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Publication Date
2010-10-26

Proceedings of 4th CIRP International Conference on High Performance Cutting, 2010

Machine Tool Design and Operation Strategies for Green Manufacturing

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Abstract:
Strategies to reduce energy demand in manufacturing processes are becoming necessary due to the growing concern of carbon emissions and the expected rise of electricity prices over time. To guide the development of these strategies, the results of a life-cycle energy consumption analysis of milling machine tools are first highlighted to show the effect of several factors such as degree of automation, manufacturing environment, transportation, material inputs, and facility inputs on environmental impact. An overview of design and operation strategies to reduce energy consumption is thereafter presented including the implementation of a Kinetic Energy Recovery System (KERS), a process parameter selection strategy, and a web-based energy estimation tool.

Keywords: Green machine tools, Energy consumption reduction

1. Introduction

Improving the performance of machine tools as measured by metrics including availability, reliability, dimensional accuracy, and precision has been a major concern for machine tool builders. To achieve the desired performance, machine tools have become increasingly complex and automated in their design. These changes, though, have resulted in increasing energy requirements, which are antagonistic to rising power costs, limited access to resources (particularly fossil fuels), increasing 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. So, strategies to implement green manufacturing in machining including machine tool design, process planning, and machine operation have become important.

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 of the use phase. [3] contended that the use of recycled material in manufacturing a machine tool was negligible when the magnitude of the use phase energy consumption 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 reduce the scope of the analysis and present design- or process-level changes, each of which affects the energy requirements of the machine tool during its manufacture and use, respectively.

Design-level changes provide the greatest flexibility and therefore potentially offer 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 have also been extensively studied, such as Minimum Quantity Lubrication (MQL). MQL enables the use of 3 to 4 times less cutting fluid than conventional flood cooling [9], but these strategies require modification of the machine tool's cooling system if using an internal cooling system [10]. Dry cutting is another area investigated to eliminate the impact of cutting fluids. While dry cutting does not require machine tool design changes, proper tooling and cutting conditions must be practiced so that the cutting tool is not quickly worn, which would overshadow initial energy savings [11].

[12] 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. This model served as the foundation for the development of an environmental process planning system that works in conjunction with conventional process planning methodologies to evaluate trade-offs between manufacturing and environmental requirements [13]. [14-15] developed a similar tool called an "environmental burden calculator" related to part manufacture which allowed the user to input cutting conditions and workpiece information.

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 and also accounted for material production and cutting fluid preparation. The effects of downsizing a CNC milling machine tool on its energy and resource requirements were studied in [17]. [18] broadened the scope to include 10 types of manufacturing processes and noted that low process rates of additive processes such as sputtering amplify the specific energies relative to other manufacturing processes even though the power requirements of the processes analyzed do not vary by more than two orders of magnitude.

A life-cycle energy assessment of machine tools is first presented to determine the appropriate strategies to apply to green a machine tool. This 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. For the first case, machine design may be used to minimize the energy consumption of peripheral equipment and processes. An example of this type of approach discussed in this paper is a kinetic energy recovery system (KERS) used in conjunction with the spindle. An alternative approach to address the first scenario is to increase the production rate of the machine tool by focusing on machine operation. Finally, because machine tool operation tends to comprise the greatest portion of energy consumption during its lifetime, energy reduction strategies during machine tool operation are explored through the development of a web-based tool that computes the energy demand of a machining process using the NC tool path.

3. Life-Cycle Energy Consumption Analysis of 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 (low automation), and (2) the Mori Seiki DuraVertical 5060 (high automation). Energy consumption and CO_2 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 manufacture. The material composition of each component was simplified. The machine tool frame was assumed to be composed of gray cast iron, the casing of low carbon steel, and the remaining components of low alloy steel. All choices were assumed to contain a 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 CO_2 emissions, a Japanese energy mix (360g of CO_2-e/kWh) was used for the Mori Seiki [19] and a Connecticut energy mix (420g of CO_2-e/kWh) was used for the Bridgeport [23- 26].

