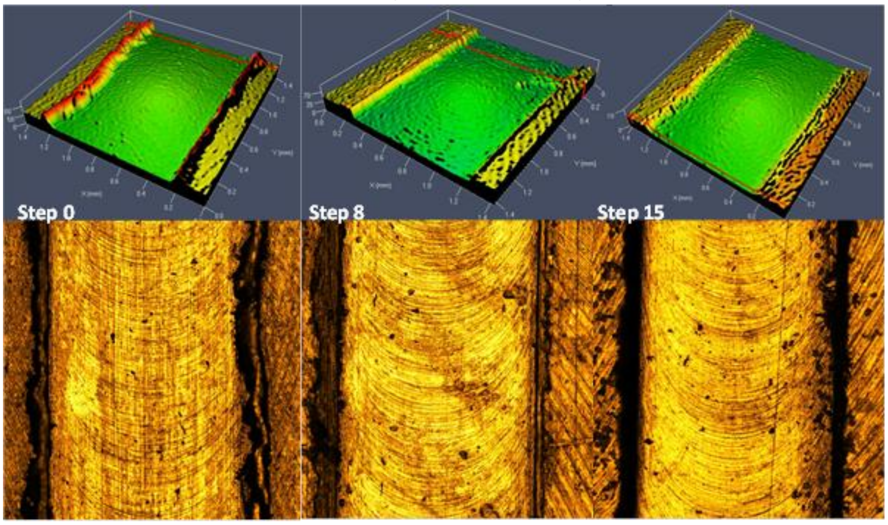

Figure 7 - Bottom: Reference Lines in 2D, Top: 3D captured by the confocal laser microscope 700

In Figure 7 the evolution of the effect of tool wear generated in the “Reference Workpiece” can be observed. The three images refer to: Step 0 - New Tool; Step 8 - Tool in half of the experiment, and Step 15 - Tool at the end of the experiment.

Performing the visual comparison of images, some differences can be emphasized, in particular in the deformation of the side edge of the reference line. To help the understanding and generate the experiment accuracy, the Table 4 was made, showing the distances in micrometres, and the evolution of reference lines according with the step. The description and explanation of each part measured is shown in Figure 4.

Reference Line (Step)	**Depth**	**Width**	**Edge**	
			Height	Thickness
0	20,11	905,60	41,01	89,40
1	20,95	906,80	35,86	74,72
2	22,93	897,00	35,40	83,01
3	23,77	871,20	33,50	79,40
4	22,60	920,00	29,62	60,96
5	22,68	906,60	17,91	58,59
6	20,66	921,40	31,02	46,84
7	6,99	916,60	10,70	37,54
8	19,59	899,80	10,37	77,66
9	12,64	888,20	6,33	43,02
10	36,13	926,00	12,52	25,16
11	23,02	910,80	4,90	18,91
12	27,16	898,60	5,82	19,52
13	28,75	911,80	4,85	10,99
14	33,54	910,40	2,13	8,43
15	31,60	883,80	5,55	14,19

Table 4 – Reference lines measurements (µm)

Table 4 presents the results obtained within measurements on the reference lines during all steps of the experiment, in 4 categories: Depth of the line, line width, height and thickness of the line edge.

Analysing the parameters depth and width of the reference line, it was not possible to observe any relation on these variables with the tool wear. Theoretically, with a higher tool wear, smaller must be the length of the tool and smaller the cutting depth. However, other variables may influence the depth, such as volumetric expansion of the machine and expansion of the workpiece, caused by external temperature or even inaccuracy of the milling machine, etc.

Analysing the results at the edge of the reference line, height and thickness, a clear trend can be observed. In Figure 8, a decrease of the continuous chip formation size at the line edge is clear. It is possible to confirm a high correlation between tool wear and this continuous chip size (-0,905 for height and -0,850 for width).

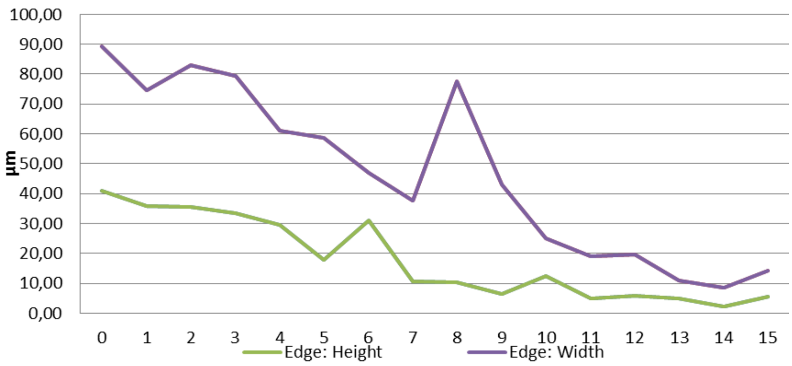

Figure 8 - Evolution of reference line edge measurements

On the one hand, according to [5], increasing the depth of cut and feed rate causes increasing cutting forces on machining operations. On the other hand increasing the cutting speed decreases the cutting machining forces. Increasing the cutting speed also results in an increase of temperature at the interface working area, causing thermal softening of titanium, and favouring the deformation of the edge. In this study the parameters were fixed in all experiment, then the increase in temperature may result in some reduction of the frictional force at the interface working area, decreasing the machining forces and thus, the forces applied to the workpiece.

