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Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use

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Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use

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Abstract

Since machine tools are used extensively throughout their functional life and consequently consuming valuable natural resources and emitting harmful pollutants during this time, this study reviews strategies for characterizing and reducing the energy consumption of milling machine tools during their use. The power demanded by a micromachining center while cutting low carbon steel under varied material removal rates was measured to model the specific energy of the machine tool. Thereafter the power demanded was studied for cutting aluminum and polycarbonate work pieces for the purpose of comparing the difference in cutting power demand relative to that of steel.

Keywords:

Green Machine Tools; Energy Consumption Reduction; Specific Energy Characterization

1 INTRODUCTION

A product undergoes three life-cycle stages: manufacturing, use and end-of-life. Consumer products whose environmental impact is dominated by the use phase include light fixtures, computers, refrigerators, and vehicles, in general products that are used extensively during their functional life. All the while these products consume resources, in particular energy in the form of electricity or fuel. The machine tool is one such product. The use phase of milling machine tools has been found to comprise between 60 and 90% of CO2-equivalent emissions during its life cycle [1]. This study presents a method for predicting the electrical energy consumed in manufacturing a product for the purpose of reducing its environmental impact.

In conducting a life cycle assessment, product designers may choose to opt for a process, economic input-output (EIO), or hybrid approach. The drawback of the process LCA, though, is that because this method entails acquiring process-specific data it is time consuming and therefore resource intensive. An alternative to measuring the machine tool's electrical energy consumption directly, for example, is to use aggregate data as is done with EIO-LCA [2]. An EIO-LCA, therefore, is not specific to the design of a particular product. The strategies presented herein provide a method for more quickly generating manufacturing energy consumption estimates for a particular product.

1.1 Cutting load profile

As described by Diaz et al. in [3] the power demand of a machine tool is comprised of cutting, variable, and constant power components. The cutting power is the additional power drawn for the removal of material. The machine tool used in this analysis, the Mori Seiki NV1500 DCG, is a micromachining center with a relatively low standby power demand when compared to large machining centers. Therefore, the cutting power can comprise a large portion of the machine tool's total power demand.

Energy consumption for high tare machine tools was found to be primarily dependent on the processing time of the part, which is dictated by the part geometry, toolpath, and material removal rate. One such method for optimizing the tool path for minimum cycle time was presented in [4].

This paper is concerned with the effect of the material removal rate on energy consumption. The material removal rate for a 3-axis machining center can be varied by changing the feed rate, width of cut, or depth of cut. Since increasing the feed rate was found to have dire consequences on the cutting tool life [5], the experiments conducted herein varied material removal rate through width of cut and depth of cut experiments for the purpose of analyzing the material removal rate's effect on cutting power and more importantly, energy consumption. Although increases in the material removal rate translate to faster machining times, the loads on the spindle motor and axis drives increase as well, resulting in higher power demand. Since our main interest is energy consumed in product manufacture, the trade-off between power demand and machining time was analyzed to confirm that the increased loads due to faster material removal was not increasing the total energy consumed.

2 POWER DEMAND FOR VARIED M.R.R.'S

Since machine tool programmers and operators have an array of options when defining the process plan for part production, this analysis strives to reduce energy consumption by process parameter selection of a machine tool. Specifically, the parameters concerning material removal rate (M.R.R.) were varied on a Mori Seiki NV1500 DCG while selecting appropriate tooling. The power demand was measured with a Wattnode MODBUS wattmeter.

In previous work, experiments were conducted in which spindle speed, feed rate, feed per tooth, and cutter type were varied to analyze the change in energy consumption while milling a low carbon steel, AISI 1018 steel [5]. Also, [6] conducted experiments on face milling, end milling, and drilling operations in which the energy consumption, machining cost, and tool wear were compared for increased cutting speeds. Tool wear and, consequently, cutting tool cost increased significantly when the process parameters veered away from the recommended cutting conditions. So in the

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following experiments the cutting tool type was changed to maintain the recommended process parameters, but reduce energy consumption while machining, nonetheless.

2.1 Width of Cut Experiments

Given the energy savings from changing the cutter type this project focused on varying material removal rate. First the width of cut was increased while machining with a:

1. 2 flute uncoated carbide end mill,
2. 2 flute TiN coated carbide end mill, and
3. 4 flute TiN coated carbide end mill.

