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Design and Operation Strategies for Green Machine Tool Development

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Abstract

Several strategies in the areas of process planning, machine design, and machine operation exist to develop green machine tools. Before exploring different solutions, a life-cycle energy analysis is first presented to guide subsequent investigation. The results of this analysis provide a range of the environmental impact of the use of machine tools in different types of manufacturing facilities. One strategy explored energy consumption reduction by process parameter selection. The specific energy of the NV1500 DCG was characterized to estimate the environmental burden of the manufacture of a standard part under various cutting conditions. Finally, we present a software solution to implement green machining strategies to aid process planning. This software is a “dashboard” program that estimates environmental impact for a given NC program.

Keywords: Green machine tools, energy consumption reduction

1 INTRODUCTION

The development of machine tools is typically focused on improving performance as measured by metrics including availability, reliability, dimensional accuracy, and precision, while lowering costs. This trend has caused machine tools to become increasingly complex and automated in their design as varied components such as massive structures and highly energy intensive peripherals have been employed to ensure high performance. These changes, though, have caused increasing energy requirements for machine tools, which are antagonistic to rising energy costs, limited access to resources and consumables, increasingly environmental consciousness among customers, and increasing government regulation. These concerns are further exacerbated by manufacturing's already large environmental impact – 19% of the world's greenhouse gas (GHG) emissions [1] and 31% of the United States' total energy usage [2] is due to industrial activities, of which manufacturing and specifically machining plays a crucial role – indicating that the problems caused by increasing energy requirements will only become a larger issue in the foreseeable future. So, design and operation strategies that implement green manufacturing in machining have become important to maintain competitiveness and lower costs.

2 BACKGROUND

Machine tool energy consumption may be reduced in one of four areas of its life-cycle: manufacturing, transportation, use, or end-of-life. Early life-cycle assessments of machine tools and manufacturing processes have focused on quantifying the energy and resource consumption during use. [3] contended that the use of recycled material in manufacturing a machine tool was negligible when the magnitude of the energy consumption during use was considered while minimizing cutting fluid consumption provides a more effective means of saving energy. However, [4] showed that the impact of the manufacturing and transportation of the machine tool with respect to carbon-equivalent emissions per part produced depended on the facility in which the machine tool was used. Much of the literature on machine tools and the environment reduces the scope of the analysis and presents design- or process-level changes, each of which affects the energy

requirements of the machine tool during its manufacture and use.

Design-level changes provide the greatest flexibility and therefore the greatest opportunity for energy savings [5]. Such strategies include design for disassembly [6-7] and remanufacturing to reuse material for the machine tool frame [8]. Strategies that require a design change of the machine tool to save energy during use are also extensively studied, such as Minimum Quantity Lubrication (MQL), which provides the added benefit of using 3 to 4 times less cutting fluid than conventional flood cooling [9]. MQL strategies require modifications to the cooling system of the machine tool if it uses an internal coolant feed, though [10]. Dry machining has been another area investigated to eliminate the impacts of cutting fluid. While dry machining does not require machine tool design changes, proper tooling and cutting conditions must be practiced to reduce excess tool wear, which would overshadow initial energy savings [11].

Munoz developed a model that incorporated cutting fluid flow as an environmentally conscious measure in machining as well as process-level dynamics such as machining mechanics and tool wear [12]. This model served as the foundation for the development of an environmental process planning system that works with a conventional process planning methodologies to evaluate trade-offs between environmental and productivity requirements [13]. Narita developed a similar tool called an “environmental burden calculator” related to part manufacture that allowed a user to input cutting conditions and workpiece information [14-15].

Recent research also includes power consumption analyses of machine tool use. [16] conducted an environmental analysis of machining that quantified the energy consumption of four types of milling machines varying in automation as well as accounted for material production and cutting fluid preparation. [17] studied the effects of downsizing a CNC milling machine tool on its energy and resource requirements. [18] broadened the scope to include 10 types of manufacturing processes, and noted that the low throughput of additive processes such as sputtering amplify the specific energies relative to other manufacturing processes even though the power requirements of the processes studied do not vary by more than 2 orders of magnitude.