Transportation energy and CO_2 emissions were calculated – the Mori originated in Nagoya, Japan, and the Bridgeport originated in Bridgeport, CT. 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 of both machine tools was studied across three manufacturing environments: a community shop, a job shop, and a large commercial facility. The functional life of a machine tool in each environment depended on its performance, and ended once downgraded or resold by the original owner. A 101 x 101 x 25.4 mm AISI 1018 steel standard part made over the functional life served as the functional unit in this analysis.

The use of the machine tool considers both the direct inputs needed for part production and the indirect inputs required from the facility. Energy consumption was measured during part production. The use of cutting fluid was considered for both machine tools, while lubricating oil was only considered for the Mori Seiki; both analyses utilized an embodied energy approach. 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 from machine tool use were calculated using a California energy mix (320g of CO_2-e/kWh) [24-26], [28-29].

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

3.2 Results

The energy required to manufacture the Bridgeport and Mori Seiki was 18,000MJ and 100,000MJ 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 tools – followed by casting. Accordingly, the machine tool frame was the component of both machine tools that required the greatest energy to manufacture.

Both machine tools had similar transportation emissions; 1,200kg of CO_2-equivalent for the Bridgeport and 1,600kg of CO_2-equivalent for the Mori Seiki. Considering the use of both machine tools, the Bridgeport consumed 600kJ per part and the Mori Seiki consumed 1,000kJ 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 tool. The most energy intensive scenario during the use of a machine tool was the Mori Seiki in the community shop due to the low production volume; the energy consumption in this scenario amounted to 2,800kJ per part.

The CO_2-equivalent emissions calculated for both machine tools in all three manufacturing environments resulted in measurable differences with the manufacture of both machine tools being significant relative to their use (see Fig. 1). The percentage of CO_2-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.

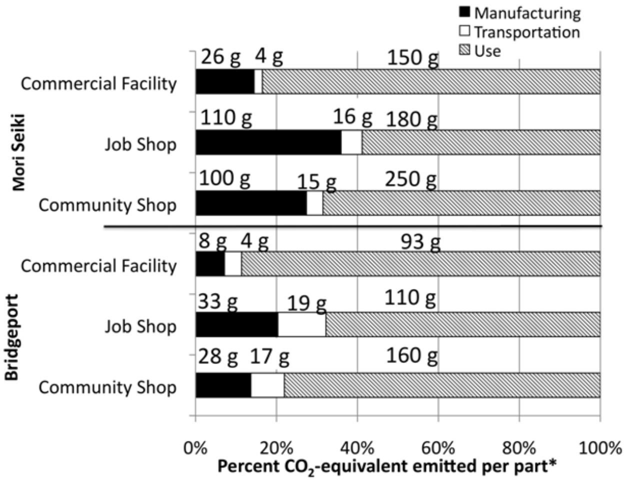

Figure 1: CO_2-equivalent emitted per standard part produced. (*) Numbers provided are in grams of CO_2-equivalent emitted per part [4].

4. KERS

The previous life-cycle energy consumption analysis of machine tools highlighted the significant energy requirements of peripheral equipment and systems such as HVAC and lighting. Given these large energy "sinks," methods that can recover energy from the cutting process using kinetic energy recovery systems (KERS) may provide substantial impact on overall energy requirements. To evaluate the feasibility of KERS systems, a dynamic model of the spindle and table of a Mori Seiki NV1500DCG was defined. Once matched to the actual machine tool performance, the deceleration of the spindle motor to stationary was the only scenario studied that provided sizable energy recovery. So, a system was modeled that recovered energy from a spindle decelerated from 20,000 to 0RPM and stored it in a bank of 400 supercapacitors rated at 350F using a voltage of 1kV and a charge/discharge efficiency of 90%. A Monte Carlo simulation was performed on this design that varied tool selection (2 to 5 tools with mean cutter diameter 5mm and standard deviation 2mm in increments of 0.5mm) and cycle time (2 to 5min) for a general, nonstandard part; these results are shown in Fig. 2.

