24th COBEM - 2017

COBEM-2017-2220
ANALYSIS OF THE RELATIONSHIP BETWEEN METAL REMOVAL RATE AND ENERGY CONSUMPTION IN MILLING

Renan Cavalcante Santos
Milton Pereira
João Carlos Espíndola Ferreira
Universidade Federal de Santa Catarina, Dep. de Engenharia Mecânica, Caixa Postal 476, 88040-900, Florianópolis, SC, Brazil
renancavalcantes@yahoo.com.br
milton.pereira@ufsc.br
j.c.ferreira@ufsc.br

Abstract. In order to carry out a machining process with high efficiency, a study was performed that relates cutting conditions with the consumption of electric energy in a CNC machining center. During the experiment, the influence of the axial depth of cut and radial depth of cut on the energy consumption was evaluated. These parameters directly influence the machining cross section and the forces involved in the process. Severe cutting conditions increase the material removal rate (MRR), but they increase the forces and require more energy consumption for cutting. Slighter conditions require less effort to perform cutting, but machining times are increased. AISI P20 steel was machined by milling in a machining center and the relationship between material removal rate and electric power consumption was evaluated.

Keywords: Energy Consumption, Material Removal Rate, Milling, Machining Parameters.

1. INTRODUCTION

Manufacturing is a fundamental activity in the world economy, but it causes negative impacts on the environment due to consumption of materials (renewable or not), waste generation and consumption of large amounts of energy. Over the last few years there has been increased concern with environmental factors and energy conservation in the industrial sector (Yingjie, 2014; Behrendt *et al.*, 2012). Energy resources are predominantly generated by the burning of fossil fuels, and the consumption of electricity in manufacturing generates a large carbon footprint. Thus, there is a need to reduce energy consumption in manufacturing to reduce CO_2 emissions (Balogun and Mativenga, 2013; Vijayaraghavan and Dornfeld, 2010). Therefore, it is important to investigate the characteristics of power consumption in computer numerical control (CNC) machining centers in order to provide important information to improve the machining energy efficiency. The profile of power consumption in modern machining centers tends to be very complex, varying significantly in relation to the equipment specification and variety of processes (Li *et al.*, 2017).

Machining processes represent a significant portion of energy consumption in the industrial sector, and increasing energy efficiency in these processes can result in both a reduction in the environmental impact and more competitive products in the market, especially in countries with high electric energy prices (Newman *et al.*, 2012; Mativenga and Rajemi, 2011). Another improvement is the replacement of traditional short-term financial considerations with sustainable long-term strategies (Peng and Xu, 2014). To execute machining processes more efficiently it is necessary to understand the phenomena surrounding this activity and to seek ways to optimize energy consumption.

Dahmus and Gutowski (2004) divided the energy consumption in machining in two portions: fixed and variable. The fixed consumption of electric energy occurs due to auxiliary devices of the machines to ensure their operational readiness, while the variable consumption of energy depends on the machining forces. Mori *et al.* (2011) pointed out that energy consumption can be reduced by modifying the machining conditions. Ma *et al.* (2014) analyzed the effects of cutting parameters and tool geometry on the energy consumption when turning AISI 4140 steel.

In this context, this work seeks to investigate the influence of material removal rate on the consumption of electric energy.

2. THEORETICAL FOUNDATION

Electric power is the main source of power for machine tools. The largest amount of electrical energy is consumed in the spindle rotation and in the linear movement of the axes, and the energy consumed by these components is directly related to the machining conditions. Other sources of consumption are the peripheral components present in the machine (e.g. hydraulic unit, cutting oil pumps, cooling devices) (Yingjie, 2014), which have more and more items that guarantee high precision, repeatability and productivity. These components, while improving the process, result in a significant increase in energy consumption (Mori *et al.*, 2011).