3.3 Cutting forces measurement

The graph in the Figure 9 presents the mean values monitored by the cutting force sensors on the axes X, Y and Z (the direction and sense of the forces are depicted in the Figure 4). All the cutting forces increase with the number of milled steps.

This phenomenon happens because, in accordance with [4], the influence of tooth chips formation and rate of cutting tool wear appears to be related primarily to the resulting high frequency cutting force variation. The flank wear and the roughness cause directly increase of friction between the tool and the workpiece. Consequently, this friction will cause an increment in the vibrations and in the cutting forces monitored on these sensors.

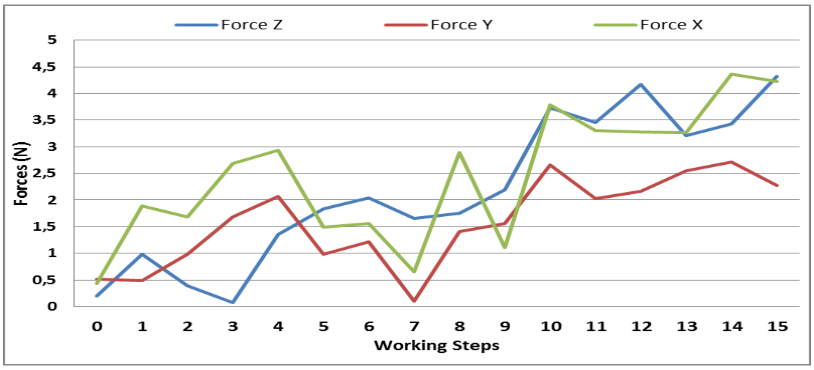

Figure 9 - Average of cutting forces (N) according to the reference line

In Table 5, the correlations between tool wear, depth of cut and cutting forces are presented. High influence of tool wear can be observed when compared with the forces in the X, Y and Z. Especially the force X axis is the most sensitive to the tool wear (0,902). As expected, also the cutting depth provides high influence when compared to the three forces involved, in particular for the X-axis (0,825) which is opposite to the displacement of the tool. This relation could be clear observed at the Step 7 in a low depth of cut (see Table 4). All three forces shown values close to 0 (see Figure 9).

	Force X	Force Y	Force Z	Depth of Cut	Tool wear
Force X	1	0,63314	0,45698	0,82469	0,90276
Force Y	0,63314	1	0,39605	0,78981	0,81928
Force Z	0,45698	0,39605	1	0,54330	0,89796
Depth of Cut	0,82469	0,78981	0,54330	1	0,65847
Tool wear	0,90276	0,81928	0,89796	0,65847	1

Table 5 - Correlation between variables [light green=1 and red= 0]

4. Conclusions and future work

With a final wear average of 24.57 µm on the top of the tool and a total of 18.3 hours of milling process, it is possible to see the evolution of tool wear in three different stages, as it is specified in Taylor's equation for Tool life expectancy. During the total time of manufacturing the tool reached a near end of life wear but did not break. The tool life will depend on the application and the material processed, (see Figure 10).
Moreover the relationship between the cutting forces and the tool wear has been high.

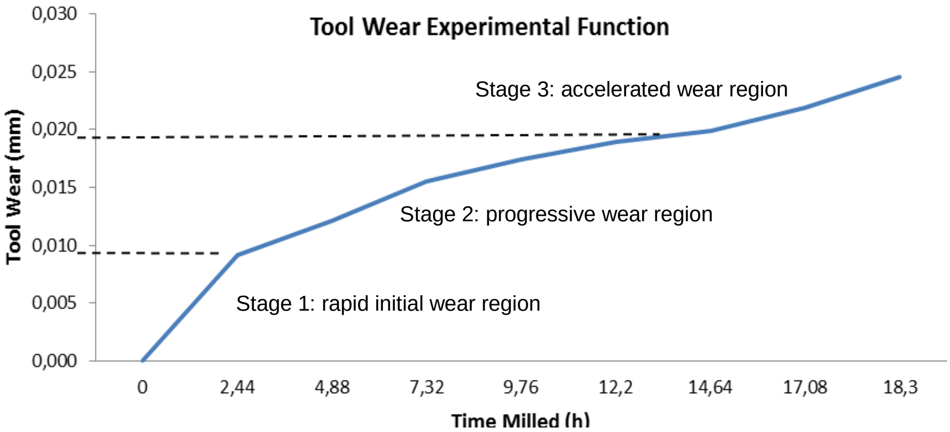

Figure 10 - Tool wear experimental function

This experiment had present results agreeing with the Taylor's equation for Tool Life Expectancy; however more experiments are necessary using different kinds of regimes to create a confident pattern and a more comprehensive picture of the method. Some uncontrollable variables, for example the variation of cutting depth, brought some variations on the process monitoring and this situation caused different results compared to the literature. However, the results obtained within the experiment are satisfactory.

In the next step of this investigation, a repetition of the experiments is performed with the same tool and the cutting force signals are processed using wavelet analysis. The resulting signals can be used as patterns in order to detect the tool wear in a currently observed milling process. This allows calculating the remaining tool life and making tool wear predictions for future milling steps.

Acknowledgement

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