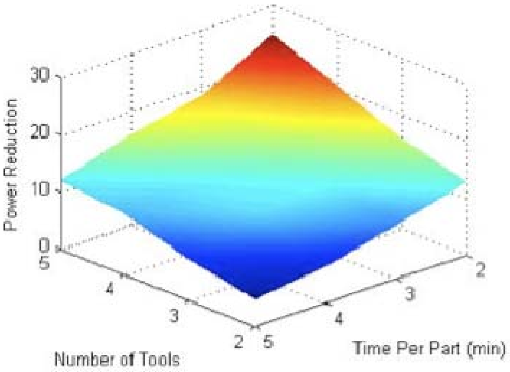

Figure 2: Estimated power reduction (%) using KERS on a Mori Seiki NV1500DCG..

An analysis of the simulation results shows that the use of KERS on a Mori Seiki NV1500DCG provides a power reduction of 5 to 25% relative to the same machine tool without KERS. If one specific simulation result is considered – 3 tools (cutter diameters of 5mm, 2.5mm, and 4mm) and a cycle time of 2min – that provides a power savings of 20.4% and assumes a lifetime of 500,000 manufactured parts with the KERS machine tool, then the supercapacitor bank must cost $162 to be economically feasible. Given the $7,200 required for the current design, either energy costs must increase or the cost of supercapacitors must decrease for a KERS system to become a viable option. Alternative approaches, though, should be considered including the direct use of recovered energy or the use of a common storage bank shared across several machine tools.

5. Process Parameter Selection

In addition to implementing machine tool design changes, energy consumption during the use of a machine tool may be reduced through process parameter selection. Although machine tools have various purposes and capabilities, power demand may be classified by three categories: constant, variable, and cutting power (see Fig. 3). The "constant" power demand can be attributed to auxiliary equipment that consumes power at a specified rate independent of material processing inputs (e.g. the computer panel, light fixture, and coolant). "Variable" power demand is consumed by machine tool components that the operator controls (e.g.

the spindle motor and the x- and y-axis drives). The constant and variable power demand together form the “tare” power demand of the machine tool since this is the minimum power that will be demanded for a given set of process parameters regardless of whether or not material is cut. The magnitude of the cutting power is determined by material type, material removal rate, cutting tool, etc., so a strong correlation exists between the load from the material removal process and the power demanded.

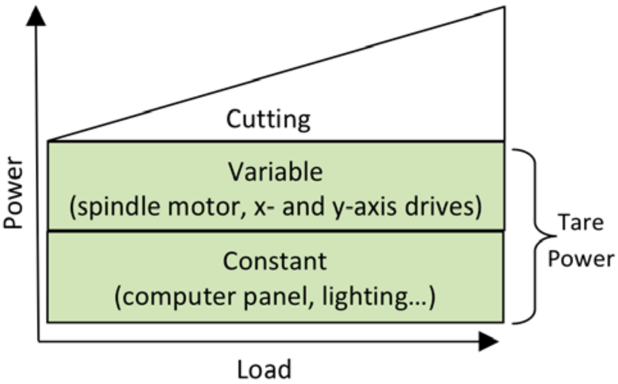

Figure 3: Power breakdown as a function of load from material removal, after Dahmus [16].

The proper energy minimization strategy to implement while machining highly depends on the division of the power structure. The energy consumption is driven by the time required to machine a specified part and the magnitude of the total machining power (both tare and cutting). Machine tools that demand high constant power because of the dominance of non-cutting operations and auxiliary equipment are classified as having a high tare power. Therefore, the energy consumed to manufacture a part in such a scenario is greatly influenced by the processing time since the magnitude of the cutting power is small relative to the machine tool’s tare power. This is often the case with machine tools that have a sizable work volume, maintain high precision, or possess a significant amount of peripheral equipment.

Since the end goal is to reduce energy consumption while machining a part, the energy consumed per volume of material processed (the specific energy of the cut) should be reduced. Strategies to reduce overall energy consumption by decreasing processing time include modifying the workpiece orientation [30] or changing the cutter type [31], which is a more straightforward strategy. For example, a change from a 2-flute to a 4-flute end mill allows the operator to double the feed rate while maintaining the same feed per tooth, thus halving the process time. Additionally, by changing the cutting tool material from high speed steel to carbide, the user can increase their cutting speeds by two to three times. Even the application of a tool coating allows increases in feeds between 25 and 50%.

