ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

STRATEGY FOR MAPPING POWER CONSUMPTION IN GRINDING

Guilherme Alves Afonso
Remo Augusto Padovezi Filleti
Eraldo Jannone da Silva
University of São Paulo – USP. School of Engineering – São Carlos - EESC
Address: Av. Trabalhador São-carlense, 400, Pq. Arnold Schimidt – 13566-590 – São Carlos, SP, Brazil
e-mail: guilherme.alves.afonso@usp.br; remo.filleti@usp.br; eraldojs@sc.usp.br

Abstract. *The search for more accurate techniques in the manufacturing process is closely linked with the search of cost, machining time and environmental impact reduction. In this scope, grinding is a key process, due the great geometrical, dimensional and surface quality of its products. This process, however, has high energy consumption per removed material, and needs the implementation of auxiliary systems to ensure the process stability, such as: dressing system, exhausting and cutting fluid filtration system, and cooling units for the hydraulic system. This paper presents a methodology to evaluate the power consumption of a cylindrical plunge grinding process unit during its different operational states. This methodology helps the identification of the power consumption behavior, quite important to perform a Life Cycle Analysis of the process, as well to decide the need of grinding machine retrofitting.*

Keywords: *grinding, energy consumption, power mapping*

1. INTRODUCTION

The reduction of production costs, time and environmental impacts, linked with the improvement of final product quality are a desirable perspective for any machining process. In this scenario, the power consumption plays a special role, interfering in the production costs and environmental impacts, chiefly at the grinding process, which has a low efficiency in material removal per power consumed, compared with other machining process like turning and milling (Machado et al, 2009).

Machado et al. (2009), point out the prominent position of grinding process among the abrasive machining process, providing the production of high dimensional and geometric quality components. Besides this importance, the process is, among the machining processes, one of that more impacts the environment, due its need of cutting fluid application and the high power consumption.

However, there are few advances on the power consumption reduction of grinding process, once it usually represents costly investments in machinery technology and the electric energy cost has a small participation at the product total cost. Therefore, inexpensive and effective solutions to reduce the grinding power consumption are required to allow the implementation of a less costly and more ecofriendly production.

The high power consumption of grinding process is due its material removal by abrasive action. Besides the low amount of material removal, the abrasive action produces a large amount of heat, making the temperatures at the grinding zone to achieve 1000 ^{o}C to 1600 ^{o}C, raising the specific power of material removal to levels much higher than the other machining processes. According to Abrão *et al.(2009),* the grinding power consumption by removed material per time unit is 2 to 20 times higher than the other machining processes.

The elevated working temperature forces the use of cutting fluid, high pressure elements and grinding wheels that allows the flow of the cutting fluid. These characteristics results on the implementation of several auxiliary systems which raises even more the process total power consumption. Hydrostatics systems, as the grinding wheel bushings and axis, and hydraulic systems are some of the highest power consumption subsystems. Thereupon, the power consumption monitoring of all subsystems (auxiliary and main systems) is an effective way to identify some optimization solutions for the grinding power consumption.

The monitoring of grinding system energy consumption is an important data source for many types of researches and studies. This data, for instance, is crucial to perform the Life Cycle Analysis – LCA of the grinding process unit, once it has a considerable paper at its environment impacts.

Another example is the use of this energy consumption data to evaluate the need of a machine retrofitting. Machining equipment has a large lifetime, higher than 10 years (Gontarz *et al.*, 2011), therefore, in order to avoid its obsolescence against the new technologies, the equipment needs to be updated with new components, software and tools, guaranteeing a better final product quality, a higher energy efficiency and the product competitive edge.

1.1 Objective

ISSN 2176-5480

This paper presents a power consumption monitoring strategy for a cylindrical plunge grinding process unit. From the electrical parameters measurement of the grinding process unit, at different working phases, it will be provided the mapping of the unit process total power consumption, as well the consumption of each subsystem.

This power mapping is underexplored in the industrial scenario, but it can provide substantial data to improve the power efficiency of the process, reducing production costs and environmental impacts. It can also provide information to project newer machines and/or to develop newer retrofitting possibilities.

2. METHODOLOGY

The proposed methodology is divided in two phases: the power consumption mapping and identification of the subsystems. The first phase consists in the definition of the measurement procedure. The second phase consists on the acquisition of the power consumption data, identification of the most important subsystems and their power consumption.

