COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-0741
NON-INVASIVE MONITORING SYSTEM FOR DETECTION OF TOOL WEAR IN POLYMER MILLING PROCESS

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Abstract. *The present work proposes a low-cost, non-invasive monitoring system. Aiming to estimate the electric current demanded, based on the variation of the cutting parameters in the top milling process of acrylic and expanded PVC, with and without the use of cutting fluid. The proposed system consists of an integrated Arduino® board with SCT-013-000 current sensor, RTC-DS3231 module and SD Card module, which perform the measurement and storage, respectively, of the current values collected directly from the power cable Router Spindle TVS. 1ZM3. 12. The data were collected in a machinability test, where there was a variation in the cutting fluid concentration and cutting parameters (*cutting speed and feed rate*). The output data were surface roughness, current consumption, chip shape and tool wear. The results were treated statistically through analysis of variance (ANOVA). Based on the statistical contrast, it can be concluded that the factors have an individual effect on the consumption of electric current and that the wear of the tool promotes an increase in the consumption of the main motor. The decrease in the consumption of electric current indicated that, with the addition of the cutting fluid (with variation in concentration), there was a decrease in friction between the tool/part.*

Keywords: *Arduino, Open source, Cutting fluid, Acrylic, PVC.*

1. INTRODUCTION

According to Maciel et al. (2010), all engineering plastics are easily milled, cut, drilled, ground and polished, i.e., they can undergo all the operations performed on metallic materials. Maciel et al. (2010) also says that the machining tools employed in the manufacturing processes of plastic products have geometries identical to the tools in the machining of nonferrous materials, such as wood, because there are still no specific technological developments for machining tools for plastic materials.

The monitoring of a cutting tool is of paramount importance in a manufacturing system (Souza and Câmara, 2020). From a monitoring system it is possible that the operator knows the real state of wear of the cutting tool, reducing the economic impacts caused by a possible tool breakage or loss in the quality of manufactured products by a worn tool.

According to Costa (1995) in indirect monitoring systems, the measurement of the parameter to be monitored is performed by means of another parameter that can be measured in real time and can be related to the first one. Currently, this is the system that has been receiving the most academic and industrial attention, since, unlike the previous one, in this case the machining process does not need to be interrupted, with a relative gain in productivity. However, when monitoring is performed indirectly, wear is no longer the only factor to be monitored, and other factors influence it, such as cutting speed, machining depth, feed, tool and workpiece materials.

For Souto (2007), measuring electrical parameters is indirectly measuring the cutting forces, because the machine tool's motor generates the mechanical power required to perform a machining operation through the consumption of electric current in an amount directly proportional to the power and the cutting forces.

According to Kovac (2008) the current signal is very accurate when related to cutting tool wear. Although there are supply variations during data collection, the errors are considered small when compared to the application range.

Monitoring through the motor's electrical parameters has as main advantages (dos Santos, 1988): Little intrusive technique; Low cost; Relatively simple technology and operation; Easy installation; Does not require much space; Can be applied to most motors (AC and DC); Can perform in-process monitoring online; It is a good monitoring system for milling operations, because the power values are little sensitive to tool input shocks.

Silva et al. (2016), studied polyacetal machining, concluding that speed, cutting speed and feed rate are parameters that affect the final surface integrity of the part produced and that, increasing the speed causes the surface roughness to decrease and increasing the feed rate increases the surface roughness.

Schneider et al. (2008) analyzed the influence of feed and tool cutting speed on the temperature and finish of machined surfaces of polyamide and polyurethane thermoplastic polymers. The work revealed that viscous deformation, caused by temperatures in the cutting zone above the glass transition temperature of the polymers, played a decisive role in the surface finish quality of these materials. Furthermore, the best conditions noted were for high feed speeds and low cutting speeds.

2. MATERIALS AND METHODS

2.1. Material

This work analyzed the behavior of the electric current consumed by the Spindle motor during the end milling machining process in the machinability of polymers (Acrylic and expanded PVC).

For the machining tests, a Lexno CNC Router mounted with a Spindle TVS.1ZM3.12 was used. The main specifications of the Spindle are maximum speed of 18000 rpm, rated power of 1 HP. The cutting tool used in the process was a Rocast 6 mm cylindrical shank end mill in HSS - 2 cuts.

