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Computer Numerical Control lathe instantaneous cutting power measurement using electric power monitoring

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Abstract. Usually, the parameters of industrial processes are adjusted experimentally according to the results obtained after the production of a large quantity of parts, without optimal efficiency. When a Computer Numerical Control (CNC) lathe is employed, the elaboration of its program requires the determination of its machining parameters, which impacts on the efficiency of the machining processes in several aspects: time of machining cycles, relation between the useful life of the tools and the quantity of parts produced, power consumption, refrigerants consumption, etc. An indicator of the state of the tool is the cutting power: a new tool presents a higher cutting efficiency. A means for instantaneously measuring useful machining power throughout the production process would allow a better perception of the progression of cutting tool wear. It would also reduce the time needed to obtain the most appropriate machining parameters in order to achieve the most efficient results. Most of the research carried out to measure cutting power during machining processes involves the use of load cells, which are invasive methods that compromise the normality of production. Unlike most works found in the literature, the present work uses a non-invasive and innovative method to determine the cutting power, in real time, by monitoring the electric power demand by the machine, which facilitates and speeds up obtaining more efficient parameters in machining processes, resulting in lower consumption of electricity and inputs (inserts, cutting fluid, lubricants, etc.). A direct correspondence between the variation in the machine's electrical power demand and the effective cutting power in the CNC lathe machining process was demonstrated, resulting in an equation to express the degradation of the cutting tool. Experimental machining tests, detailed in this work, were implemented to test and validate the developed methodology.

Keywords. *cutting power, wear of tools, machining parameters, signals processing, electric energy consumption.*

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Introduction. Efficient industrial processes provide economic gains and greater environmental sustainability, as they impact directly or indirectly on less waste generation, electricity consumption and carbon emissions.

Usually, the parameters of those processes are adjusted experimentally according to the results obtained, after the production of a large quantity of parts. They are tailored to each case and throughout the process, that is, a large part of the processes is developed without optimal or even adequate efficiency.

When a Computer Numerical Control (CNC) lathe is employed, the elaboration of its program requires the determination of the main machining parameters, which are the cutting speed (v_c), the cutting depth (a_p) and the feed per revolution (f_n).

The choice of parameters values directly impacts on a greater or lesser efficiency of the machining processes in several aspects: time of machining cycles, relation between the useful life of the tools and the quantity of parts produced, power consumption, refrigerants consumption, consumption of other resources (water, lubricating oil, grease etc.).

A reliable indicator of the state of the tool (chip) is the cutting power: a new tool presents a higher cutting efficiency, requiring less mechanical power to remove material. As the tool wears out, its cutting efficiency decreases, progressively increasing the cutting power required for the same operation.

A means for instantaneously measuring useful machining power throughout the production process would allow a better perception of the progression of cutting tool wear. It would also reduce the time needed to obtain the most appropriate machining parameters in order to achieve the most efficient results. It would also be an efficient cost-benefit comparative method for the various modeling options and tool brands available.

Most of the research carried out to measure cutting power during machining processes involves the use of load cells (transducers, strain gauges, etc.). These are invasive methods that compromise the normality of production. Therefore, they are not suitable for use concomitantly with production. On the other hand, a system that allows the measurement of the instantaneous (real-time) cutting power by monitoring the electrical power demanded by the machine, throughout the production process and without compromising it, is the ideal one for simple and practical application.

Related works. Edem and Mativenga (1) presented a study in milling machine simulating different loads with masses on transverse and longitudinal displacement cars, monitoring the consumption of electric energy in different situations (loads and speeds), through acquisition of voltage and current signals recorded in an appropriate instrument for later computer analysis. The results showed a direct relationship between the loads and speeds used and the consumption of electric energy. However, the study did not involve simulations that are closer to real life processes in machining situations.

The objective of Lv et al. (2) was to characterize the energy consumption of machining processes, which depends on the availability of energy supply data of CNC machine tools. An experimental study has been performed to obtain the machines power models. The machines operation was divided into two categories: non-cutting motions and material removal. The electrical power consumption has been measured using voltage and current transducers connected to the main bus of the electrical cabinet of the machine tools. It was concluded that the power consumption of non-cutting motions is dependent on machine tools and the power consumption of turning is almost independent from the machine tools.

The focus of Lv et al. (3) was on the spindle accelerations in computer numerical control (CNC) lathes, because these accelerations produce energy intensive power peaks. The authors propose a model to control the spindle by avoiding unnecessarily stopping and restarting it, among other measures. In the experiments, the electrical power of machine tool was measured using voltage and current transducers, a data acquisition card and NI Labview software.

Luo et al. (4) implemented a hybrid approach to predict the useful remaining lifetime for the tool. It was based on a real physical system (CNC milling machine) and a model developed from the results (measurements) obtained from sensors installed in the machine. The measurements comprise the cutting force (by means of a dynamometer), vibration (accelerometer) and sound intensity (acoustic sensor), coming from the cutting tool (cutter) in operation. The study is based on the Johnson-Cook (JC) model, to describe the material behavior in the machining that involves high deformation and high deformation rates accompanied by high temperature. However, the authors do not refer to the sources from which they obtained the parameters used in the study. The results obtained with the hybrid modeling were compared with conventional predictive models (based on data and theoretical modeling) and proved to be more accurate.

Hu et al. (5) made a dynamic analysis of turning operations aiming at a reduction of electricity consumption in order to promote more sustainable processes, especially during times when they are not productive (when there is no machining). The authors also discuss the machining parameters (cutting speed, feed, spindle speed etc.) more suitable to obtain greater efficiency in the processes.

Muñoz-Escalona et al. (6) studied the influence of cutting parameters on the finished surface and power consumption when machining austenitic stainless steels in a milling machine electrical power was measured directly at the entrance of the machine by means of an instrument Hioki 3169-20 analyzer.

Ratava et al. (7) developed a study to predict tool wear/failure in operations with interrupted turning by means of vibration signals on the tool acquired by means of a Piezotronic 353B03 PCB accelerometer, directed to a Kistler 5114 conditioner and digital conversion with a National Instruments PCI-6251. The analysis of the obtained signals was made later (not in real time) in Matlab and the authors concluded that the methodology resulted in a correct classication of tool failures in 80% of the experiments carried out. The biggest errors occurred with high cutting speeds associated with low machining depth.

Wang et al. (8) presented an integrated method to evaluate energy efficiency in machining workshop in which the energy profile is viewed from the machine tool layer, manufacturing unit layer, task layer and workshop layer. The evaluation in each layer includes an effective energy indicator and a specific energy consumption indicator. An integrated calculation method of energy indexes is used which combines off-line experiments with theoretical formulas. The proposed method avoids the power monitoring during machining and relies on theoretical formulas and on data available in manuals.

Schudeleit et al. (9) proposed and analyzed indices for energy efficiency assessment of machine tools. In search of appropriate metrics to quantify the energy efficiency of such equipment designs, considering the efficiency of each of their separate systems and their association with others, the authors concluded that none of the existing metrics adequately met this objective. In that work, an index was proposed, which is based on the monitoring of the energy demands of the possible combinations of the different systems in three states: off, standby and in process. The proposed methodology was tested in a case study of a lathe where compressed air production, cutting fluid pumping, spindle rotation, cooling and control systems were monitored.

A similar line of research was developed by Hacksteiner et al. (10) which presented a methodology relating energy demands to determine relevant KPIs (Key Performance Indicators) of energy efficiency and real-time machining process productivity. The approach was tested in a CNC machining center equipped with power meters and compressed air sensors. Sensor and control data were read, processed and recorded via SCADA software to automatically calculate 115 KPIs. As the main objective, the authors highlighted a better perception of operators and programmers regarding the performance of different systems and processes and results of their actions towards energy efficiency and productivity. In addition, they concluded that the methodology developed was adequate to compare different machine tools that produce similar products. It has also been shown that the power demanded increases with tool wear and the KPIs can function to indicate the tool wear and workpiece quality.