Ultimately, a life-cycle energy assessment is required to determine the appropriate strategy to “green” a machining process. This type of analysis yields two general possibilities: (1) high constant energy demand due to the dominance of non-cutting operations and peripheral equipment, or (2) low constant energy demand due to the dominance of cutting operations. Sample strategies to address the first case include using machine design to minimize the energy requirements of peripheral equipment (e.g. kinetic energy recovery systems used in conjunction with the spindle) and focusing on machine operation to increase the production rate of the machine tool. Strategies to address the second case generally require optimization of the cutting process itself. This may be difficult to accomplish from a design perspective due to the influence of desired process parameters, but energy savings may be achieved by considering typical machine tool use in design (e.g. ensure that axes with high motion carry less weight).

Given these requirements and strategies for green machining, this paper first presents a life-cycle energy assessment of milling machine tools to guide further development. Process parameter optimization on a Mori Seiki NV1500DCG is one green machining strategy considered. Finally, this paper discusses a software solution to implement green machining strategies in process planning.

3 LIFE-CYCLE ENERGY CONSUMPTION ANALYSIS OF MILLING MACHINE TOOLS

While the current literature provides an extensive knowledge of the life-cycle energy consumption of machining, it is limited by the assumption that machine tool operation dominates the overall impact such that other aspects of the machine tool's life-cycle, such as its manufacture, are neglected. Furthermore, much of the literature neglects transportation, material inputs (e.g. cutting fluid), or facility inputs (e.g. HVAC and lighting), which may all have a significant impact on the overall energy consumption. So, it was the goal of [4] to study the effect of these aspects as well as that of the manufacturing environment and degree of automation on the life-cycle energy requirements of milling machine tools.

3.1 Methods

Two types of machine tools were studied in this analysis: (1) the Bridgeport Manual Mill Series I (for low automation), and (2) the Mori Seiki DuraVertical 5060 (for high automation). Energy consumption and CO₂ emissions were calculated for each life-cycle stage in different manufacturing environments [4].

Each machine tool was divided into its primary components (machine tool frame, spindle, ball/lead screws, X/Y axes, tool changer, casing, and controller) to determine the energy consumed during its manufacture. The material composition of the components were simplified – the machine tool frame was assumed to be gray cast iron, the casing was low carbon steel, and the remaining components were low alloy steel – and all choices assumed standard recycling content [19].

The following processes were considered when calculating the energy consumed during the production of each component: casting, extrusion, rolling, stamping, milling, turning, grinding, case hardening, annealing, and

tempering. Embodied energy of deformation processing was used for the extrusion, rolling, and stamping processes [19]. Specific energies were used for the milling, turning, grinding, case hardening, annealing, and tempering processes [18, 20-22]. To compute resultant CO₂ emissions, a Japanese energy mix (360 g of CO₂-e/kWh) was used for the Mori Seiki [19] and a Connecticut energy mix (420 g of CO₂-e/kWh) was used for the Bridgeport [23-26].

Transportation energy and CO₂ emissions were calculated – the Mori Seiki originated in Nagoya, Japan, and the Bridgeport originated in Bridgeport, CT [19]. Both were sent to San Jose, CA for use and then to Los Angeles, CA for resale at the end-of-life.

To analyze the effect of different facility characteristics and production schedules, the use phase of both machine tools was studied across three manufacturing environments: a community shop, a job shop, and a large commercial facility. The functional unit of a machine tool in each environment depends on its performance and ends once resold by the original owner. A 101 x 101 x 25.4 mm AISI 1018 steel standard part served as the functional unit in this analysis.