The methodology proposed by Dahmus and Gutowski (2004) is to generate a power vs. time chart during machining, and the area below the generated curve represents the energy consumed. The energy consumption profile represented in the chart can be divided into three states to better represent the process: (a) Idle mode: the machine remains on, having a constant power consumption and, in general, the machine components cannot be disconnected; (b) Execution phase: the components that performs machining are actuated, there is movement of shafts, but without removal of material; (c) Production mode: material removal takes place and, in addition to the constant consumption of the machine, consumption is added due to the machining forces.

Wang *et al.* (2015) presented results in the turning operation following the same methodology, as shown in Figure 1.
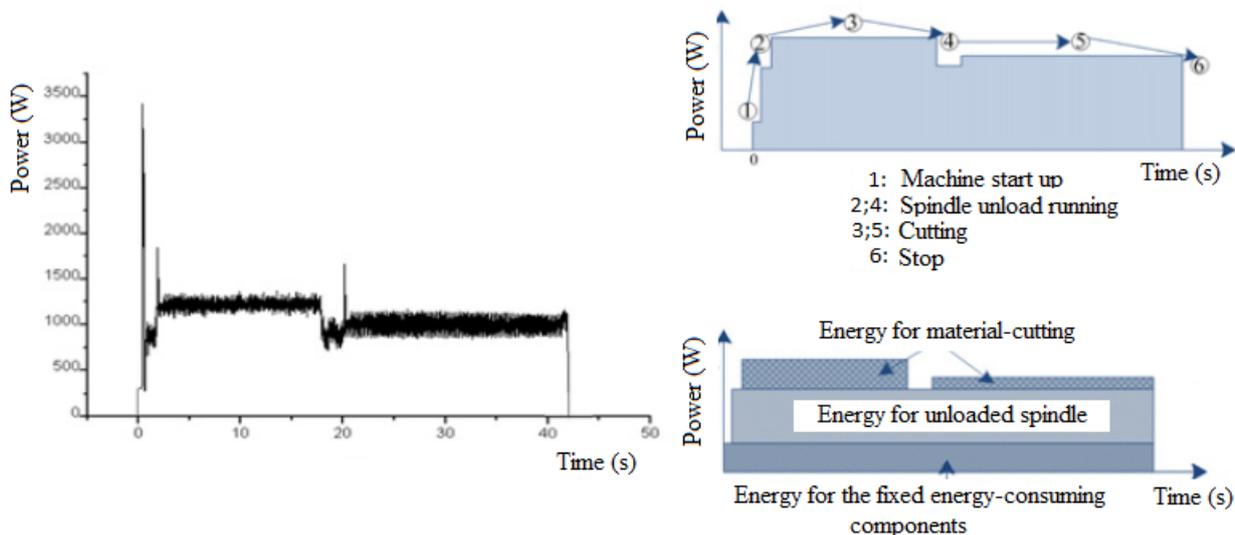

Figure 1. Energy consumption in turning (Wang *et al.*, 2015)

The energy consumed in the process equals the area below the power vs. time chart. The use of reduced values of the machining parameters requires lower power, but the operating time is longer, which increases the area below the curve in the chart. On the other hand, the more severe the cutting conditions, the greater the power required to perform cutting, but the operating time is lower and it is possible to reduce the area below the curve. However, the cutting conditions should not be increased indiscriminately, since excessive cutting speed and feed can cause premature tool wear or poor surface finish (Mori *et al.*, 2011).

3. EXPERIMENTAL PROCEDURE

In this work an experiment was carried out at the Charles MVC 955 vertical machining center with Siemens Sinumerik 840Di CNC, located at the Federal University of Santa Catarina. The cutter used has a diameter of 20 mm and is composed of interchangeable inserts of carbide, class P 20 and TiAlN + TiN coating. The machined material was AISI P20 steel with 31 HRC hardness. The energy consumption data were collected using the Mult-K current transducer from the manufacturer Kron, and monitoring was performed in real time via the internet through a data acquisition system based on MTConnect (2017), which allows the generation of power vs. time charts.