Figure 1 presents the different inputs and outputs of a grinding process unit. Elements as cutting fluid and debris can be quantified after its utilization. Parameters as superficial and geometrical quality can be identified after the grinding process. However, the power consumption parameters can be just acquired by on-time measurement. The diagram shown by Fig. 1 indicates that the electric energy is an input, and, therefore, it can be measured only at this instance, because it will be converted, during the process, at other forms of output, as product aggregate value, heat and other forms of energy.

The power consumption mapping methodology aims to supply relevant data to improve the power efficiency of the process unit, by the identification of the grinding phases and subsystems which has the highest power consumption, in order to find and decrease power waste.

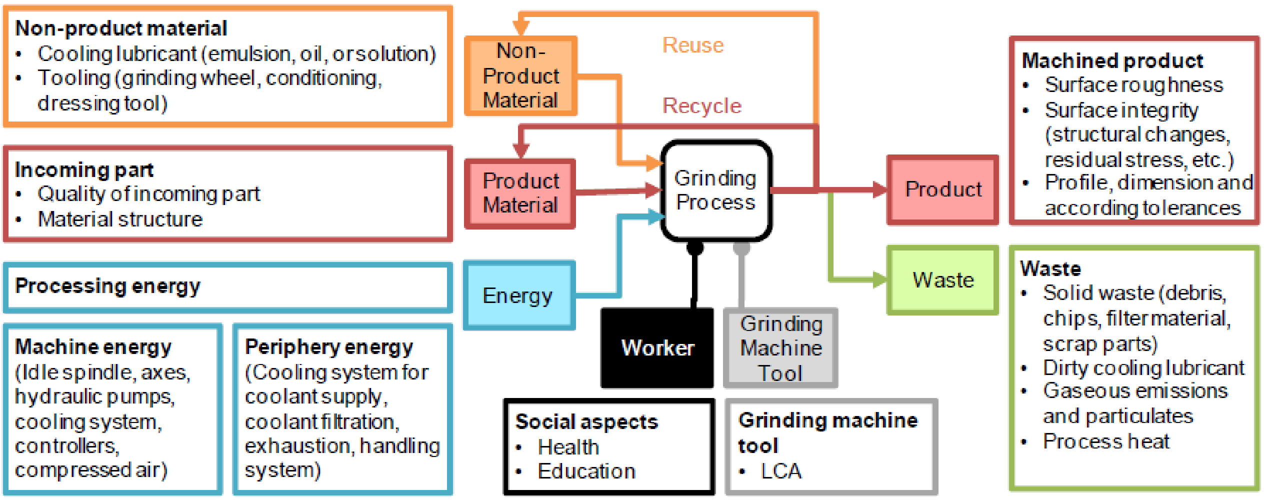

Figure 1. Comprehensive input-output diagram of a grinding process (Linke *et al.*, 2011)

2.1 Power Consumption Mapping

The cylindrical plunge grinding machine Zema Numerika G-800 HS was chosen to perform the power consumption mapping. This machine has a Computer Numerical Control – CNC device and is used to machine crankshafts, pump axis, motor axis and other cylindrical components, which high superficial quality is desirable. Figure 2 shows a picture of the chosen machine.

ISSN 2176-5480

Figure 2. . Zema Numerika G-800 – HS with CNC GE-FANUC model 180i

The measurement of power consumption has to be done at the 220V three-phase machine power supply system. The acquisition by regular wattmeters would demand a costly and complex measurement system and may not have a friendly interface with computers.

In order to overcome these obstacles, other solutions were evaluated. The chosen solution was the electric multivariable measurer, because of its relative low implementation cost and a friendly and flexible interface with computers. This device consists in a microprocessor transducer with analogic inputs and digital outputs and the data transmission through a serial network: the device send the acquired data by a RS-485 serial protocol, which is converted to a RS-232 protocol by a converter device, in order to turn possible the communication with the computer. The sampling rate is adjusted by the computer and has been defined in one sample per second.

The installation of the measurer adopted a 3 wired and 2½ element configuration (Fig. 2) to perform the data acquisition. The chosen device supports voltages higher than 220V, however it just supports electric current under 6A, what forced the implementation of electric current transformer to limit the input device current to working values.