For the CNC programming of the process the G language was used, and only one machining pass of 185 mm in length was performed. At the end of each test, the part was removed for roughness measurement.

The cutting fluid used was MV AQUA 180, a synthetic cutting fluid with translucent water base, non-toxic, biodegradable, and composed of organic raw materials that avoid solid residues on treated surfaces (VCI Brazil, 2020). According to the manufacturer, the recommended use of MVAqua180 generally ranges from 10 to 15% (actual concentration, m/V), having a refractive index is 2.5.

The rugosimeter used for checking the average roughness of the specimens was the RP-200 model, from Instrutherm. The model has a measurement scale of 160 μm, with a precision of less than 10%, and the refractometer used to measure the fluid concentration was the Vixshopping analog refractometer, model Vodex VX090, with a scale of 0 to 90% Brix.

The polymers used as specimens in the experiment were acrylic and expanded PVC in plate form with 200 mm x 200 mm x 10mm.

For the acquisition system we used: an Arduino Mega board, SCT-013-000 current sensor, 120 Ω (5%) resistor, 10 kΩ resistors for voltage division, 10nF filter capacitor, Jumpers, Protoboard, DS3231 RTC Module and SD Card Module.

The sensor SCT-013-000 is capable of measuring a nominal current of 100 A and in its output values between 0 and 50 mA proportional to the value of current flowing in the main conductor. The logic programming of the Arduino and the other components listed was performed in the ARDUINO IDE software and the measured data was stored in the Sd Card module.

The construction of this system for data acquisition demanded an investment of 350.00 Reais. This makes it highly attractive compared to commercial acquisition systems. To validate the data collected by the acquisition system, an ammeter pliers (Minipa) was used.

2.2. Experimental design and data analysis

The cut parameters, chosen in pre-tests, were defined aiming the stress of the cutter, in order to present a greater current variation, to be detected by the data acquisition system. For the system calibration, the current values measured by the system were compared with an ammeter pliers.

For the tests it was opted for end milling aiming to achieve a greater stress in the milling cutter, consequently a greater change in the value of the measured current. The machining operations were performed in a CNC Router Splindle, with and without the application of cutting fluid. The cutting parameters adopted as input variables were the cutting speed (v_c) and the feed rate (vf). The depth of cut ap was kept constant at the value of 0.5 mm in all trials.

Two HSS end mills (6mm diameter and 2 cuts) were used. The first cutter was used in the dry tests and the second was used in the tests with MV AQUA 180 cutting fluid, a synthetic coolant. According to the manufacturer, the recommended use of MV AQUA 180 is generally from 10 to 15% (actual concentration, m/V), having a refractive index of 2.5. During the tests a concentration of 12% was used.

Thus, two experiments were conducted at the Laboratório do Grupo de Automação e Instrumentação Aplicada (GAIA) da Universidade Tecnológica Federal do Paraná, campus Londrina. The experimental design adopted was a randomized complete block design in a factorial scheme 2^3, i.e., two levels of v_c, vf and material, as illustrated in Table 1.

Table 1. Control factors and levels.

Control Factors	Levels	Specifications	
Cutting speed (v_c)	2	150 [mm/min]	250 [mm/min]
Feed rate (vf)	2	200 [mm/min]	300 [mm/min]
Material	2	Acrylic	Expanded PVC

So, in the first experiment we have:

- Six blocks: three blocks without fluid (B1, B2 and B3) and three blocks with fluid (B4, B5 and B6).
- In each block, eight treatments (combinations of factor levels) were randomized, totaling 48 trials.
- For each trial, the response variable observed was the electric current.