Energy consumption was measured during part production. Cutting fluid was considered for both machine tools, while lubricating oil was only considered for the Mori Seiki; both analyses utilized embodied energy. The energy required for HVAC and lighting to support machine tool operation was calculated based on facility square footage and data from [27]. Total HVAC and lighting energy was allocated to the machine tools according to the size of the workspace required to operate the tool. Emissions were calculated using a California energy mix (320 g of CO₂-e/kWh) [24-26, 28-29].

Labor and workpiece preprocessing were omitted. An end-of-life analysis has also been omitted due to the uncertainty in the amount of times a machine tool is reused. But, material recyclability was accounted when considering the manufacture of the machine tool.

3.2 Results

The energy required to manufacture the Bridgeport and Mori Seiki was found to be 18,000 MJ and 100,000 MJ per machine tool, respectively. Material extraction was the most energy intensive process – it was responsible for 70% of the total energy consumed in manufacturing for both machine tools – followed by casting. Accordingly, the machine tool frame was the component of both machine tools that required the greatest amount of energy to manufacture.

Both machine tools have similar transportation emissions; 1,200 kg of CO₂-equivalent for the Bridgeport and 1,600 kg of CO₂-equivalent for the Mori Seiki. Now considering the actual use of the machine tools, the Bridgeport consumed 600 kJ per part and the Mori Seiki consumed 1,000 kJ per part to manufacture the standard part that served as the functional unit. Maintenance energy consumption was negligible while HVAC and lighting consumed 40-65% of the total energy required during use of the machine tools. The most energy intensive scenario during use of the machine tool was the Mori Seiki in the community shop due to the low production volume; the energy consumed in this scenario was 2,800 kJ per part.

The CO₂-equivalent emissions calculated for both machine tools in all three manufacturing environments resulted in measureable differences with the manufacture of the machine tools being significant relative to their use (see Figure 1). The percentage of CO₂-equivalent emissions during the manufacture of the machine tools was smallest for both machine tools in the commercial facility because of the higher production rates possible. The use of the machine tools dominated the total emissions, varying from 70-90% of the Bridgeport's emissions and 60-85% of the Mori Seiki's emissions.

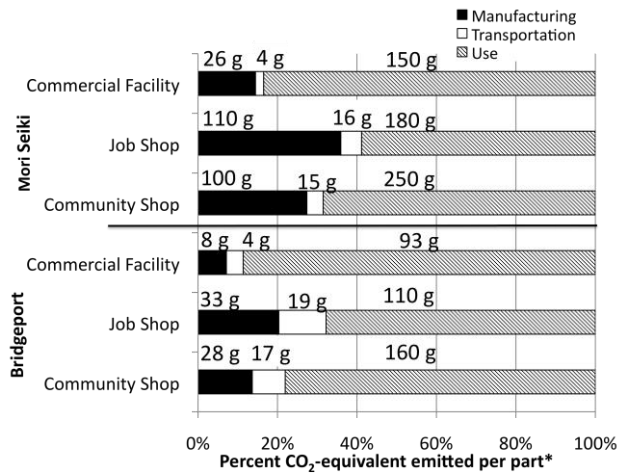


Figure 1: CO₂-equivalent emitted per standard part produced. (*) – Numbers provided are in grams of CO₂-equivalent emitted per part [4].

4 PROCESS PARAMETER SELECTION

4.1 Methods

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. 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 [30-31]. Tool wear and surface finish suffered when the process parameters veered away from the recommended cutting conditions, so changing the tool type to increase the material removal rate was found to be the best method of reducing energy consumption while machining.

Given the energy savings from changing the cutter type this project focuses on varying material removal rate by increasing the width of cut while machining with (1) 2 flute uncoated, (2) 2 flute TiN coated, and (3) 4 flute TiN coated carbide end mills. The power consumption of the machine tool was measured with a wattmeter while AISI 1018 steel was cut along the y-axis at a depth of cut of 2 mm with a 5/16 in. diameter end mill (approximately 7.9 mm). The width of cut was varied by 1 mm increments between 1 mm and 7 mm, and a 7.5 mm width of cut was also made. Table 1 summarizes the cutting conditions used per recommendations from the machinists in the U.C. Berkeley Mechanical Engineering Student Machine Shop. The chip

load was maintained at approximately 0.03 mm/tooth to avoid tool wear and breakage.