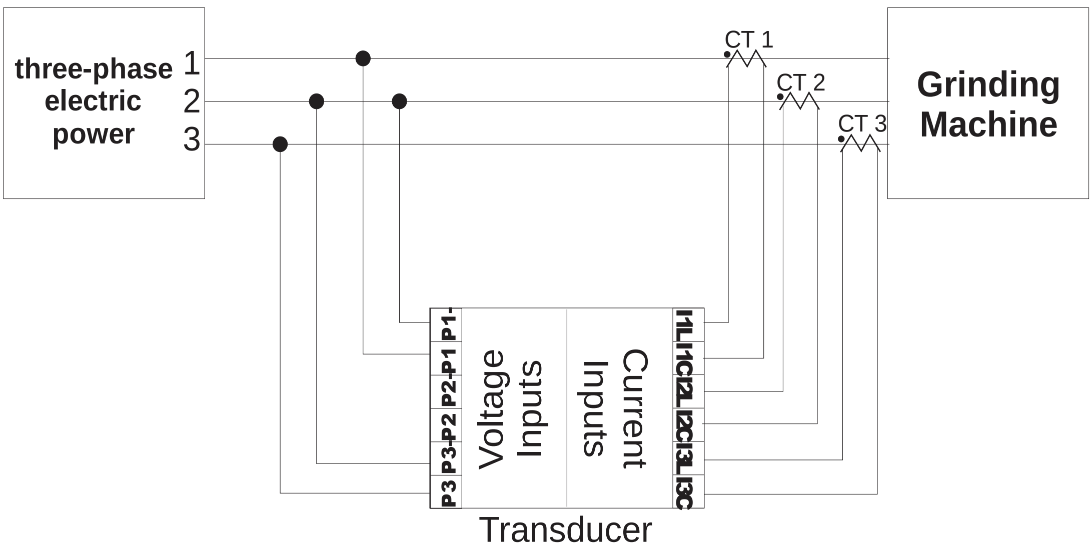

Figura 2: Connection between line, transducer and machine

ISSN 2176-5480

2.2 Identification of the subsystems

2.2.1 Identifying the systems

According to Sena (2007a), the grinding process unit can be divided at the following subsystems:

- Structural Components: drives, measurement and control systems, safety devices, hydraulic and pneumatic systems, wires, pipes, collect and removal systems for debris and fluids;
- Fixation Systems: Fixation of the grinding wheel and the cylindrical workpiece;
- Progress Systems: Electric drive, movement converter and measurement system;
- Position Sensors: Encoders, acoustic emission sensors and inductive or resistive sensors;
- Heat changers: Hydraulic and cutting fluid and cooling systems.

Figure 3 presents a detailed view of some of these grinding machine components:

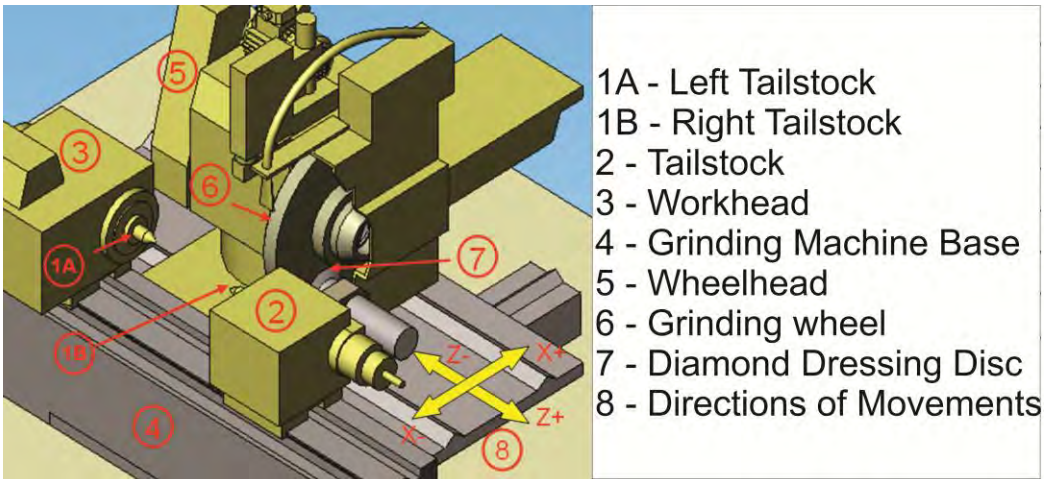

Figure 3. Grinding machine components (Sena, 2007)

Observing the grinding process unit subsystems it was possible to define a framework of the power consumption mapping. It was considered only the systems which the power supply comes directly from the grinding machine main power supply.