Peripheral cuts were made along the y-axis at a depth of cut of 2 mm with an 8 mm diameter end mill over a length of 101 mm in a 1018 steel work piece. The width of cut was varied by 1 mm increments between 1 mm and 7 mm, in addition to a 7.5 mm width of cut. Table 1 summarizes the cutting conditions used. The chip load was maintained at approximately 0.03 mm/tooth to avoid excessive tool wear and breakage.

Cutter	Spindle Speed	Feed Rate	Chip Load	M.R.R.
	$[\frac{rev}{minute}]$	$[\frac{mm}{minute}]$	$[\frac{mm}{tooth}]$	$[\frac{mm^3}{second}]$
(1)	5426	330	0.033	11 - 83
(2)	7060	430	0.030	14 - 108
(3)	7060	860	0.030	29 - 215

Table 1: Process parameters for width of cut experiments.

Once the power was measured for each width of cut experiment, the power demand was measured for the machine tool while air cutting, that is, while running the toolpath without material removal. This way the power associated with the material removal process could be extracted, known hereafter as the cutting power demand. The average air cutting power demand was found to be 1510 W for the cutter (2) process parameters, so it was subtracted from the average total power demand. Figure 1 shows the cutting power demand as a function of the M.R.R. for cutter (2). This plot has a slightly parabolic trend with a point of inflection at approximately 75 mm^3/s.

The cutting power demand for the 7.5 mm width of cut was almost nine times greater than the 1 mm width of cut. Since the total air cutting power demand was only 1510 W, though, the resulting increase in total power demand of the machine tool was only 28%. Thus in terms of energy consumption, the operator still experiences energy savings with the increase in M.R.R.

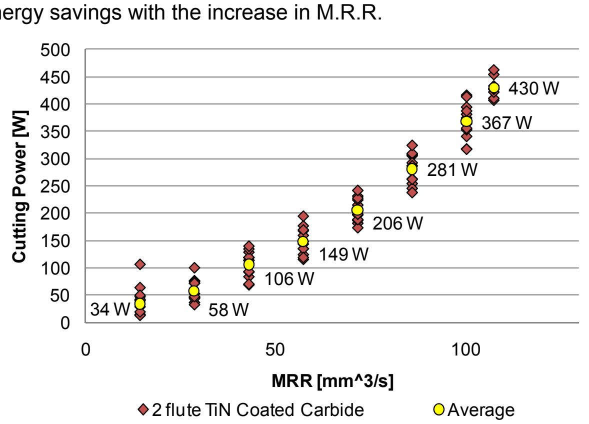

Figure 1: Cutting power demand using cutter (2) while cutting 1018 steel.

Figure 2 shows the average power demand of the NV1500 DCG for cutters (1) – (3). The relationship between power and M.R.R. shifts from parabolic to linear in moving from the conditions imposed on cutter (1) to cutter (3). The increase in power demand is the greatest for cutter (3), but the load on the spindle motor and axis drives is also much greater than that of the 2 flute cutting tools since the feed rate is twice as large or greater.

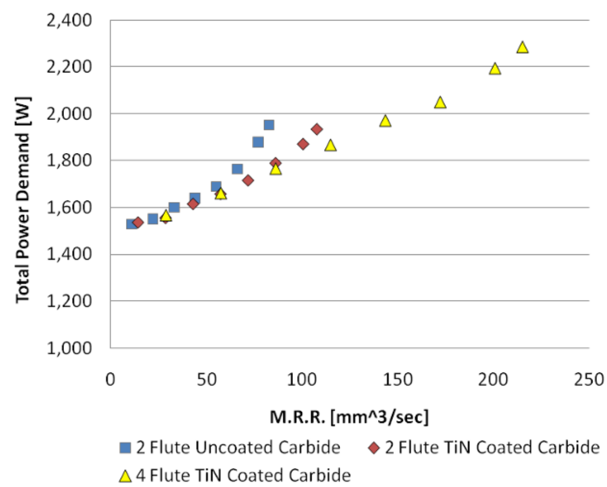

Figure 2: Average total power demand as a function of M.R.R.

2.2 Depth of Cut Experiments

Depth of cut experiments were also conducted on a 1018 steel work piece 101 mm in length. Cuts were made along the y-axis using 8 mm diameter, 2 flute uncoated and TiN coated carbide end mills under near slotting conditions (a width of cut of 7.5 mm). The power demand was measured at depths of cut of 1, 2, 4, and 8 mm. The chip load was maintained constant across the various cutters at 0.051 mm/tooth. The spindle speed and feed rate were varied, though, to account for higher loads on the machine tool during the depth of cut experiments (see Table 2 for a summary of the processing conditions).