Kreitlein et al. (11) proposed the use of an index called Relative Energy Efficiency (REE) which, like in other related works, is based on the relationship between the minimum energy required and the actual energy used. However, they proposed careful computational simulations of the processes, using CAD software, before the production implementation.

Albertelli (12) simulated and analyzed the energy efficiency of direct drive axle systems compared to traditional gearbox-based systems. The author demonstrated that about 7% of the energy demanded by the machine can be reduced in the case of direct drive, and that this improvement represents 147% of the cutting energy. The analysis was repeated considering different production scenarios and ways of using the machine, consolidating the obtained results.

Zhou et al. (13) carried out a comprehensive review of the literature related to the power consumption of machine tools and the various parameters that impact their results. This type of study and research is interesting and challenging due to its complexity related to the variables involved, such as the wide variety of types and models of machine tools and accessory systems, characteristics of work pieces and cutting tools, cutting processes, different methodologies for data acquisition and processing, etc.

Using a five-axis turning center, Yoon et al. (14) sought to develop mathematical models for the consumption of electrical energy in each axis and to associate them with the total consumption of the machine tool. This was done in order to facilitate the development and implementation of strategies aimed at reducing the consumption of electrical energy in the machining processes. In the proposed models, the peaks of power resulting from changes in states of inertia or direction of movement were not considered, which the authors consider necessary to deepen the research in future works. They also identified the great importance in the energy consumed in function of the direction of the movement in relation to the direction of the gravitational acceleration.

Wójcicki et al. (15) established a question for directing their research: what is the lowest possible energy consumption that the machine tool demands to produce a certain part in a certain time? An indicator is created to serve as a reference, called by the authors as Minimal Energy-cycle Time (MET). The indicator relates the energy consumed to the process time. A methodology is sought to determine the best MET ratio.

A line of research more related to the present work was developed by Shi et al. (16), who proposed a model to determine energy consumption, considering the effects of tool wear. The work concludes that the more worn the cutting edge, the greater the energy consumption. The level of tool wear is determined by the surface roughness of the workpiece.

Lv et al. (17) tested three existing methodologies in the literature to determine energy consumption based on specific energy, shear force and exponential functions. The authors performed machining tests (turning) on three materials: aluminum, alloy steel and low carbon steel. According to the authors, using machining coefficients in the current literature, they achieved precision between 51.5% and 96.7% (the highest precision in machining aluminum). Using coefficients obtained experimentally by them, the average precision was 95%.

In the work developed by Liu et al. (18), a model is proposed to determine the energy efficiency of machine tools in order to support the decision to purchase new equipment. However, the accuracy of the energy efficiency estimate depends on characteristic and specific factors of each machine tool model that are not made available, at least in a reliable and certified way, by its manufacturers. In this way, an efficient comparative model can only be implemented after experimental tests to obtain the real factors of each equipment, that is, it is necessary to access the equipment in question in order to obtain true comparative parameters.

In the work of Utsumi et al. (19), the objective was to analyze the efficiency of turning operations on milling machines with five axes, in which both the workpiece and the tool rotate simultaneously. A dynamometer attached to the machine table was used to directly measure the cutting forces involved.

An innovative solution, but with a different approach to this work, for measuring the cutting force around it, was proposed in the work of Totis and Sortino (20). The authors developed a triaxial dynamometer, associating three piezoelectric sensors mounted on the tool holder.

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Although efficient, it has the disadvantages of being invasive to the machining space and also require three sensors for each machine tool. In the present work, unlike in the related works, no indexes are used to visualize the efficiency of equipment and processes. The approach is more practical, directly relating machine power demand to real-time cutting power during the process, enabling continuous corrections and improvements for both lower power consumption and longer tool and input life, two actions which simultaneously contribute to continuous process improvement.

Methodology. The methodology developed here was based on the monitoring of the electric power demand by the machine during different machining operations, in different materials, in order to establish its relation with the cutting power.

The amount of energy in the output of a system is always lower than the one entered into it due to the losses and energy stored by the system itself, as shown in Fig. 1. The best situation to be expected, in terms of energy efficiency, is that the absolute energy amounts in the input and in the output are very close to each other.

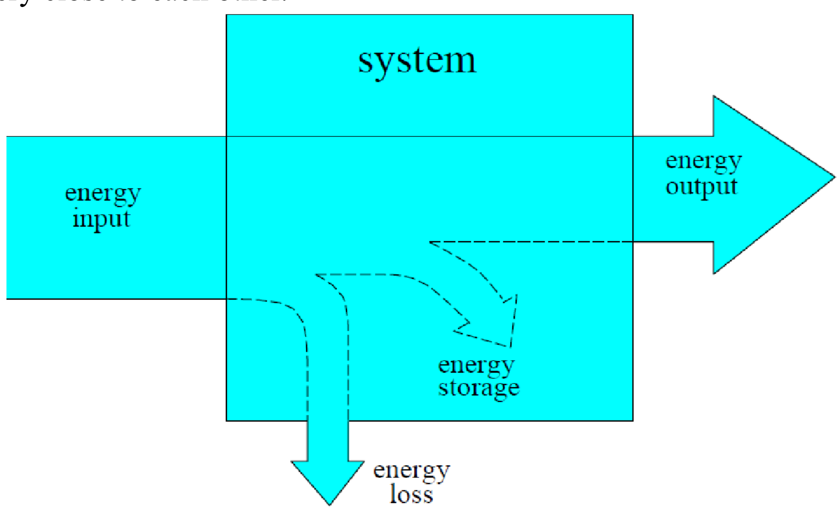

Figure 1. Energy flux in a system

In this work, relating to the CNC lathe, the system is the set comprised between the power input of the control modules of the machine, through the cables, servomotors, mechanical transmission elements, etc. to the tip of the tool (carbide insert) that removes material from the workpiece.

The power supplied to a three wire three-phase circuit connected in Y or Δ, balanced or unbalanced, can be measured using only two wattmeters if they are properly connected to the circuit and the readings are correctly interpreted Boylestad (21), as shown in Fig. 2.

In this research, each wattmeter was replaced by a current sensor (to measure $\boldsymbol{I_1}$ and $\boldsymbol{I_2}$) and a voltage sensor (to measure $\boldsymbol{V_{AB}}$ and $\boldsymbol{V_{BC}}$) to calculate the power values as the products of these corresponding currents and voltages. The total power is obtained by the sum (power factor > 0.5) or subtraction (power factor < 0.5) of the partial powers (21).

In CNC lathes, the electric power measured at the inputs of the control modules feeds the three servomotors responsible for the movement of the shaft, longitudinal axis of displacement and transverse axis of the tool. Servomotors are characterized by a power factor of more than 0.5. In this way, the power demanded by the system represents the sum of the powers measured according to the Eq. 1.

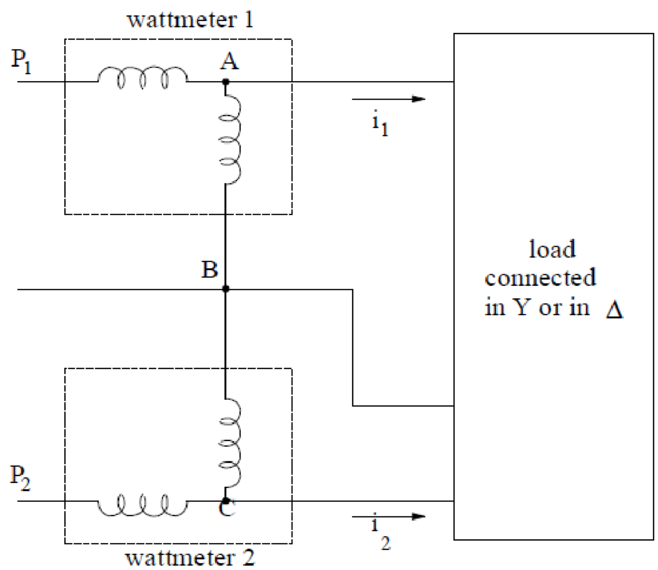

Figure 2. Two wattmeters method applied to a load connected in Y or in Δ (21)

$$P_T = P_1 + P_2 \tag{1}$$

where $\boldsymbol{P_T}$ is the total power demanded by the machine and $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$ are the total powers measured in wattmeters 1 and 2, respectively.