The pneumatic systems are supplied by an external pressured air pipelines, therefore, the consumption of these systems is not associated with the grinding machine main power supply, so it won't be considered in this study.

The hydraulic system of the grinding machine is basically consisted by a motor-pump set and has high power consumption, once it has to allow, among other things, the movement of the system drives and hydrostatics bushings.

The cutting fluid application system also consists by motor-pump set, which are responsible to control the grinding surface temperature. Both cutting fluid and hydraulic system shares a cooling system, fed by cold water, in order to maintain both types of fluid under the temperatures specified by the fabricant. The cutting fluid application system also counts with an air filtering exhaustion system.

Another relevant subsystem is the grinding wheel drive system, based on a 37 KW "built-in" electric motor, directly linked with the grinding wheel shaft. This wheel achieves cutting speeds over 100 m/s, which result on relative high power consumption. The dressing process also includes an electric motor to perform the dressing operation for superabrasive wheels.

All the subsystem cited above increases, significantly, the power consumption of the grinding process units and, by this reason, must be identified and measured in order to achieve an efficient power consumption mapping.

Lastly, the grinding process can be divided in three distinct modes:

- **Stand By:** all the subsystems are down, just the machine computer is on;
- **Idle:** The machine is ready to grind, the auxiliary systems, the CNC and the machine computer are on.
- **Machining:** The workpiece grinding; different auxiliary systems are set in different grinding steps.

ISSN 2176-5480

2.2.2 Identifying the subsystems power consumption

The first step to identify the subsystem power consumption is to discover which the limitations are and safety procedures related with the subsystems drives. In order to overcome these issues, it is necessary to identify, during the process, the behavior of each subsystem to define its power consumption. For instance, it will be shown the following situations of an ordinary machine:

- **Situation A:** Computer is on;
- **Situation B:** Computer and hydraulic system on.

The computer must be on to allow the drive of the other devices and systems. In this case, the power consumption of the hydraulic system $\mathbf{P_{hydr}}$ can be obtained by the subtraction of the computer power consumption $\mathbf{P_{comp}}$ from the total power consumption $\mathbf{P_{global}}$ (Eq. 1).

$$P_{hydr} = P_{global} - P_{comp} \tag{1}$$

Equation 2 represents an overview method:

$$P_i = P_{global} - \sum_{k=1}^{m} P_k \tag{2}$$

The index *i* refers the system that will be analyzed, the index *k* the subsystem that have been driven and the index *m* is all the other subsystems.

This method can present some problems during the power consumption identification of systems with controlled action. In these cases, the power consumption varies according to the system control effort. Thus, the identification of the power consumption is done by the machine operator, which has to observe the moment of the rise and fall of the control effort.

During the data acquisition, the time of the systems/components drives has to be documented, in order to identify some the peaks of power consumption. Table 1 shows an example of time documentation.

Table 1. Register of systems/components driven

Hour	Components
13:00	Component A was switched on
13:10	Component B was switched on
13:14	Component C was switched on
13:25	Component C was switched off
13:32	Component B was switched off
13:35	Component D was switched off

Gontarz (2012) presents a way to calculate the total power consumption of for the process, shown by Eq. 3 and Eq. 4:

$$E_i = \sum_{j=0}^{n} P_{i,j} \tag{3}$$

$$n = \frac{t_{total}}{t_{sample}} \tag{4}$$

The element E_i (KWh) is the consumed energy by the *i* subsystem/component, during the time t_{total}. The element $P_{i,j}$ represents the instant power of the *i* subsystem/component at the time *j*. The element *n* is the number of samples during the time t_{total}.

ISSN 2176-5480

3. RESULTS

The verification of the proposed method was performed by test on the grinding machine. This test aimed to verify the efficiency of the method, identifying the consumed power from each subsystem of the grinding process unit. Table 2 presents the test time register.