In the second experiment we have:

- Twelve blocks: three blocks without fluid (B1, B2 and B3), three blocks with low concentration (5%) of cutting fluid (B4, B5 and B6), three blocks with ideal (12%) concentration (B7, B8 and B9) and three blocks with high concentration (27.50%) of the fluid (B10, B11 and B12). The cutting fluids were prepared according to the tests, adding the product concentrate to the mixture inside the milling machine's reservoir. For the concentration of the mixture, a refractometer was used, obtaining the value in brix degrees, multiplying the value obtained by the refractive index factor informed by the manufacturer. The tests consisted of one pass through the straight-end milling operation, under the flat surface of two different polymers, expanded PVC and acrylic, applying three different concentrations of the MV Aqua 180 cutting fluid.
- In each block, eight treatments were randomized again, totaling 96 trials.
- For each trial, the response variables observed included roughness, chip sample and current variation. The average roughness (Ra) values were collected in the machined range and always adopting the direction of the cutting tool feed.
- For the cutting fluid analysis, samples were collected, verifying the pH and conductivity behavior.

In this context, the statistical analysis of data was performed. So, considering a significance level of 5%, the following hypotheses were tested in the analysis of variance (ANOVA):

- H_0: There is no block (fluid) effect versus H_1: There is block (fluid) effect.
- H_0: There is no triple interaction effect versus H_1: There is triple interaction effect.
- H_0: There is no double interaction effect versus H_1: There is double interaction effect.

On the other hand, there is no effect of the iterations, the following hypotheses were tested:

- H_0: There is no effect of cutting speed versus H_1: There is an effect of cutting speed.
- H_0: There is no effect of feed rate versus H_1: There is an effect of feed rate.
- H_0: There is no material effect versus H_1: There is a material effect.

The procedure for obtaining the test statistic (F_0) and its respective descriptive level are summarized in the ANOVA table for a randomized complete block design as showed in Montgomery (2013). If the effects of the controlled factors are significant, a Tukey test was conducted to test the following statistical hypotheses:

- H_0: There is no difference between the means versus H_1: There is at least one pair of means that are different from each other.

3. RESULTS AND DISCUSSIONS

It was carried out preliminary tests with machining at no load, certifying the accuracy of the acquisition system, obtaining reference values of electric current consumption by the CNC Spindle motor during the movement at no load. After this procedure, the tests were performed according to the defined order and the interaction analysis of the variable levels was carried out regarding the electric current consumed by the Spindle motor.

Initially, a residual analysis was performed considering all response variables. The results of the Shapiro-Wilks test indicated non-rejection of the hypothesis of normality of the residuals (p-value >0.05). With the assumptions met, the ANOVA was performed.

3.1. ANOVA of the current data

The ANOVA of the current data is summarized in Table 2. Through these results, it is possible to observe that the hypothesis null (H_0) defined in Sub-section 2.2 about the triple interaction was not rejected (*p*-value>0.05). Therefore, there was no effect of the triple interaction on the electric current. The same is observed for double interactions, that is, none showed an interaction effect (*p*-value>0.05).

Table 2. Analysis of variance of the current data.

Source of variation	Degrees of freedom	Sum of squared	Mean square	F_0	*p*-value
Block (Fluid)	5	0.48562	0.00971	153.42	0.000
v_c	1	0.01587	0.01587	250.69	0.000
vf	1	0.00054	0.00054	8.49	0.006
Material	1	0.00130	0.00130	20.6	0.000
v_c: vf	1	0.00012	0.00012	1.87	0.180
v_c: Material	1	0.00001	0.00001	0.87	0.357
vf: Material	1	0.00001	0.00001	0.16	0.692
v_c: vf: Material	1	0.00003	0.00003	0.51	0.482
Residuals	35	0.00221	0.00006		
Total	47	0.68705			

As discussed in Sub-section 2.2 if the interaction effects are not significant, the main effects are evaluated. As it is possible to see from the data exposed in Table 2 all main effects are significant (*p*-value<0.05). Therefore, we have evidence that there is an effect of the blocks, cutting speed, feed rate and material. The Figure 1 illustrates the effects of the factors on the current.

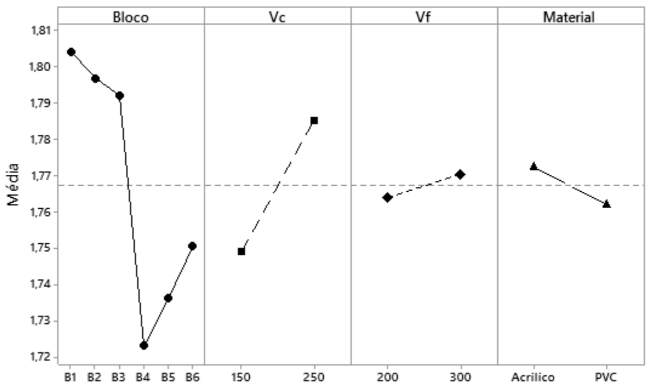

Figure 1. Behavior of the parameters with effect on the electric current (Ampere).