In this study, the power demanded by the machine, in the machining of different materials in different machining situations, was compared with the theoretical cutting power calculated by means of the well-known Kienzle Equation (Eq. 2).

$$F_C = k_C A \tag{2}$$

where $\boldsymbol{F_C}$ is the total power demanded by the machine, $\boldsymbol{k_C}$ is the specific cutting force and $\boldsymbol{A}$ is the area of the machining section.

The specific cutting force ($\boldsymbol{k_c}$) is also called by some authors as specific shear pressure. It is an experimentally determined coefficient for different materials. When accompanied by an index, it indicates the feedrate and depth of machining used. For example, $\boldsymbol{k_{c1}}$ is the specific cutting force for an advance of 1 mm/rotation and 1 mm machining depth.

The area of the machining section can be calculated by Eq. 3.

$$A = f_n a_p \quad (3)$$

where $\boldsymbol{A}$ is the area of the machining section, $\boldsymbol{f_n}$ is the tool advance and $\boldsymbol{a_p}$ is the machining depth.

By definition, cutting speed is the tangential velocity with which the tool (insert) travels through the material during the machining process, in the case of turning operations, the diameter resulting from the operation. Thus, in this case, the cutting rate can be calculated by Eq. 4.

$$v_C = \pi d n \quad (4)$$

where $\boldsymbol{v_c}$ is the cutting speed, $\boldsymbol{d}$ is the turned diameter and $\boldsymbol{n}$ is the angular velocity of the spindle.

However, in most situations it is not necessary to calculate the cutting speed which, as mentioned in the introduction, is a machining parameter established within a program. It is kept constant automatically by the machine during the processes, by means of the appropriate variation of the angular velocity of the tree axis, within limits established in the program itself and as a result of equipment specifications. Knowing the cutting speed vc and the theoretical cutting force $\boldsymbol{F_c}$, the theoretical cutting power $\boldsymbol{P_c}$ can be obtained by the Eq. 5.

$$P_C = v_C + F_C \quad (5)$$

The equation for the calculation of theoretical cutting power can also be presented as the Eq. 6.

$$P_C = v_C a_P f_n k_C \quad (6)$$

where $\boldsymbol{P_c}$ is the theoretical cutting power, $\boldsymbol{v_c}$ is the cutting speed, $\boldsymbol{a_p}$ is the machining depth, $\boldsymbol{f_n}$ is the tool advance and $\boldsymbol{k_c}$ is the specific cutting force.

Considering two different situations in the machining process in lathes, as shown in Fig. 3, we have:

1. In empty, the tool advances toward the workpiece while the spindle rotates to theworkpiece. In this case, the cutting power is zero ($\boldsymbol{P_C}$ = 0) because the tool is not in contact with the rotating part and, consequently, it is not removing material. On the other hand, the power demanded by the machine ($\boldsymbol{P_{e0}}$) is the necessary one for the movement of tool advancement, rotation of the piece, and other systems (refrigeration, oil circulation, ventilation, etc.);
2. In machining, the tool continues advancing, but in this case by removing material. In this situation, there is a cutting power ($\boldsymbol{P_C}$), theoretically determinable by means of Eq. 5. The effective electric power ($\boldsymbol{P_{ef}}$) demanded at this instant will correspond to the sum of the electric power in empty ($\boldsymbol{P_{e0}}$) with the product of the cutting power ($\boldsymbol{P_C}$) by a system performance factor ($\boldsymbol{\eta}$), which will be a constant (greater than one), representing the losses corresponding to the system performance, according to the concept presented by Boylestad (21).

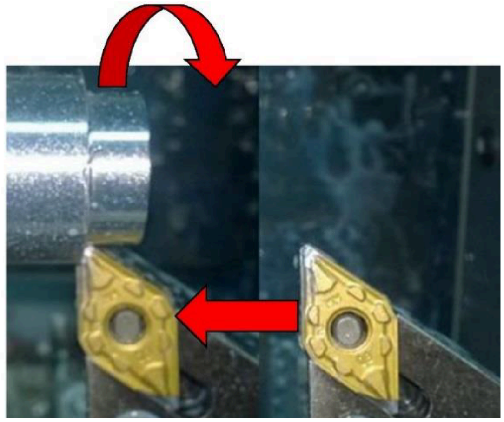

Figure 3. Tool advances in empty (right) and machining (left)

Thus, translating this postulate to a mathematical expression for the determination ofthe Effective Electric Power, we arrive at the Eq. 7.

$$P_{ef} = P_{e0} + P_{C}\eta \quad (7)$$

where P_{ef} is effective electrical power required by the machine during machining, P_{e0} is electrical power demanded by the machine during empty run, P_c is the cutting power and η is the system efficiency factor.

Referring to Eq. 7 and exemplified in Fig. 1 and Eq. 1, P_{ef} is the energy that enters the system and P_C is the energy leaving the system, and η is the energy loss factor that occurs in the process.

Subsequently, after an in-depth analysis of the results obtained (presented below) with the realization of tests with different materials, in different machining conditions, it was concluded that Eq. 8 was more adequate for the representation of the relations involved in the process.

$$P_{ef} = P_{e}(n) + P_{C} + \Delta P(P_{C}) \quad (8)$$

where P_{ef} is the effective electrical power required by the machine during machining, $P_e(n)$ is the electrical power demanded by the machine in empty as a function of the angular velocity of the shaft, P_C is the theoretical cutting power calculated by Eq. 5 and $\Delta P(P_C)$ is the power difference as a function of theoretical power.

In this work, the studies were planned, developed and implemented in three stages in different situations and objectives:

1. Development of the methodology and system of acquisition and treatment of signals based on the theoretical foundation presented;
2. Application of the developed system, aiming the determination of the conversion equation to relate the power demand difference by the machine with the effective cutting power;

3. Proof of the efficiency of the methodology and system developed in real situation of machining of parts in production.

The first stage was implemented through experiments and measurements on a ROMI Centur 30D lathe with a Siemens 802D CNC. Subsequently, in a second stage, aiming to validate and generalize the system and methodology developed on other equipment, experimental tests were extended and implemented on an ERGOMAT TND 200 lathe equipped with a Fanuc CNC. Sandvik DNMG 110408 GC2015 inserts mounted on a Sandvick PDJNR 2525M 11 support were used in the machining tests.

The materials used in the first stage machining tests were chosen taking into account, mainly, their great application in mechanical construction of machines and devices, in bars of the same diameter, in order to standardize the programs elaborated with the same parameters of machining. This made possible a comparative analysis of results obtained under the same conditions and with their characteristics, such as the Specific Cutting Force ($\boldsymbol{k_c}$), well known. Thus, the experiments of the first step were performed with the following materials:

- Aluminum alloy ABNT 6351T6 in round bars having 31.75 mm diameter;
- SAE 1020 carbon steel in round bars having 31.75 mm diameter.

In the second stage, after an understanding and improvement of the methodology and results, the following materials were used in the tests:

- Aluminum alloy ABNT 6351T6 in round bars having 38.1 mm diameter;
- Stainless steel AISI 304 alloy in round bars having 31.75 mm diameter;
- SAE P20 Steel tool in round bars having 31.75 mm diameter;
- Bronze aluminum UNS C63000 in round bars having 24.4 mm diameter.

The aluminum alloy ABNT 6351T6 is equivalent to the alloys ASME SB221, AA6351-T651 and UNS A96351. UNS C-63000 is a bronze alloy equivalent to SAE J463, ASME SB150 and ASTM B-150.

In the first and second machining stages, the trials were carried out with successive longitudinal passages of 40 mm, 20 mm in empty and 20 mm in machining, according to Fig. 4.