Table 2. Time register table

Hour	Component Driven
09:00	The computer was turned on
09:12	Hydraulic system was driven
09:13	Cooling System was turned on, however it was not driven by the control system still
09:14	Sensor drove the cooling system
09:14	Cutting fluid pump was driven
09:17	Cutting fluid pump was turned off
09:17	Cutting fluid pump was driven again
09:18	Dresser (no load) was driven
09:19	Dresser was turned off
09:20	Mist filtration system was driven
09:28	Grinding wheel was driven at 15m/s without cutting fluid (no preheating)
09:28	Grinding wheel was driven at 30m/s without cutting fluid (no preheating)
09:29	Grinding wheel was driven at 45m/s without cutting fluid (no preheating)
09:30	Grinding wheel was turned off
09:43	Machine was left for more than 10 minutes in the warm-up
09:43	Grinding wheel was driven at 15m/s without cutting fluid (With warm-up)
09:44	Grinding wheel was driven at 30m/s without cutting fluid (With warm-up)
09:44	Grinding wheel was driven at 45m/s without cutting fluid (With warm-up)
09:45	Grinding wheel was turned off
09:46	Grinding wheel was driven at 15m/s (still no cutting fluid)
09:46	Cutting fluid system was driven
09:47	Grinding wheel was driven at 30m/s with cutting fluid
09:48	Grinding wheel was driven at 45m/s with cutting fluid
09:48	Cutting fluid system was turned off
09:50	Grinding wheel was turned off

Figure 4 presents a chart with the identification of the power consumption of each defined grinding process system. The blue area (1) is the Stand By power consumption, representing the consumption of the computer and other related circuits. The pink area (2) is the hydraulic system power consumption. The green area (3) represents the power consumption of the cooling system at steady mode. The yellow area (4) represents the additional power consumption of the cooling system by the raising of the control effort (target setpoint for returning water temperature). The orange area (5) represents the consumption of the cutting fluid application pump.

ISSN 2176-5480

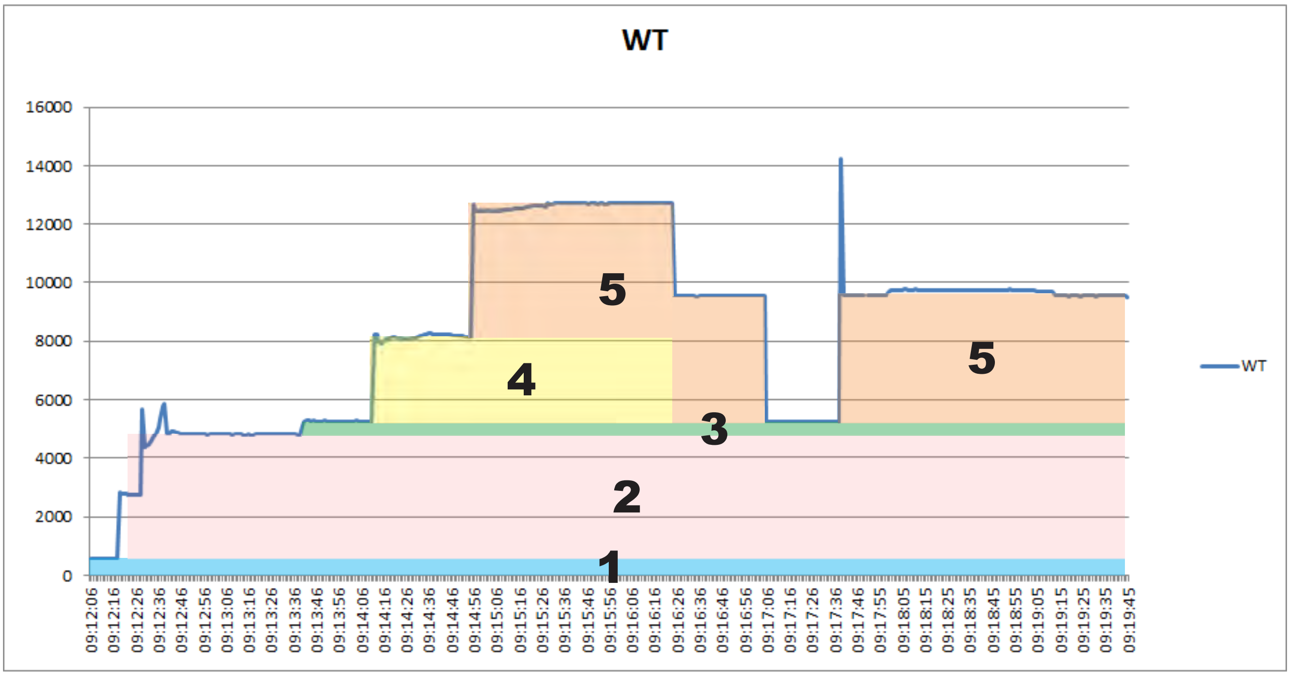

Figure 4. Chart of the power consumption of each system

During the drive of the different systems/components, it was noticed some instant power peaks or even wider peak intervals before the power consumption stabilization. These situations are considered as outliers and both were not considered at the following average power consumption calculations.