The Tukey's test results are shown in Table 3. The blocks corresponding to the tests without cutting fluid have a higher consumption of electric current and that their average values are distinguished only in two groups A and B. While the blocks corresponding to the tests with cutting fluid have each repetition in a different group and the average electric current increased gradually in each repetition. This behavior is possibly due to tool wear, evidenced in Figure 2.

Table 3. Tukey's test for blocks.

Groups					Block	Mean current [A]
A					B1	1.80416
A	B				B2	1.79680
	B				B3	1.79198
		C			B6	1.75038
			D		B5	1.73611
				E	B4	1.72288

Figure 2. (a) New 6 mm end mill; (b) Mill after all cutting fluid tests.

From Table 4 it can be concluded that the electric current consumption is high with increasing cutting speed. As for the feed rate, Table 4, an increase in electric current consumption was noted with the increase in speed, as well as in the cutting speed parameter. However, the increase in the average current consumed based on the increase in feed speed was small. As for the electric current consumption, Table 4, in the different materials it is observed that the averages of electric current are equal to those calculated for the feed rate. The current consumption is higher when machining acrylic.

Table 4. Tukey's test.

Groups	**Mowing speed**		**Forward speed**			
	Cutting speed	**Mean current [A]**	**Feed rate**	**Mean current [A]**	**Material**	**Mean current [A]**
A	250 [m/min]	1.78523	300 [m/min]	1.77040	Acrylic	1.77040
B	150 [m/min]	1.74887	200 [m/min]	1.76370	Expanded PVC	1.76370

3.2. ANOVA of the influence of the cutting fluid

The average roughness was measured at three points, beginning, middle and end of machining, and these data are in the roughness matrices. Similarly, the ANOVA of the roughness data is summarized in Table 5. It is noted that there was no effect of triple interaction and the interactions between v_c and vf and the interactions between vf and material (*p*-value>0.05). However, the H_0 about non-effect of the interaction between material and cutting speed on the average roughness data was rejected (*p*-value<0.05). The same is observed for blocks (*p*-value<0.05).

Table 5. Analysis of variance of the roughness data at the machining starting point.

Source of variation	**Degrees of freedom**	**Sum of squared**	**Mean square**	F_0	***p*-value**
Block (Fluid)	11.000	41.412	3.765	4.580	0.000
v_c	1.000	2.196	2.196	2.670	0.106
vf	1.000	0.083	0.083	0.100	0.751
Material	1.000	155.110	155.110	188.500	0.000
v_c: vf	1.000	0.172	0.172	0.210	0.649
v_c: Material	1.000	46.567	46.567	56.590	0.000
vf: Material	1.000	0.038	0.038	0.050	0.830
v_c: vf: Material	1.000	0.001	0.001	0.000	0.971
Residuals	77.000	63.360	0.823		
Total	95.000	308.938			

After finding the factors that affect the roughness data, we proceed to perform the respective Tukey's tests: between the interaction and effect of the block. For the interaction between cutting speed and material, Table 6 shows that when machining with PVC, the lowest speed had the greatest effect on the average roughness, while in acrylic, at higher speeds, the average roughness increased.

Table 6. Tukey's test (Cutting speed x material).

Material	**Cutting speed [m/min]**	**Mean**	**Grouping**			
PVC	150	5.21321	A			
PVC	250	4.12275		B		
Acrylic	250	2.97346			C	
Acrylic	150	1.27804				D

Using Tukey's Test with block effect on average roughness it can be observed that in the absence of fluid (B2 and B3) and with fluid at low concentration (B6 and B5), the average roughness values were higher, showing that the fluid interferes in the machinability of the materials. For high concentrations (B10 and B11) and with fluid at the ideal concentration (B7 and B9), mean roughness values were lower, showing that tool/material friction decreases with increasing fluid concentration (Table 7).