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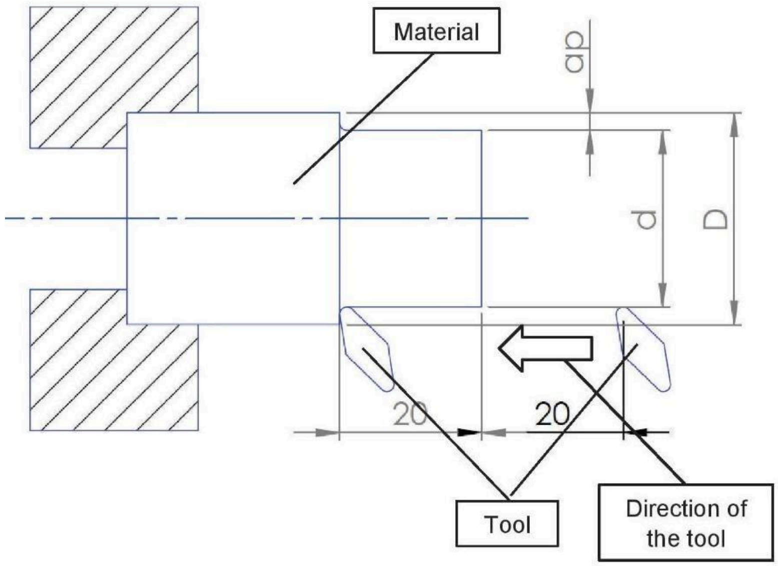

Figure 4. Machining trial

It should be considered that the results obtained in the first step are not totally reliable, due to the following facts:

- The machining operation, from the initial diameter of the bar, has an additional variable which is the dimensional inaccuracy, resulting in a variation of the machining depth;
- The attachment of the material to the lathe plate may exhibit an eccentricity making the machining depth unstable;

It should be considered that, during the machining process of materials, due to the compression forces resulting from their production process, the outermost part of the material may present different mechanical characteristics in relation to its inner part.

In order to allow a better comparison of the results (difference in electric power demand by the machine), the tests were planned with the fewest possible variables. Thus, the machining program for the first stage was developed with the following parameters: cutting speed $\boldsymbol{v_c}$ = 150 m/min, machining depth $\boldsymbol{a_p}$ = 2.5 mm (from the second pass on), tool advance $\boldsymbol{f_n}$ = 0.4 mm / rotation and maximum shaft axle of 3000 rpm.

The machining conditions (turning) in each pass are detailed in Tab. 1. It can be seen that, until the third pass, the machine maintains the cutting speed constant, by increasing the speed of rotation of the plate according to the diameter of machining decreases from the fourth to the sixth pass, the maximum spindle velocity (3000 rpm) is reached and this is kept constant, resulting in a variation of the cutting speed, according to Eq. 4.

Table 1. Machining parameters in the first stage trials

operation (pass)	diameter before, D (mm)	diameter after, d (mm)	machining depth, a_p (mm)	cutting speed, v_c (m/min)	plate speed (rpm)
1	32	30	0.9	150	1292
2	30	25	2.5	150	1910
3	25	20	2.5	150	2390
4	20	15	2.5	141	3000
5	15	10	2.5	94	3000
6	10	5	2.5	47	3000

Using Eq. 5, it has been possible to calculate the theoretical cutting power in each pass for different materials. The results are presented in Tab. 2.

Table 2. Theoretical cutting powers (W)

operation (pass)	aluminium ABNT 6351 T6	steel SAE 1010/20	stainless steel AISI 304
1	720	1800	2070
2	2000	5000	5750
3	2000	5000	5750
4	1880	4700	5410
5	1250	3130	3610
6	630	1570	1800

In the second test stage, in order to obtain a larger (double) data sample in each test, the feed rate was reduced to 0.1 mm / rotation, which is also a more common value for this parameter in operations of machining. The program was also modified to insert an additional pass, by using aluminum bars of larger diameter (1.1/2 inches instead of 1.1/4 inches). Because of the higher rotational velocity available on the Ergomat shaft axle, the maximum velocity was set at 5000 rpm. Thus, it was possible to maintain the programmed cutting speed until the last sixth pass of the total of seven. The conditions are detailed in Tab. 3.

Table 3. Machining parameters in the second stage trials

operation (pass)	diameter before, D (mm)	diameter after, d (mm)	machining depth, a_p (mm)	cutting speed, v_c (m/min)	plate speed (rpm)
1	38	35	1.5	150	1363
2	35	30	2.5	150	1590
3	30	25	2.5	150	1910
4	25	20	2.5	150	2390
5	20	15	2.5	150	3180
6	15	10	2.5	150	4770
7	10	5	2.5	78	5000

Using the same procedure as in the previous step, the theoretical powers were calculated for each material and machining condition, as shown in Tab. 4.

Table 4. Theoretical cutting powers (W)

operation (pass)	aluminium ABNT 6351 T6	steel SAE P20	stainless steel AISI 304	bronze UNS C63000
1	310	-	-	-
2	500	560	520	-
3	500	1560	1440	-
4	500	1560	1440	1060
5	500	1560	1440	1060
6	500	1560	1440	1060
7	263	820	760	820

In the final stage, the methodology and system were tested and validated under real machine production conditions. For this, a batch of AISI 304 stainless steel parts was produced, as detailed in Fig. 5, starting from a new insert and used in the machining process until its wear, determined by visual analysis of the surface finish of the parts and cutting edges tool.

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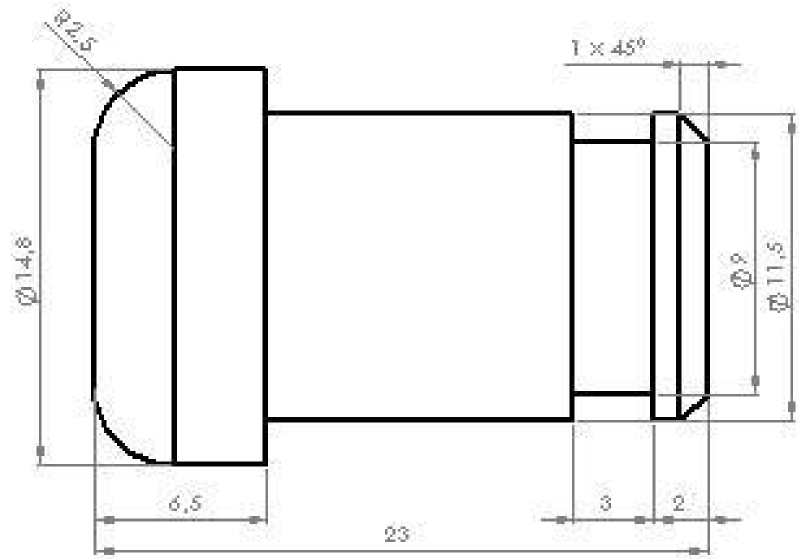

Figure 5. Stainless steel pin produced for testing (dimensions in mm)

In order to eliminate errors caused by the variation of the power demand by other machine systems (cutting refrigerant pumping, lubricating oil pumping, lighting, ventilation system, etc.) the signals were captured at the three-phase input of the controller modules servomotors (Fig. 6). The electric current values were acquired using two current sensors model SCT-013-000, as shown in Fig. 7. This Hall effect sensor allows non-invasive measurements of electrical currents up to 100 A with an accuracy of ±1%.

Voltage signals between phases were acquired through three cables with clips on the side connected to the module power connection terminals, and banana plug connectors at the other ends. A preliminary measurement (using clamp meters) between the module supply phases indicated voltages of the order of 280 V.

For the acquisition, processing and recording of voltage and current signals, we used a platform based on Arduino Uno board with ATmega328 microcontroller with 32 KB flash memory and 10-bit resolution, executing a program for acquisition and treatment of voltage and current signals and power calculations.

Since the analog inputs on the Arduino board do not support voltages above 5 VDC, it was necessary to add a suitable circuit designed and built to condition the signals in order to reduce and rectify the voltages and to handle the captured current values of the sensors, according to Figure 8. The assembled device is shown in Figure 9. The Arduino board has a serial output (lower right corner of Fig. 9) which allows the data to be sent to a microcomputer (via USB input) so that it can be observed, recorded and eventually subject to some additional processing.