Table 1: Process parameters used in width of cut experiments

| Cutter | N [rpm] | f [mm/min] | f _{tooth} [mm/tooth] | M.R.R. [mm ³ /s] |
|--------|---------|------------|-------------------------------|-----------------------------|
| (1) | 5,426 | 330 | 0.033 | 11-83 |
| (2) | 7,060 | 430 | 0.030 | 14-108 |
| (3) | 7,060 | 860 | 0.030 | 29-215 |

Initially, climb milling was distinguished from conventional milling because the cutting forces when climb milling are known to be greater than when conventional milling. However, only at high loads with a 4 flute TiN coated cutter was there a significant difference in power consumption. Also, since the x-axis table of the NV1500 DCG sits on top of the y-axis drives, experiments were conducted where primary cuts were made along the x-axis to see if an observable difference in power consumption existed. The total power consumption, though, was found to be similar to that of the y-axis cuts.

In characterizing the energy consumption of the 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 given the constraints on M.R.R. and the inability to reach a specific energy of zero at very high material removal rates, a curve of the following form:

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

was fit to the specific energy data, where "a" essentially has units of power and "b" represents the steady state value.

4.2 Results

The total specific energy, which accounts for cutting and air cutting power consumption, was indeed found to have an inverse relationship with the M.R.R. (see Figure 2). The air cutting power consumption dominated the specific energy. The contribution of the cutting power consumption was not evident in the total specific energy trend line since it must be aggregated over the time required to cut and compete with the air cutting power consumption.

There is a sharp decrease in specific energy until a M.R.R. of approximately 75 mm³/s is reached. Thereafter the energy savings gained from increasing the material removal rate is slightly over 10 J/mm³, which can be substantial for large work pieces.

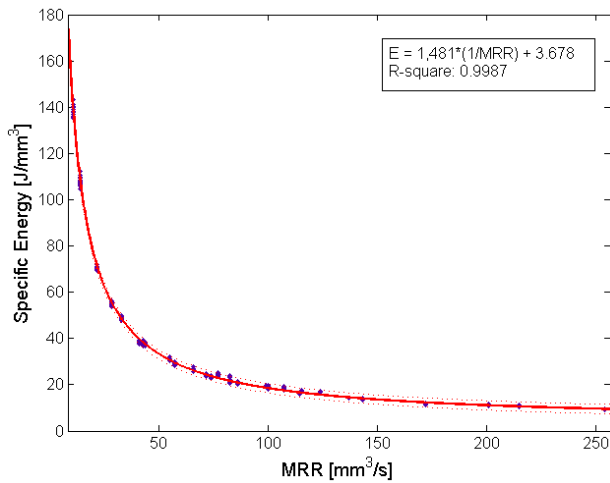


Figure 2: Curve fit of specific energy as a function of M.R.R.

The best fit model was found to be:

$$e_{cut} = 1,481 * \frac{1}{M.R.R.} + 3.678 \quad (2)$$

where the first constant is similar to the average air cutting power consumption values. Upper and lower bounds with a 95% confidence level are provided below:

$$e_{cut} = 1,478 * \frac{1}{M.R.R.} + 3.541 \quad (3)$$

$$e_{cut} = 1,488 * \frac{1}{M.R.R.} + 3.853 \quad (4)$$

The total energy consumption while cutting can therefore be calculated by multiplying the specific energy by the volume of material removed. 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 very high M.R.R.s the specific energies were well within the bounds.

4.3 Estimating the Environmental Burden of a Part's Production

Since a specific energy consumption model has been developed for the NV1500 DCG, a case study was conducted on the standard part created in [4]. The energy consumed to manufacture the part was calculated using Equation 2 for the three types of cutting tools with the conditions presented in Table 1. Two-thirds of the diameter was used as the width of cut. Only the part features which are cut with an end mill are taken into consideration, thus the holes produced with a drill are neglected since an energy consumption study has yet to be conducted on drilling with the NV1500 DCG.