Table 7. Tukey's test for blocks.

Block	Mean	Grouping	
B6	4.6265	A	
B3	4.5996	A	
B2	3.6595	A	B
B5	3.4461	A	B
B8	3.4211	A	B
B1	3.3730	A	B
B12	3.3624	A	B
B9	3.3529	A	B
B7	3.0381		B
B4	2.9740		B
B11	2.6260		B
B10	2.2831		B

3.3. ANOVA of roughness at the machining midpoint

The ANOVA of the roughness at the machining midpoint data is summarized in Table 8. It is noted that there was no triple and double interaction effect between v_c and vf and vf and material, because the H_0, defined in Sub-section 2.2, was not rejected (p-value <0.05). On the other hand, there is an interaction effect between material and cutting speed (p-value<0.05) on the average roughness data and also, there is a block effect (p-value<0.05).

Table 8. Analysis of variance of the roughness data at the machining median point.

Source of variation	Degrees of freedom	Sum of squared	Mean square	F_0	p-value
Block (Fluid)	11.000	26.475	2.407	2.330	0.016
v_c	1.000	0.203	0.203	0.200	0.659
vf	1.000	0.210	0.210	0.200	0.653
Material	1.000	202.455	202.455	196.160	0.000
v_c: vf	1.000	0.129	0.129	0.130	0.724
v_c: Material	1.000	55.913	55.913	54.170	0.000
vf: Material	1.000	0.136	0.136	0.130	0.718
v_c: vf: Material	1.000	0.043	0.043	0.040	0.839
Residuals	77.000	79.471	1.032		
Total	95.000	365.034			

After finding the factors affecting the roughness data, we proceed to perform the respective Tukey tests: between the interaction and the block effect.

3.3.1. Tukey test – double interaction between cutting speed and material

The Table 9 shows that in PVC the lowest speed had the greatest effect on average roughness, while in acrylic, at higher speeds, average roughness increased.

Table 9. Tukey's test (Cutting speed x material).

Material	Cutting Speed [m/min]	Mean	Grouping			
PVC	150	5.72938	A			
PVC	250	4.29496		B		
Acrylic	250	2.91688			C	
Acrylic	150	1.29863				D

3.3.2. Tukey test – block effect on average roughness

The Table 10 shows in the absence of fluid (B2 and B3) and with fluid at low concentration (B6 and B5), the average roughness values were higher, showing that the fluid interferes in the machinability of the materials. On the other hand, for high concentrations (B10 and B11) and on occasions with fluid at the ideal concentration (B7 and B8) the average roughness values were lower, showing that the tool/material friction decreases with increasing fluid concentration.

Table 10. Tukey's test for blocks.

Block	Mean	Grouping	
B3	4.7428	A	
B12	3.8920	A	B
B2	3.8666	A	B
B5	3.8363	A	B
B9	3.8290	A	B
B6	3.7366	A	B
B1	3.4409	A	B
B8	3.3443	A	B
B11	3.2488	A	B
B7	3.1201	A	B
B4	3.0685	A	B
B10	2.5938		B

3.4. ANOVA of roughness at the machining end point

The ANOVA of the roughness at the machining end point data is summarized in Table 11. Through analysis, it is noted that there was no effect of triple interaction as well, as well as the interaction between v_c and vf and vf and material (*p*-value>0.05). Although, the H_0 about non-effect of the interaction between material and cutting speed on the average roughness data was rejected (*p*-value<0.05). The same is observed for blocks (*p*-value<0.05).

Table 11. Analysis of variance of the roughness data at the machining end point.

Source of variation	Degrees of freedom	Sum of squared	Mean square	F_0	*p*-value
Block (Fluid)	11.000	30.189	2.744	2.430	0.012
v_c	1.000	4.039	4.039	3.570	0.063
vf	1.000	0.106	0.106	0.090	0.760
Material	1.000	182.367	182.367	161.240	0.000
v_c: vf	1.000	0.122	0.122	0.110	0.743
v_c: Material	1.000	45.033	45.033	39.820	0.000
vf: Material	1.000	0.020	0.020	0.020	0.894
v_c: vf: Material	1.000	0.156	0.156	0.140	0.712
Residuals	77.000	87.087	1.131		
Total	95.000	349.119			

After finding the factors affecting the roughness data, we proceed to perform the respective Tukey tests: between the interaction and the individual effects.