Cutter	Spindle Speed	Feed Rate	Chip Load	M.R.R.
	$[\frac{rev}{minute}]$	$[\frac{mm}{minute}]$	$[\frac{mm}{tooth}]$	$[\frac{mm^3}{second}]$
(1)	2500 - 3200	254 - 325	0.051	40 - 250
(2)	3250 - 4160	330 - 425	0.051	50 - 330

Table 2: Process parameter ranges for depth of cut experiments.

Figure 3 summarizes the power demanded by the NV1500 DCG for the 2 flute TiN coated end mill (cutter (2)) and the energy consumed as a function of material removal rate. Although the power demand increases with load the energy consumption still drops drastically with the increase in material removal rate. The machine tool experiences a power demand increase of approximately two-thirds, whereas the energy consumption reduces to less than one-third of its original value. This shows that the decrease in processing time effectively dominates over the increase in power demand due to increased loads.

Since the power demand was shown to increase with load, and experimentally this increase in load was not enough to increase the overall energy consumption, the trade-off between power demand and processing time will be analyzed.

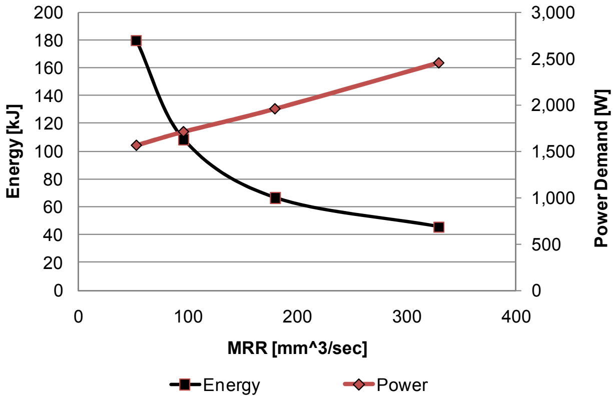

Figure 3: Energy and power demand as a function of M.R.R. for depth of cut experiments with cutter (2).

2.3 Trade-off Between Power Demand and Processing Time

The machine tool's electrical energy consumption is dependent on the power demand, p_{avg}, and processing time, Δt, as seen in Equation 1. Since the power demand shows some variability due to the internal cooling unit of the machine tool, the average power demand, p_{avg}, will be used. As was mentioned previously, the average power demand is composed of a cutting, p_{cut}, and air cutting, p_{air}, component; consequently the energy consumption can be expanded as follows:

$$e = p_{avg} * \Delta t = (p_{cut} + p_{air}) * \Delta t \quad (1)$$

Two scenarios will be compared. Scenario (1) is the base scenario, while scenario (2) will be the scenario in which the material removal rate is increased for the purpose of reducing processing time. The constants, α and β, were created to represent the increase in p_{cut} and decrease in Δt, respectively (see Equations 2 and 3). Note that both constants are less than unity.

$$\alpha = \frac{p_{cut_1}}{p_{cut_2}} \quad (2)$$

$$\beta = \frac{\Delta t_2}{\Delta t_1} \quad (3)$$

Equation 4 shows the relationship between p_{avg1} and p_{avg2}, which assumes that the air cutting power demand, p_{air}, remains relatively constant for both scenarios.

$$p_{avg_1} = \alpha * p_{avg_2} + p_{air} * (1-\alpha) \quad (4)$$

If the relative size of the air cutting power demand is denoted by:

$$\eta_i = \frac{p_{air_i}}{p_{avg\,i}} \quad (5)$$

where i is 1 or 2 for scenarios 1 and 2, respectively, then the inequality presented in Equation 6 shows the condition that must be met in order for the energy consumption of scenario (2) to be smaller than that of scenario (1).

$$\eta_2 > \frac{\beta - \alpha}{1-\alpha} \quad (6)$$

So if β is less than α, then e_2 will always be less than e_1. Also, as η_2 increases (i.e. if the air cutting power demand comprises a large portion of the total power demand) then the probability of e_2 being less than e_1 increases. This would be the case for machine tools with large work volumes which have a high standby power demand. Further work can be conducted in which the assumption that the air cutting power demand does not stay constant to expand the applicability of the power and processing time trade-off analysis.

3 CHARACTERIZING THE SPECIFIC ENERGY

The specific energy of various manufacturing processes was previously summarized by Gutowski et al. [7], but for any given manufacturing process the data was limited to only a sample of process rates. This study, though, will focus on milling machine tools and the operable range of the machining center when characterizing the specific energy.