The present study follows the methodology proposed by Dahmus and Gutowski (2004), however the cutting motion is divided into two stages: (a) Idle: the rotating tool performs movement of approach or exit of the part, without performing removal of material. The energy consumption in this stage is mainly due to peripheral components and is considered constant; (b) Machining: the tool comes into contact with the part and removes material. Energy consumption is due to the idle consumption plus the power required to make the cut.

Figure 2 describes the experimental procedure. The tool performs the idle move with the same distance as the machining length, and then performs machining. The comparison between the no-load motion and the effective cutting motion is very important because, in this way, the difference between the cutting forces is analyzed. Figure 3 illustrates the movement of the tool.
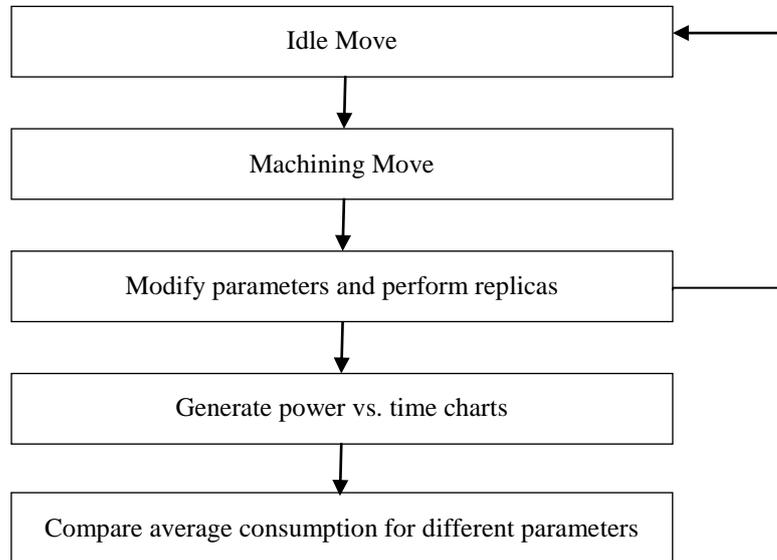

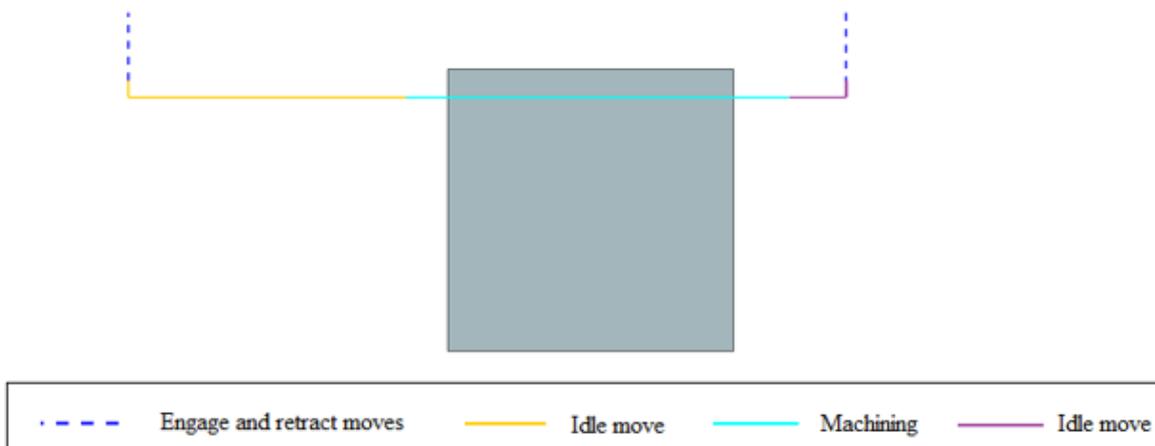Figure 2. The steps of the experimental procedure

Figure 3. The movement of the tool in the experimental procedure

The cutting parameters, based on the limits suggested by the tool manufacturer, were defined as follows: cutting speed v_c = 144 m/min, feed rate v_f = 720 mm/min, constant machining length l = 44 mm. Up-milling cutting was adopted, and combinations between axial depth of cut a_p and radial depth of cut a_e and were used according to Table 1. Two replicates were machined for each combination.