3.4.1. Tukey test – double interaction between cutting speed and material

The Table 12 shows that in PVC the lowest speed had the greatest effect on average roughness, while in acrylic, at higher speeds, average roughness increased.

Table 12. Tukey's test (Cutting speed x material).

Material	Cutting Speed [m/min]	Mean	Grouping			
PVC	150	5.32921	A			
PVC	250	4.36963		B		
Acrylic	250	2.98287			C	
Acrylic	150	1.20283				D

3.4.2. Tukey test – block effect on average roughness

The Table 13 shows in the absence of fluid (B2 and B3) and with fluid at low concentration (B6 and B5), the average roughness values were higher, showing that the fluid interferes in the machinability of the materials. On the other hand, for high concentrations (B10) and on occasions with fluid at the ideal concentration (B7 and B8) the average roughness values were lower, showing that the tool/material friction decreases with increasing fluid concentration.

Table 13. Tukey's test for blocks.

Block	Mean	Grouping	
B3	4.7765	A	
B9	3.9519	A	B
B6	3.7661	A	B
B2	3.7304	A	B
B5	3.7028	A	B
B11	3.5841	A	B
B12	3.3866	A	B
B8	3.3728	A	B
B1	2.9751		B
B4	2.8953		B
B10	2.7746		B
B7	2.7375		B

As the machining occurred, it was noted the formation of chips of the chip type, in both materials, differing only in sizes. However, in dry machining with low and ideal concentrations of PVC, a large number of burrs were formed in the machining pass, while in machining with high concentration, there was, in addition to the small chips in chips, the formation of short washer type helical chips instead of significant burrs. In addition, a decrease in chip size occurred with increasing cutting fluid concentration.

As for acrylic, in dry machining the chips were more opaque chips, while in fluid machining, with increasing concentration, smaller were the chips, as expected.

3.5. Cutting fluid analysis

During all trials containing the fluid, conductivity and pH data were collected to monitor its behavior. The pH remained practically unchanged between the low (9.1), ideal (9.1) and high (9.2) concentrations. The conductivity, on the other hand, had its value increased according to the variation in concentration, low (3.61), ideal (6.47), and high (8.93).

Another important factor noticed was that as the concentration of the fluid increased, its odor became stronger, requiring the use of masks. In addition, the fluid became increasingly viscous at higher concentrations.

The tool cooling was also noticeable with the implementation of the cutting fluid in the machining process of polymeric materials. At high concentrations, in addition to the strong odor, the expanded PVC parts showed a slight darkening and slight stains, due to the fluid, something not noticed in the other concentrations, even when cleaning the part in water after the machining process.

4. CONCLUSIONS

Based on the experimental data, an analysis of variance (ANOVA) was performed to evaluate the influence of the control parameters on the variation in the electric current monitored.

From the results obtained from the statistical analysis it can be determined that all parameters had an effect on the electric current measured individually. The parameter with the greatest influence on the behavior of the electric current consumed by the spindle motor is the cutting speed. The feed speed and the material proved to be less influential.

The measured electric current in the test blocks with cutting fluid was lower than in the dry tests. The results also made it possible to see a progressive increase in the average current measured in each repetition of the tests with cutting fluid. This fact is associated with tool wear. In this way, the wear of the cutting tool also has an influence on the monitored current value.

By variance analysis, it was noted that the interaction of the parameters cutting speed and material had much influence on the data of average roughness, with higher values when machined at cutting speed of 150 m/min in PVC and when machined at cutting speed of 250 m/min in acrylic. Regarding the materials, the machining process on acrylic presented better surface quality when compared to the expanded PVC, that is, the acrylic had lower average roughness values. As for the feed rate, its variation did not present a significant effect on the surface integrity of the parts.

Moreover, by the variance analysis, it was justified that the fluid has influence on the surface integrity of the part, i.e., the average roughness values decreased with the increase of the MV Aqua 180 fluid concentration.

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