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Figure 6. Control modules

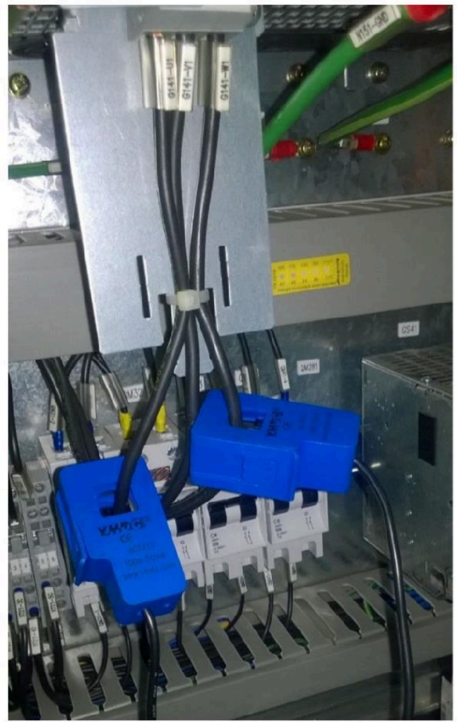

Figure 7. Electric current sensors

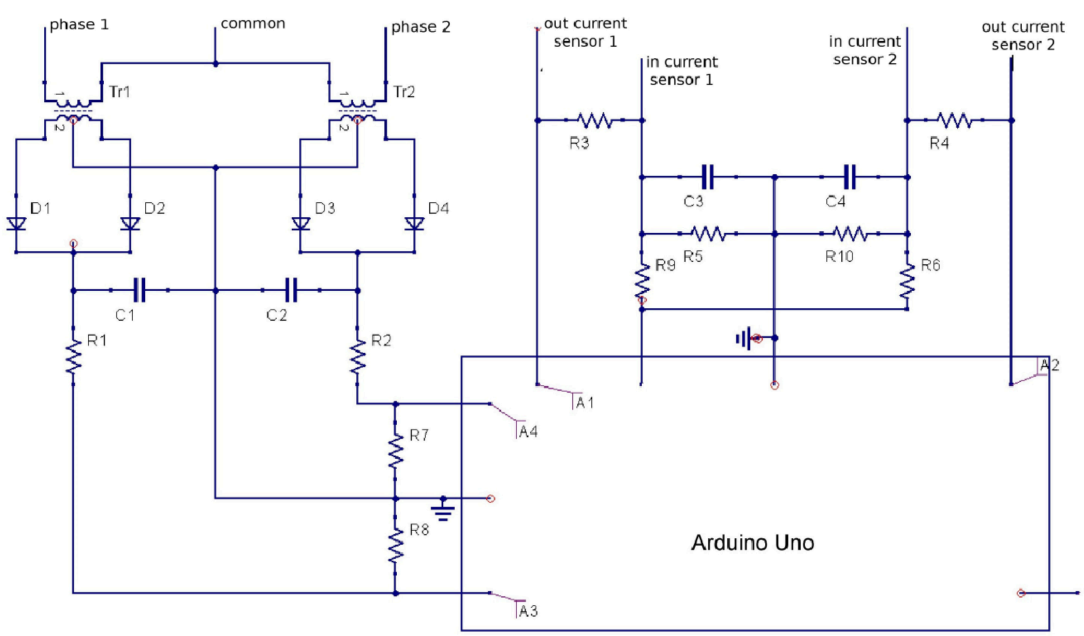

Figure 8. Signal acquisition circuit

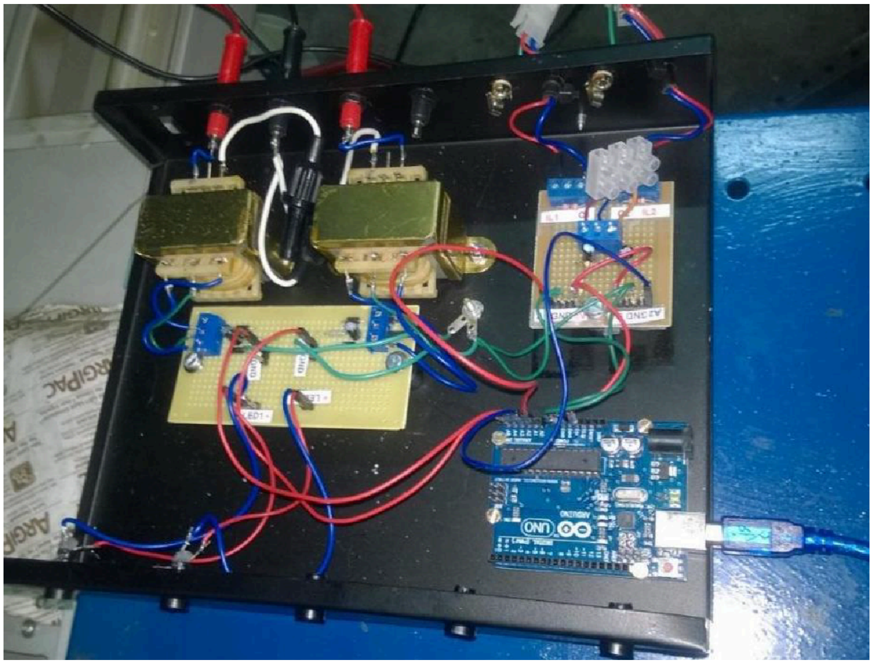

Figure 9. Acquisition, conditioning and signal processing device

Procedures and results. In the first stage, 26 tests were performed under different conditions of machining parameters (as detailed in table 3) and state of inserts and materials. The averages of the results obtained for each machining condition are detailed in Tab. 5. In the case of tests with worn inserts, the value of theoretical cutting power is followed by a "+" sign because one expects higher values, due to the loss of efficiency of the tablet, by the assumption previously mentioned.

The measured electric power ($\boldsymbol{P_e}$) was obtained for each situation by capturing the current and voltage signals at the input of the machine's servomotors power modules. The theoretical cutting power was calculated as presented in Tab. 2.

Taking the differences of the electric power measured in machining with the electric power measured with the respective advances in empty, an estimate of the effective cutting power is obtained (without considering any yield losses in the system transmission). Tab. 6 and the graph in Fig. 10 show the comparison between the obtained cutting powers and those calculated theoretically.

Although some results show significant deviations from theoretical machining power, it can be seen that, in most cases (results with green background), the variation of the measured electrical power demand (determined by the developed methodology) was sensitive to the different machining conditions generally following the theoretically expected behavior, without expecting great accuracy in relation to the theoretically calculated. Only seven results (red background) out of 24 showed lower values than the expected results. Of these, three are related to the first pass, with deviations already foreseen and commented on in the description of the machining tests.

Table 5. Summary of machining tests results, first phase

test condition	comparison between electric power (P_e) averages measured in advances and the theoretical cutting powers (P_c) (W)											
	pass 1 1292 rpm		pass 2 1910 rpm		pass 3 2390 rpm		pass 4 3000 rpm		pass 5 3000 rpm		pass 6 3000 rpm	
	P_e	P_c	P_e	P_c	P_e	P_c	P_e	P_c	P_e	P_c	P_e	P_c
advance in empty	2301	0	2752	0	3498	0	4052	0	3710	0	3647	0
new Al insert	2499	720	4193	2000	5657	2000	6288	1880	5221	1250	4657	630
worn Al insert	2802	720+	4464	2000+	4801	2000+	5072	1880+	5233	1250+	5069	630+
new steel insert	3405	1800	8138	5000	8710	5000	8825	4700	7938	3130	6456	1570
worn steel insert	4750	1800+	8663	5000+	9629	5000+	9541	4700+	8859	3130+	6639	1570+

Table 6. Comparison between measured and theoretical electric powers

test condition	comparison between differences in measured electric powers (ΔP_e) and theoretical cutting powers (P_c) (W)											
	pass 1 1292 rpm		pass 2 1910 rpm		pass 3 2390 rpm		pass 4 3000 rpm		pass 5 3000 rpm		pass 6 3000 rpm	
	ΔP_e	P_c	ΔP_e	P_c	ΔP_e	P_c	ΔP_e	P_c	ΔP_e	P_c	ΔP_e	P_c
new Al insert	198	720	1441	2000	2159	2000	2236	1880	1511	1250	1010	630
worn Al insert	501	720+	1712	2000+	1303	2000+	1020	1880+	1523	1250+	1422	630+
new steel insert	1104	1800	5386	5000	5212	5000	4773	4700	4228	3130	2809	1570
worn steel insert	2449	1800+	5911	5000+	6131	5000+	5489	4700+	5149	3130+	2992	1570+

Results with higher-than-expected values can be attributed to the yield losses between the electrical power taken at the power supply of the servomotor control modules and the effective machining power, as already predicted in Eq. 7 and are not considered at this stage because its estimate would require more machining tests.