In characterizing the energy consumption of a machine tool, as the M.R.R. approaches infinity the specific energy is expected to reach a steady state of zero. But, given the work volume, spindle speed, and table feed constraints of a machine tool as well as the maximum loads that can be applied without deforming the main body frame or breaking the spindle motor, the operator will never reach a M.R.R. anywhere near infinity. So under the constraints of the M.R.R. a curve of the following form:

$$e_{cut} = k * \frac{1}{M.R.R.} + b \quad (7)$$

was fit to the data from the width of cut and depth of cut experiments. Note that the constant, k, essentially has units of power and b represents the steady-state specific energy.

The total specific energy, which accounts for cutting and air cutting power demand, was indeed found to have an inverse relationship with the M.R.R. (see Figure 4). The air cutting power demand dominated the specific energy. The impact of the cutting power demand on the specific energy was minimal since at high loads (i.e. at high M.R.R.'s) the machining time decreased significantly.

The specific energy decreases rapidly until a M.R.R. of approximately 75 mm^3/s is reached. For M.R.R.'s lower than 75 mm^3/s, a slight increase in the material removal rate causes a sharp drop in the specific energy because machining time improves dramatically. At M.R.R.'s greater than 100 cm^3/s, the gain from increasing the process rate is minimal since the specific energy begins approaching a steady-state value. This gain could be significant for work pieces requiring a substantial amount of material removal, but since the machine tool used in this study is a micromachining center a M.R.R. greater than 100 mm^3/s would show only a minor decrease in energy consumption given standard work piece sizes.

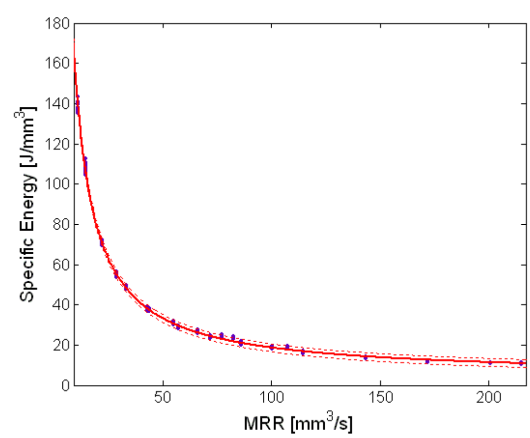

Figure 4: Specific energy as a function of M.R.R.

The best fit model was found to be:

$$e_{cut} = 1481 * \frac{1}{M.R.R.} + 3.678 \quad (8)$$

where the first constant, *a*, is similar to the average air cutting power demand values. As was expected, the specific energies at low M.R.R.'s had such large variations (due to the internal cooling unit) that they surpassed the bounds of the model, but at high M.R.R.'s the specific energies were well within the bounds. Upper and lower bounds with a 95% confidence level are provided below:

$$e_{cut} = 1478 * \frac{1}{M.R.R.} + 3.541 \quad (9)$$

$$e_{cut} = 1488 * \frac{1}{M.R.R.} + 3.853 \quad (10)$$

This specific energy model can be used to estimate the total energy consumed while cutting. The part features and tolerances would dictate the size and type of machine tool required for part manufacture. The optimal M.R.R. can be determined using standard process parameters based on the work piece material and the appropriate cutting tool for the feature creation. Therefore, the total energy consumption while cutting can be calculated by multiplying the specific energy estimate by the volume of material removed.

The machine tool analyzed in this paper is a micromachining center. Larger machine tools can process material at higher rates, therefore shifting the specific energy curve to the right. But these machine tools will also have higher standby power demand due to the peripheral equipment [8] causing an upward shift in the specific energy curve (see Figure 5).

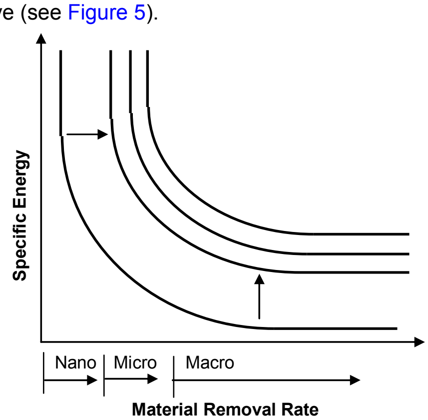

Figure 5: Shift in specific energy plot for larger machine tools.

4 EFFECT OF WORK PIECE MATERIAL ON POWER DEMAND

The aforementioned experiments were conducted with a low carbon steel work piece. The type of material being machined is also a factor in the cutting power demand of the machine tool, though. A plastic work piece, for example, is expected to generate a smaller load on the spindle motor than a metal work piece and therefore result in a lower cutting power demand.