Table 1. Different combinations of a_p and a_e

a_p ⇓ a_e ⇒	5 mm	10 mm	15 mm	20 mm
0.375 mm	C1	C2	C3	C4
0.750 mm	C5	C6	C7	C8
1.125 mm	C9	C10	C11	C12
1.500 mm	C13	C14	C15	C16

The power vs. time chart was generated for each combination in Table 1. The chart was divided according to the idle and machining stages. An average power value was adopted for each stage, and the difference between these values represents the net power required for the cut.

Another set of data was the specific energy for the removal of material in each combination, which enables to estimate the energy required to remove material in order to determine the most efficient combination.

4. RESULTS AND DISCUSSION

Figure 4 shows the power consumed by the C8 and C16 combinations. It is noticed in the chart the increase in power at the moment when the tool leaves the idle stage and starts the machining stage. The average power values at each stage and the power required for the cut are shown in Table 2.
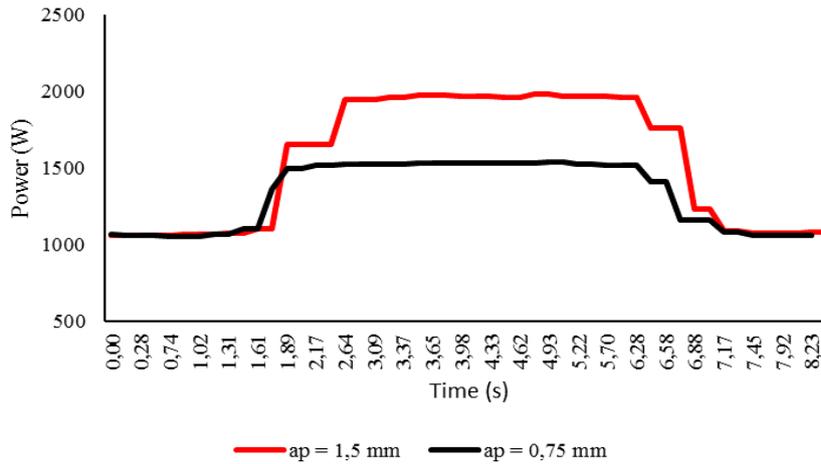

Figure 4. Chart showing power vs time

Table 2. Average powers for combinations C8 and C16

	Power – idle	Power – machining	Power only for cutting (machining minus idle)
C8 ($a_p = 0.75$ mm ; $a_e = 20$ mm)	1057.2 ± 5.34 W	1513.11 ± 8.95 W	455.91 W
C16 ($a_p = 1.50$ mm; $a_e = 20$ mm)	1061.89 ± 13.13 W	1960.82 ± 13.13 W	898.93 W

It is noticed that in the idle stage there is no statistical difference between the power of the two combinations, and this is because the feed rate is the same and the consumption is influenced mainly by peripheral components. The power needed to perform the cut was obtained by subtracting the power in the two stages. When comparing the measured values, an increase of 97% from C8 to C16 is noticed. This result is in agreement with the literature, since the value of a_p was duplicated. However, when analyzing the power during the machining stage it is noticed that the power increase was only 29.6%.

This means that despite machining forces doubled, the portion of consumption due to peripheral items is still much higher than the consumption related to material removal. This situation occurs due to the constructive characteristics of machining centers today.

The specific energy for the removal of material for each combination is shown in Table 3.