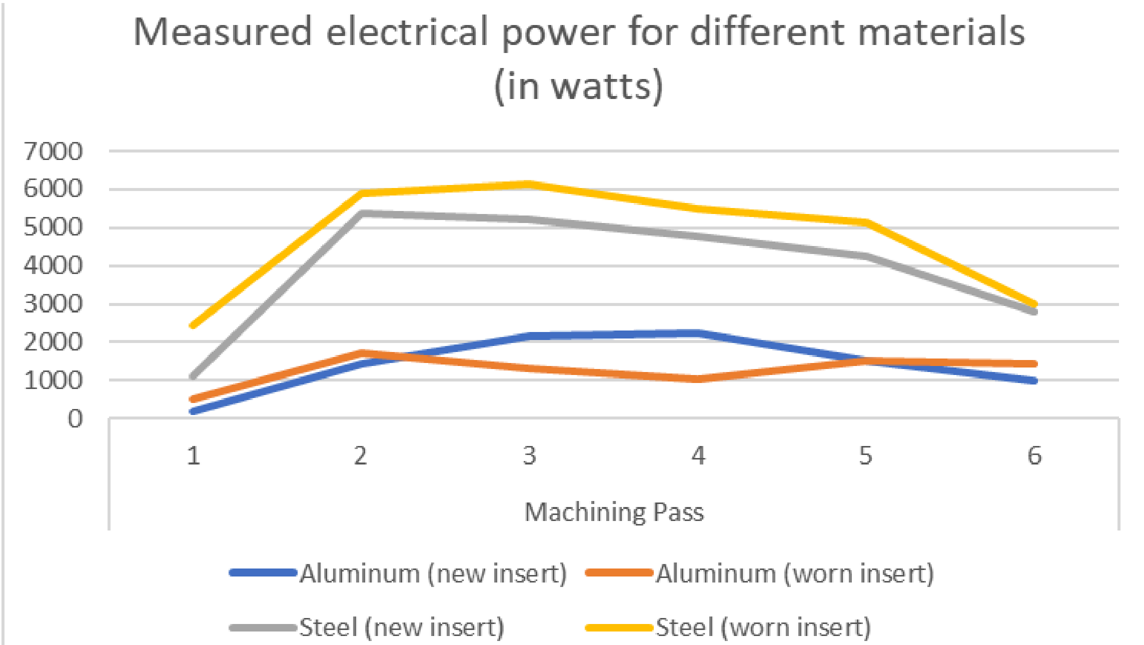

Figure 10. Comparative graph of measured electric powers with theoretical cutting powers

In the first stage of the tests, it was concluded that the developed methodology and system proved to be effective in identifying a correspondence between the variation of the electric power demand by the machine and the effective cutting power in the CNC lathe machining process. The variation in electrical power demand by the machine has increased in aluminum machining (material with good machinability) in relation to the state of empty feeds, with a further increase when machining steel (material whose machining is more severe than aluminum). The obtained results validated the methodology of calculation of theoretical cutting power through the Kienzle equation and the specific cutting pressure (K_S) attributed to the materials used.

The analysis of the results of the first trial step was also useful to direct the research towards the following procedures for the second trial step:

- Use of more materials with different machinability characteristics;
- Carry out a larger number of trials;
- Check if there is any mismatch of the electric current measured between the values captured in line 1 and line 2 of the three-phase supply of the servomotor controller modules, to be considered for calculation of the electric power;
- With the largest number of results obtained, establish the equation that determines the relationship between the measured electrical power and the instantaneous cutting power in the ongoing machining process.

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In the second stage of testing, after improving the methodology and system, we sought to obtain the equation for converting the electrical power demand by the machine into instantaneous cutting power.

A question that arose after the first stage of the tests was about a possible lag between the currents measured in the two supply lines. It could compromise the values obtained if it was not determined and considered in the processing to obtain the electric powers, since these powers represent the sums of the partial powers of lines 1 and 2, obtained through the respective electric currents measured by the system.

Thus, with the first results obtained in the machining tests of the second stage, this was verified. As shown in the graph in Fig. 11, the peak current ranges numbered 1 through 10, there is no lag between the electrical currents of line 1 (series 1 in blue color) and line 2 (series 2 in orange color), i.e., overlapping graphs of the two measured currents are observed.

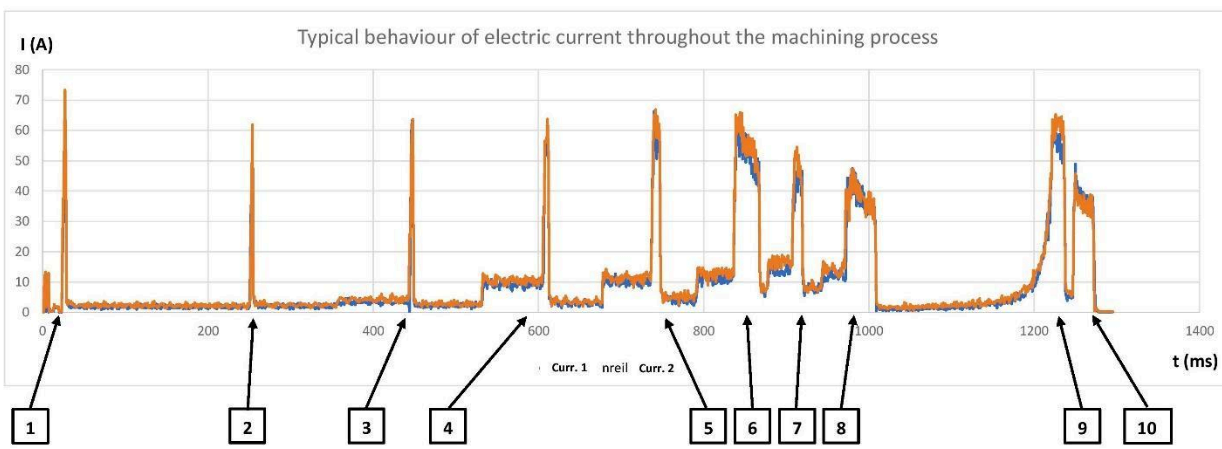

Figure 11. Graph detailing current peaks (A)

Therefore, the electrical powers determined from the monitoring of the measured electric currents effectively represent a response to meet the power demands of the machine at the moment of signal capture.

Analyzing the graph in detail in its sections and comparing it with that observed during the machining tests, it was noticed that the higher demand of electric power by the machine does not occur during the material removal process (machining), but in the fast displacement of the machine repositioning tool for new pass or tool change. This phenomenon is shown in the detail of the graph in Fig. 12.

In the second stage, 29 tests were performed with new inserts and different materials, totaling data sets (one set for each machining pass).

Tab. 7 presents the results summarized and compared at each pass. In it, $\boldsymbol{P_e}$ is the average of the maximum electric power measured at each pass and conditions (advance in empty or machining)

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for each material, $\boldsymbol{P_c}$ is the corresponding theoretical cutting power and $\boldsymbol{\Delta P}$ is the difference between $\boldsymbol{\Delta P_e}$ in machining and $\boldsymbol{P_c}$ in empty in the same pass.