The total volume of material removed was approximately 5,492 mm³. The energy consumed to create the end milling features on the standard part was estimated to be 160, 127, and 74 kJ/part for cutters 1, 2, and 3, respectively. Note that this estimate only represents the energy consumed to cut material and does not account for standby energy consumption nor air cutting. These estimates show that more than twice the energy is consumed when a 2 flute uncoated carbide cutter is used over a 4 flute coated carbide cutter.

The energy consumption estimates were used to calculate the carbon emissions associated with part production. For a California energy mix where the carbon intensity of electricity is 320 g CO₂-e/kWh, as suggested in Section 3.1, the carbon emissions for part production varied from 6.6 to 14 g CO₂-e/part (see Table 2). Connecticut uses more carbon-intensive energy sources; the state's electricity generation has a carbon emissions factor of 480 g CO₂-e/kWh, and results in carbon emissions between 8.6 and 19 g CO₂-e/part.

Table 2: Carbon emissions for standard part production in CA and CT

| Cutter | CA Energy Mix | CT Energy Mix |
|--------|-------------------------------|-------------------------------|
| (1) | 14 g CO ₂ -e/part | 19 g CO ₂ -e/part |
| (2) | 11 g CO ₂ -e/part | 15 g CO ₂ -e/part |
| (3) | 6.6 g CO ₂ -e/part | 8.6 g CO ₂ -e/part |

The difference between the best-case scenario and the worst-case scenario is substantial. Almost three times the carbon is emitted if a 2 flute uncoated end mill is used in Connecticut versus a 4 flute TiN coated end mill in California. The results are of course scalable by the number of parts produced so a high volume part provides a greater reason to produce at the highest M.R.R. possible using electricity generated from a "clean" energy mix.

4.4 Energy Consumption of Coating Process

Since the TiN coating, which allows for faster feed rates, is one of the primary differences amongst the end mills, the energy associated with tool coating was estimated to find the number of parts that must be produced to realize actual energy savings. The coating is typically applied by either sputtering or chemical vapor deposition (CVD). In estimating the coating energy consumption only the coating manufacturing process was considered, i.e. the TiN material production process was neglected, since the thickness of the coating is on the order of 2.8 μm [32]. Amongst Gutowski's electrical energy consumption values of manufacturing processes, sputtering and CVD were found to have energy intensities between 7.52 and 645 MJ/cm³ and between 4.63 and 244 MJ/cm³, respectively [18]. The surface area, A_{surf} , was simplified to that of a cylinder such that:

$$A_{surf} = \pi * d_{tool}^2 + \pi * d_{tool} * L_{flute} \quad (5)$$

where L_{flute} is the length of the flutes (13/16 in. or ~20.6 mm) and d_{tool} is the tool diameter. The energy consumption for tool coating was between 30 and 240 kJ/end mill and between 19 and 110 kJ/ end mill for sputtering and CVD, respectively. Note that the highest energy intensities for CVD and sputtering in [18] resulting in 980 kJ/end mill and 2,600 kJ/end mill, respectively, were omitted since they correspond to process rates an order of magnitude lower than the rest. Therefore, since the energy consumed in the coating process is between 19 and 240 kJ/end mill, when switching from a 2 flute uncoated carbide end mill to a 4 flute coated carbide end mill 1 to 3 parts must be manufactured to realize the energy savings.