- Stand By power consumption: 4810 W;
- Hydraulic System power consumption: 4810W – 580W= 4230W;
- Cooling system power consumption (Steady Mode): 5180W – 4230 – 580W = 370W;
- Additional power consumption of the Cooling System, by the control effort: 8080W – 5180W = 2900W;
- Power consumption of the Cutting Fluid Application Pump: 12610W – 8080W = 4530W.

Similar calculations were made to determine the power consumption of the dressing system and the air filtering exhausting system, respectively 160W and 2370W.

The cooling system shutdown time was not record, because this is a closed loop control system. However, once its power consumption is known, it could be possible to identify its shutdown at 9:14:56.

Similar calculations were made to determine the power consumption of the dressing system and the air filtering exhausting system, respectively 160W and 2370W.

The grinding wheel drive system was tested by changing the cutting speed (15 m/s, 30 m/s and 45 m/s) in idle (no grinding) and the cutting fluid application (on and off). Table 3 presents the average power consumption for all the possible combinations.

Table 3. Grinding wheel drive average power consumption

	Cutting fluid application	
Grinding wheel tangential velocity (m/s)	ON	OFF
15	740 W	970 W
30	1360 W	1720 W
45	2200 W	2450 W

The power consumption increasing at the grinding wheel drive system after the cutting fluid nozzle was open and fluid flow released due to the hydrodynamic barrier caused by the cutting fluid around the grinding wheel, which forces its deceleration.

4. CONCLUSION

ISSN 2176-5480

The results shows that it is possible to measure and identify the power consumption of the grinding process unit main subsystems, from the main machine power supply, with the performing of a low implementation cost and flexible solution.

However, subsystems as the hydraulic and cutting fluid cooling system and other independent controlled subsystems need a special attention. The identification of their average power consumption is only possible after the identification of the other subsystems.

The proposed methodology shows to be efficient and easy to perform. This power consumption mapping is extremely important to perform a Life Cycle Analysis of the process unit, as well to ascertain the need of a machine remanufacturing.

5. ACKNOWLEDGEMENTS

The authors would like to thank the CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for supporting this research.

6. REFERENCES

Xu, X., Feb 2012. “From cloud computing to cloud manufacturing”. *Robotics and Computer-Integrated Manufacturing*, New Zealand, Vol 28, n. 1, p. 75-86.

Catai, R. E., 2004. *Optimization of the coolant/lubrication conditions in the cylindrical plunge grinding process*. Ph.D. thesis (Mechanical Engineering Doctoral Program), Faculty of Engineering of Guaratingueta Campus, UNESP, Sao Paulo State University, Guaratiguenta.

Delgado M., M. L., 2012. *Mapping and Evaluation of Energy Consumption during the Use-able Phase of a Machine Tool Aiming at Sustainability*. Dissertation (Master Degree), São Carlos School of Engineering, University of São Paulo. São Carlos.

Linke, B., and Overcash, M., 2012. “Life Cycle Analysis of Grinding”. In *Leveraging Technology for a Sustainable World. Retrieved* from http://link.springer.com/chapter/10.1007/978-3-642-29069-5_50.

Machado A. R.; ABRÃO A.M.; Coelho, R. T.; Silva, M.B., 2009. *Theory of Machining of Materials*. Blucher Ltda, São Paulo, 1st edition.

Diniz, A. E.; Marcondes, C. M.; Coppini N. L., 2010 *Machining technology of materials*. São Paulo, Artliber Ltda, São Paulo, 7th edition.

Sena, L., 2007 *Evaluation of Positioning System of a Wheelhead in a CNC Grinding Machine Flexa 600-L with the Help of Acoustic Emission Signals*. Dissertation (Master Degree), Federal University of Santa Catarina, Florianópolis.

Gontarz, A. M.; Hänni, F.; WEISS, L. B.; Wegener, K., 2012. “Machine tool optimization strategies for ecologic and economic efficiency”, *Journal of Engeneering Manufacture, Zurich*, p.54-61.

Reinhardt, S., Maretta, L., Robinson, S., Linke, B., 2011: LMAS report on Life Cycle Assessment for Discrete Manufacturing Processes.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.