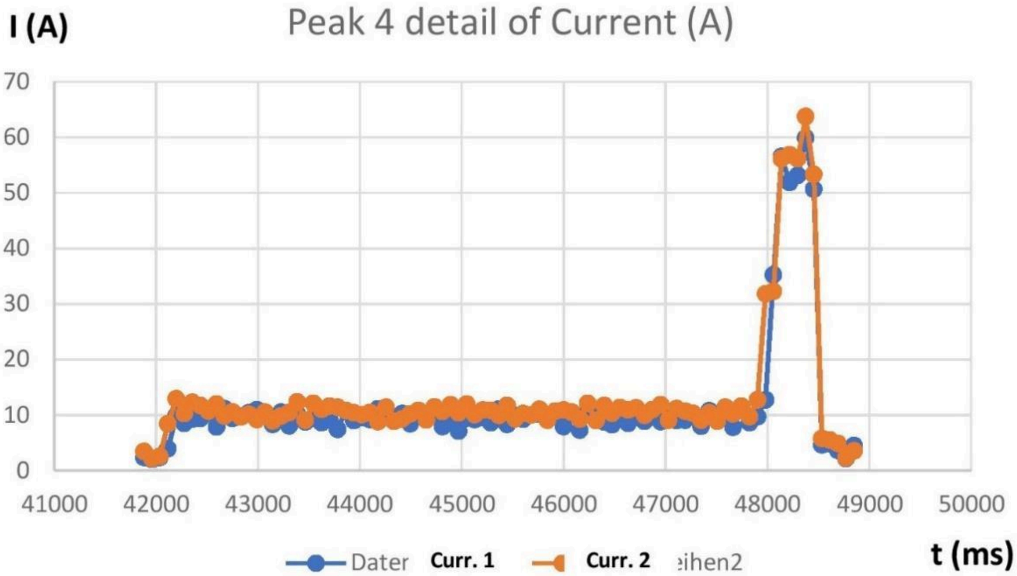

Figure 12. Current peak detail 4 showing machining interval

Table 7. Average of machining tests results, second phase

test condition	average of measured maximum electrical powers in advances (P_e) and the theoretical cutting powers (P_c) (in W), second phase																				
	pass 1 35 mm / 1363 rpm			pass 2 30 mm / 1590 rpm			pass 3 25 mm / 1909 rpm			pass 4 20 mm / 2386 rpm			pass 5 15 mm / 3182 rpm			pass 6 10 mm / 4773 rpm			pass 7 5 mm / 5000 rpm		
	P_e	P_c	ΔP	P_e	P_c	ΔP	P_e	P_c	ΔP	P_e	P_c	ΔP	P_e	P_c	ΔP	P_e	P_c	ΔP	P_e	P_c	ΔP
in empty	1308	0	0	1420	0	0	1582	0	0	2011	0	0	2824	0	0	4113	0	0	4383	0	0
Al 6351 T6	2357	310	730	3370	500	1450	3681	500	1599	4292	500	1781	4998	500	1674	6386	500	1773	5846	263	1200
bronze Al super	-	-	-	-	-	-	-	-	-	5147	1063	2073	6173	1063	2286	7505	1063	2329	6389	560	1446
tool steel P20	-	-	-	2149	563	166	5682	1563	2537	6025	1563	2451	6794	1563	2407	8193	1563	2517	6820	823	1614
stainless steel 304	-	-	-	2105	518	167	5112	1438	2092	5500	1438	2051	6245	1438	1983	7664	1438	2113	6627	757	1487

Analyzing the data obtained, it can be observed that the electric power measured ($\boldsymbol{P_e}$) depends on the electric power of the in empty advance, on the cutting power (in this case, theoretical cutting power) and also on a factor related to the difference between the total electric power (which is $\boldsymbol{P_e}$ itself) and the cutting power ($\boldsymbol{P_c}$). On the other hand, the in empty electric power is a function of the spindle rotation velocity.

Thus, it is concluded that Eq. 7 does not express well the dynamics of the relationship between the variables involved in the system energy flow.

Eq. 8 reflects what was analyzed in the previous paragraph and shows that the total power demanded by the machine is the sum of partial powers, a function of independent variables.

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Thus, the relationship between the variables was determined by analyzing the partial equations separately, properly selecting and arranging the data in Tab. 7.

By isolating the values of the spindle angular velocity (***n***) in rpm and the respective values of the electric power measured with the feed-rate as shown in Tab. 8, one can obtain the curve fitted to the linear trend of the results shown in Fig. 13.

Eq. 9 represents the power demand portion related to the spindle speed.

$$P_e(n) = 0.8616n + 33.586 \quad (9)$$

where $P_e(n)$ is the electrical power (in ***W***) in empty as a function of the spindle speed ***n*** (in rpm).

Table 8. Measured electrical power as a function of the spindle angular velocity

n (rpm)	P_e (W)
1363	1308
1590	1420
1909	1582
2386	2011
3182	2824
4773	4113
5000	4383

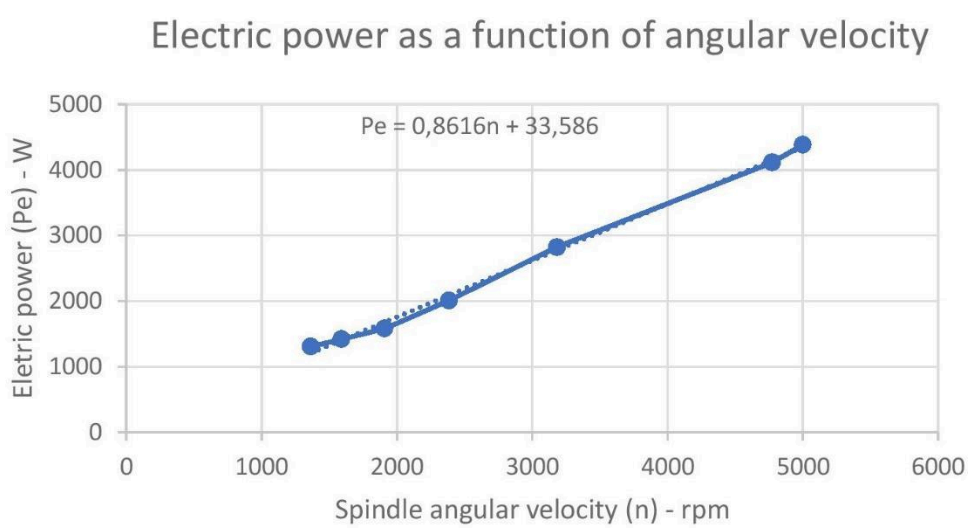

Figure 13. Electric power as a function of the spindle angular velocity

The same methodology was used in the treatment of the calculated theoretical cutting power values and the measured power difference, shown in Tab. 9 and in Fig. 14 which relate the two variables, as stated in Eq. 10.

$$\Delta P(P_c) = 0.873P_c + 1010.4 \quad (10)$$

where ***ΔP(Pc)*** is the measured electrical power difference (in ***W***) as a function of the theoretical cutting power and P_c is the theoretical cutting power (in ***W***).