Since the cutting load is expected to vary with the work piece material, the following experiments were conducted to measure the power demand of the Mori Seiki NV1500 DCG while machining peripheral cuts on 1018 steel, 6061 aluminum, and polycarbonate. A depth of cut and width of cut of 2 mm and 4 mm, respectively, was used. The chip load of 0.0254 mm/tooth was maintained constant across the experiments, to allow for the comparison of the results. The process parameters used in the experiment are outlined in Table 3.

Parameter	Units	1018 Steel	6061 Aluminum	Poly-carbonate
Chip Load	$[\frac{mm}{tooth}]$	0.0254	0.0254	0.0254
Feed Rate	$[\frac{mm}{minute}]$	248	621	310
Spindle Speed	$[\frac{rev}{minute}]$	4889	12223	6112
M.R.R.	$[\frac{mm^3}{second}]$	44	82.8	41.3

Table 3: Process parameters for power demand experiments with multiple work piece materials.

The recommended cutting speed varied with the work piece material. Aluminum was cut at the highest speed, followed by polycarbonate, then steel. The use of coolant while machining aluminum was recommended by the cutting tool manufacturer due to the material's ductility and its tendency to build-up on the cutting tool. Coolant was also recommended for polycarbonate to prevent it from melting because of the high temperature at the cutting tool and work piece interface. Steel can be cut without coolant (which would greatly reduce the total power demand of the machine tool), but since cutting fluid aids with chip exit and this study is primarily concerned with the cutting power demand, coolant was used when cutting all material types.

The power demand of the NV1500 DCG is shown in Figure 6, and is broken down into cutting and air cutting power demand. The air cutting power demand is approximately the same across the three processing conditions. The difference is due primarily to the change in spindle speed, the highest of which was used while cutting aluminum. The difference in the power demanded by the axis drives was found to be negligible even though the feed rate for aluminum is more than two times that of steel.

The cutting power demand shows greater variability for the three work piece materials. The cutting power was the greatest while machining the steel work piece. In fact, it was approximately 7% of the total power demand. This may be due to the fact that it has the highest tensile strength, followed by aluminum, then polycarbonate. The cutting power while machining the polycarbonate work piece was the smallest and almost negligible, only 1% of the total power demand.

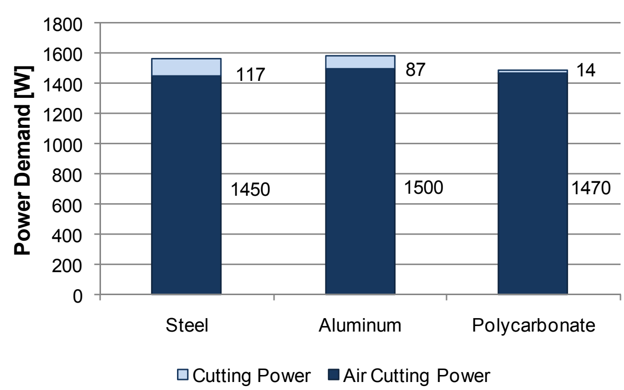

Figure 6: Power demand of NV1500 DCG for steel, aluminum, and polycarbonate work pieces.

A particular work piece material can be machined at a range of process parameters while maintaining minimal tool wear and good surface finish. So future experiments should be conducted in which the material removal rates overlap as much as possible across the work piece materials under study when calculating the cutting power demand for the purpose of comparison. Also, the power demand of the spindle motor and the axis feed drives should be measured directly since presently the cutting power demand is obtained by subtracting the air cutting power demand from the total power demand of the machine tool.

5 CONCLUSIONS

This study has shown that the machining time dominates energy demand for high tare machine tools. Additionally, it has provided a method for characterizing the specific energy of a machine tool as a function of process rate, which can be extended to other types of manufacturing processes.

The specific energy model allows a product designer to estimate the manufacturing energy consumption of their part's production without needing to measure power demand directly at the machine tool during their part's production. Since the specific energy as a function of M.R.R. for the micromachining center presented herein varied by as much as an order of magnitude, it is important to use process parameters and machine tool-specific data to determine accurate electrical energy consumption. This model could therefore be used in place of aggregate embodied energy values for manufacturing processes as provided by [9] or to replace process estimates with great uncertainty when conducting hybrid life cycle assessments.

6 ACKNOWLEDGMENTS

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