Table 3. Specific energy for material removal (values in J/mm³)

$a_p \Downarrow$	$a_e \Rightarrow$	5 mm	10 mm	15 mm	20 mm
0.375 mm		45.22	23.98	16.49	13.08
0.75 mm		24.13	13.05	9.32	6.99
1.125 mm		16.78	9.42	6.93	5.85
1.50 mm		13.08	7.62	5.80	4.95

5. CONCLUSION

This research used as a basis the procedure proposed by Dahmus and Gutowski (2004) for the evaluation of the electric power consumption in machine tools. Several authors use this approach with some modifications. The approach used in this paper was applied in a CNC machining center performing milling. The data acquisition occurred in real time through the Internet, and the proposed methodology addressed both the power consumed and the power required for the cut.

According to the results obtained, the power required to perform the cut varies linearly, so that when doubling the machining section, the power required for cutting is also doubled.

When analyzing the specific energy (energy required to remove 1 mm³), it can be noticed that for higher values of depth of cut, the specific energy decreased. This is because, with more severe parameters, a higher material removal rate is obtained and, even if the power increases, it does not increase to the point of exceeding the consumption of the peripheral items.

As future work we suggest the analysis of the energy consumption by considering the specific energy for material removal, but varying other parameters such as the cutting speed and the characteristics of the cutting tool.

6. REFERENCES

Balogun, V.A. and Mativenga, P.T., (2013). "Modelling of direct energy requirements in mechanical machining processes". *Journal of Cleaner Production*, Vol. 41, p. 179-186.

Behrendt, T., Zein, A. and Min, S., 2012. "Devolopment of an energy consumption monitoring procedure for machine tools". *CIRP Annals - Manufacturing Technology*, Vol. 61, No. 1, p. 43-46.

Dahmus, J.B. and Gutowski, T.G., 2004. "An environmental analysis of machining". In *American Society of Mechanical Engineers (ASME)*, International Mechanical Engineering Congress and Exposition, p. 13-19.

Li, L., Li, C., Tang, Y. and Yi, Q., 2017. "Influence factors and operational strategies for energy efficiency improvement of CNC machining". *Journal of Cleaner Production*, Vol. 161, p. 220-238.

Ma, J., Ge, X., Chang, S.I. and Lei, S., 2014. "Assessment of cutting energy consumption and anergy efficiency in machining of 4140 steel". *International Journal of Advanced Manufacturing Technology*, Vol. 74, No. 9-12, p. 1701-1708.

Mativenga, P.T. and Rajemi, M.F. (2011). "Calculation of optimum cutting parameters based on minimum energy footprint". *CIRP Annals - Manufacturing Technology*, Vol. 60, No. 1, p. 149-152.

Mori, M., Fujishima, M., Inamasu, Y. and Oda, Y., 2011. "A study on enrgy effitiency improvement for machine tools". *CIRP Annals - Manufacturing Technology*, Vol. 60, No. 1, p. 145-148.

MTConnect, (2017). "MTConnect". 25 Mar. 2017 <http://www.mtconnect.org>

Newman, S.T., Nassehi, A., Imani-Asrai, R. and Dhokia, V., 2012. "Energy efficient process planning for CNC machining". *CIRP Journal of Manufacturing Science and Technology*, Vol. 5, No. 2, p. 127-136.

Peng, T. and X, X., 2014. "Energy-efficient machining systems: a critical review". *International Journal of Advanced Manufacturing Tchnology*, Vol. 72, No. 9-12, p. 1389-1406.

Vijayaraghavan, A. and Dornfeld, D., (2010). "Automated energy monitoring of machine tools". *CIRP Annals - Manufacturing Technology*, Vol. 59, No. 1, p. 21-24.

Wang, Y., He, Y., Y. Li, Yan, P. and Feng, L., 2015. "An analysis framework for characterization of electrical power data in machining". *International Journal of Precision Engineering and Manufacturing*, Vol. 16, No. 13, p. 2717-2723.

Yingjie, Z., 2014. "Energy effiency techniques in machining process: a review". *International Journal of Advanced Manufacturing Technology*, Vol. 71, No. 5-8, p. 1123-1132.

7. RESPONSIBILITY NOTICE

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