Table 9. Values of the measured electric power difference as a function of the cutting power

P_c (W)	ΔP (W)
263	1200
500	1655
560	1446
757	1487
823	1614
1063	2229
1438	2060
1563	2478

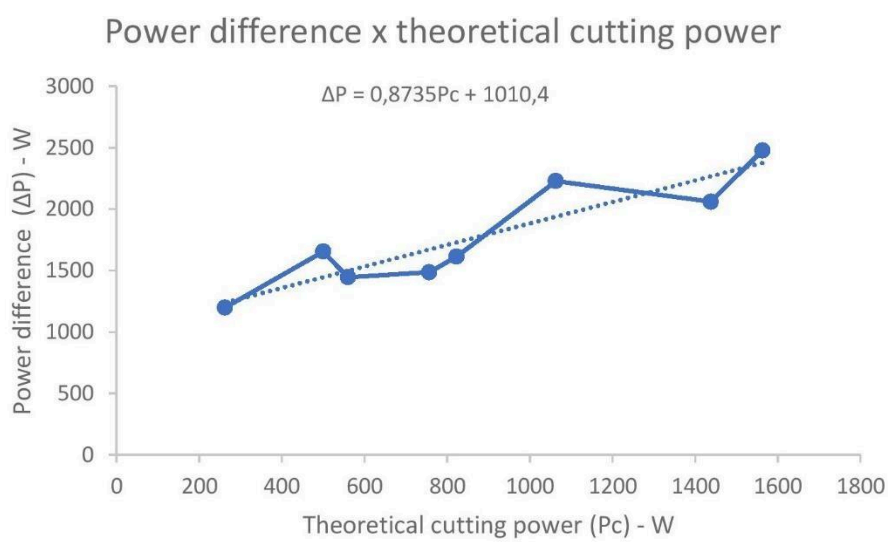

Figure 14. Power difference as a function of theoretical cutting power

Substituting $\boldsymbol{P_e(n)}$ and $\boldsymbol{\Delta P(Pc)}$ in Eq. 8 by the expressions founds in Eqs. 9 and 10, respectively, the Eq. 11 is obtained.

$$P_{ef} = 0.8616n + 33.586 + P_C + 0.873P_c + 1010.4 \quad (11)$$

Isolating $\boldsymbol{P_c}$ is obtained the Eq. 12.

$$P_C = \frac{P_{ef} - 0.86n - 1044}{1.87} \quad (12)$$

where $\boldsymbol{P_c}$ is the instantaneous cutting power (in ***W***), $\boldsymbol{P_{ef}}$ is the electrical power (in ***W***) and ***n*** is the spindle speed (in rpm).

Equation 12 allows the determination of the instantaneous cutting power from the electric power obtained by monitoring the electric currents and electrical voltages in the power supply to the servomotor controller modules.

To test and validate the methodology, the system and the electrical energy conversion equation measured in cutting power, the machining of a part in production was simulated, the AISI 304 stainless steel detailed in Fig. 5, where a new insert with a single cutting edge was used until to complete deterioration. In this way, 36 parts were produced. When machining the last part, the insert was completely deteriorated and for this reason, there was no scheduled material removal. Fig. 15 shows the first part produced within specifications. Fig. 16 shows the last part produced, which shows that the material was not completely removed during the machining process and the surface finish proves the high wear of the insert.

Figure 15. The first test piece produced

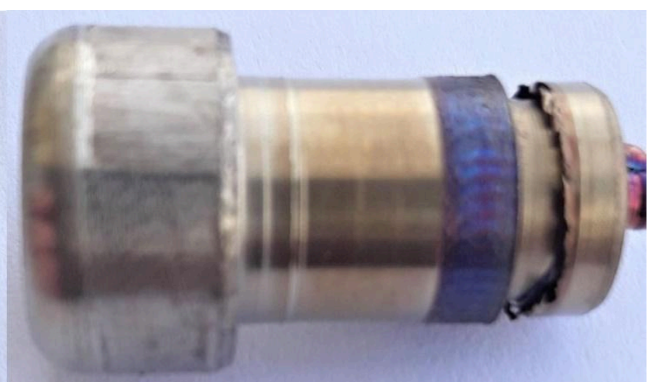

Figure 16. The last test piece produced

The results are detailed in Tab. 10. It is observed that there was a progressive increase of the cutting power with the production process, except for the last piece in which, effectively, there was no adequate cutting of material.

The graph in Fig. 17 allows a clearer view of the increase in cutting power as the wear of the tool in use evolves. In the construction of the graph, the results obtained in the machining of the last part were disregarded, since the total removal of material was not performed, invalidating the results obtained in this machining. It can be observed that in the first pass, where the machining depth was greater, and consequently also the power, the cutting curve also showed an exponential growth trend, while in the second pass, with lower machining depth and cutting power, the growth trend was linear. This can be better studied in a future work.

Table 10. Results obtained with the part in production

Results obtained for the powers with the part in production				
pin (sequence)	first pass (W) (d = 12.5 mm, n = 3820 rpm)		second pass (W) (d = 10.5 mm, n = 4550 rpm)	
	measured electric power, P_{ef} (W)	equivalent mechanical power, P_c (W)	measured electric power, P_{ef} (W)	equivalent mechanical power, P_c (W)
1	5105	415	5137	96
2	5061	391	5191	125
3	4993	355	5204	132
11	5114	420	5241	152
12	5358	550	5297	182
21	5086	405	5307	187
22	5269	503	5371	221
31	5813	794	5414	244
32	5947	865	5517	299
34	6178	989	5584	335
36	5816	795	5283	174

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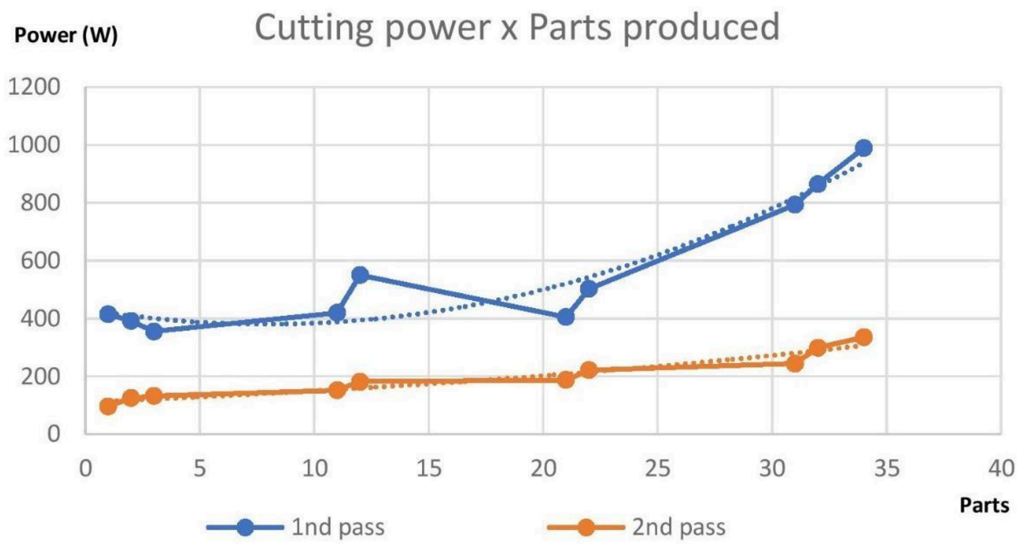

Figure 17. Increase in cutting power as the wear of the tool in use evolves

Conclusions. Unlike other studies found in the literature, the present work uses a non-invasive method to determine cutting power, in real time, by monitoring the electric power demand by the machine, enabling its application in industrial production systems without compromising productivity. This facilitates and speeds up the achievement of more efficient parameters in machining processes, resulting in lower consumption of electrical power and inputs (inserts, cutting fluid, lubricants, etc.), contributing to the sustainability of the process.

The methodology and apparatus developed in this work effectively proved a correspondence between the variation of the electrical power demand by the machine and the effective cutting power in the CNC lathe machining process. As the insert wears out, it loses its efficiency, gradually increasing the cutting power involved in the machining process. It can be concluded that for each different equipment in which the methodology and system will be applied, tests will be necessary to determine the conversion equation.

However, after determining the representative function of the degradation of the cutting tool in the respective machining process, its remaining useful life can be estimated and, consequently, its replacement can be planned at the most appropriate time.

To enable its industrial application through an efficient and precise technological system with simplicity of implementation, it will be necessary a microcontroller with higher processing capacity, which allows a higher rate of capture and signal processing in the order of intervals less than 8 ms (resolution better than 0.5 Hz) instead of 60 ms (resolution of 3.6 Hz). In other works, such as those referenced in the literature review, devices used for capture and treatment of signals have been those that are well established in the market. However, this is not the purpose of this work, either because of the high cost of that equipment (prohibitive for small businesses) or the complex installation process they require.

Some degree of automation will also be needed, in particular for spindle speed measurement and for tool position and offset identification that enables data to be identified at the time of machining.

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