5 WEB-BASED ENERGY ESTIMATION TOOL

Software tools are required to implement green machining strategies that focus on machine operation at the process planning stage. One such example is a web-based energy estimation tool that estimates energy demand and processing time of a candidate NC code so that tool-path alternatives may be considered. This approach calculates total energy consumption by considering constant and variable “tare” as well as cutting energy consumption as described in the previous section. Equations and data from [30] are utilized to determine the theoretical energy consumption in these cases. Additionally, the energy required to accelerate and decelerate the machine tool is also included in this analysis. To determine the processing time, the time to execute each block of NC code was determined by summing the time required for accelerating (beginning of block), decelerating (end of block), and moving the axis at the commanded feed rate. Characteristic times for accelerating and decelerating were obtained from Mori Seiki. Non-motion times (e.g. time for tool changes) were also included in this analysis.

To execute the “dashboard” program, an NC code is uploaded as well as basic machine tool parameters such as motor drive characteristics and motor ratings. The candidate NC code is parsed block-by-block sequentially considering only those blocks that either cause axis motion (e.g. G00/1/2/3/28/81) or imply tool movement (e.g. M06). During the parsing process, the software tracks the tool tip position, current active command, and current feed to enable efficient energy and time computations. It is important to also note that assumptions of machine tool design are also required as component specifications influence the energy needed for axis and spindle motion; this analysis assumed the geometry of a Mori Seiki NV1500 DCG machining center.

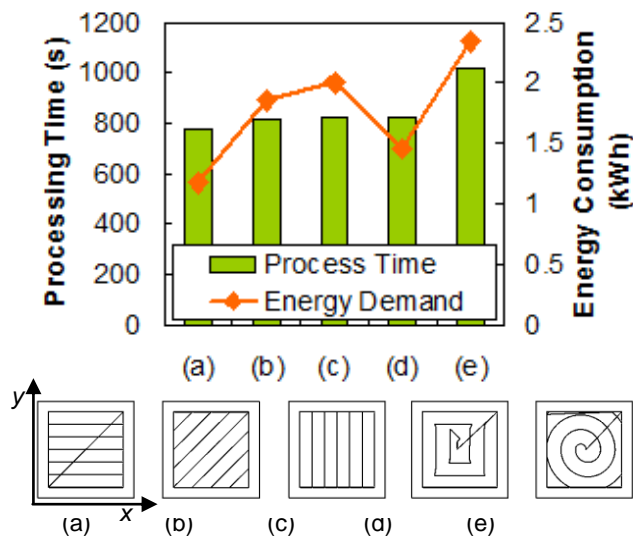


Figure 3: Processing time and energy consumption of various tool paths.

A part may be manufactured in a number of alternative ways depending on how the axes are driven and tools are fed. Thus, most CAM packages today offer flexibility in generating alternative tool-paths (NC codes) for the same part. A pilot analysis was performed on 5 NC codes to produce a 100 x 100 x 40 mm pocket with a 20 mm diameter end mill (for rough cutting) and a 10 mm diameter

end mill (for finishing); see Figure 3. These results show that moving principally in the y-direction requires more energy due to the design of the Mori Seiki NV1500 DCG – more mass is in motion since the x-axis is carried by the y-axis and 2 drive motors are utilized versus only 1 for the x-axis. These results also highlight that longer tool paths generally result in larger energy consumption since due to the direct correlation between processing time and energy as described in the previous section.

6 SUMMARY

The magnitude of the manufacturing sector’s environmental impact calls for an emphasis on energy consumption reduction strategies to supplement machine tool performance improvements. Given the prevalent nature of machining, strategies to reduce the energy consumption of machine tools in the design and operation phases were presented. The life-cycle analysis of machine tools showed that the manufacturing portion of the machine tool is indeed relevant depending on the manufacturing facility that is used and that HVAC and lighting effects are significant. Transitioning from design changes to operational changes, process parameter selection was presented as an alternative for energy reduction, which can be estimated using the web-based tool, a further advantage of which is to incorporate tool-path alternatives.

In targeting the operation phase, energy consumption may be reduced without requiring the machine tool builder to increase the efficiency of the machine tool. In addition, information can be shared with the part designer to make further improvements on the environmental impact of the part being produced. While the examples presented restrict the scope of the analyses to the machine tool, opportunities to green manufacturing exist at all levels of manufacturing.

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