While energy savings result from such a change in cutting tool since machining time decreases, the variable and cutting power demanded by the machine tool increase since the spindle speeds, feed rates, and material removal rates increase with such a change in the cutting tool. The scope of the analysis must therefore be expanded to incorporate the manufacture of the cutting tool since the material extraction and processing energies of the cutting tools would differ. For example, the application of a cutting tool coat typically involves sputtering which [18] showed to be an energy intensive process. So, a thorough analysis of energy consumed during machine tool use requires that the manufacturing energy of the cutting tool be amortized over the number of parts produced if process parameters are to be accurately optimized to decrease machining time.

6. Web-Based Energy Estimation Tool

The relationship between machining time and energy consumption was used to create a web-based tool to estimate the energy consumption of machine tools. As highlighted in [30], the direction of axis movement can strongly influence the processing time. Moreover, non-idealities in machine tool components may result in deviation between the ideal and actual processing times. Although [30] dealt with machine tool performance, a similar approach is applicable when considering energy consumption. In this analysis non-idealities that arise only from the acceleration and deceleration of a drive motor (among various non-idealities appearing in [30]) as well as the direction of a tool path are used as a basis for the estimation of energy consumption. Based on this methodology, a web-based tool was developed to estimate the energy demand and processing time of a candidate NC code.

To compute the total energy consumption during machine tool operation, constant, variable, and cutting energy were considered [32]. The variable energy comprises two parts: the steady state ($E_{var\text{-}steady}$) when the spindle motor and the axis drives reach a specified value and the transient state ($E_{var\text{-}trans}$) when the spindle and the axis drives accelerate or decelerate. It was assumed that only the feed rate and the spindle speed influence $E_{var\text{-}steady}$ and that they are proportional to $E_{var\text{-}steady}$. The total energy consumption during the process, $E_{machine}$, was computed by summing the four components as follows:

$$E_{machine} = E_{const} + E_{cut} + E_{var\text{-}steady} + E_{var\text{-}trans} \,, \tag{1}$$

where E_{const} is the constant energy consumption and E_{cut} is the cutting energy consumption (see Fig. 3). Two cases were taken into account to compute the total energy consumption: non-productive movement (or air cutting) where E_{cut} is 0 and productive movement where E_{cut} is non-zero.

Utilizing the equations in [32] for the theoretical energy consumption, the following relation was used to estimate E_{cut}:

$$E_{cut} = K_{cut} \cdot w \cdot b \cdot z^{p} \cdot v_f^{1-p} \cdot n^{p} \,, \tag{2}$$

where v_f is the feed rate, n is the rotational speed of the spindle, w is the width of cut, b is the depth of cut, z is the number of flutes of the cutter, and p and K_{cut} are empirically determined fitting constants. Experimental data from [32] was used to calculate p while K_{cut} was estimated from best practices.

When calculating the processing time, the time to execute a single block of NC code was first calculated by summing the time required for accelerating (at the beginning of the block), decelerating (at the end of the block) and moving the axis at the commanded feed rate. Characteristic times for accelerating or decelerating an axis were obtained from Mori Seiki. Non-motion times, such as the time required for tool changes, were also considered when calculating the total processing time.

To estimate energy demand and processing time, an NC code is uploaded to the software tool as well as basic machine related parameters such as motor drive characteristics and motor ratings. The candidate NC code is parsed block-by-block sequentially considering only those blocks that cause either an actual motion of the axes (e.g. G00/1/2/3/28/81) or imply tool movement as a result of some other function (e.g. M06). During the parsing process the software tracks the tool tip position, the active command, and the feed rate to enable efficient calculations of energy and time.

While the time and energy for accelerating or decelerating drive axes are influenced by the specification of the drive motors, the energy required to move a specific axis is affected by the specification and number of drive motors for the axis and the axes configuration. This analysis assumed the geometry of a Mori Seiki NV1500DCG where the y-axis has two drive motors and the x-axis has one drive motor (since it sits on top of the y-axis). Gravity was neglected in calculating the energy consumption of the z-axis drive. It was assumed to be the same as that of the x-axis drive.

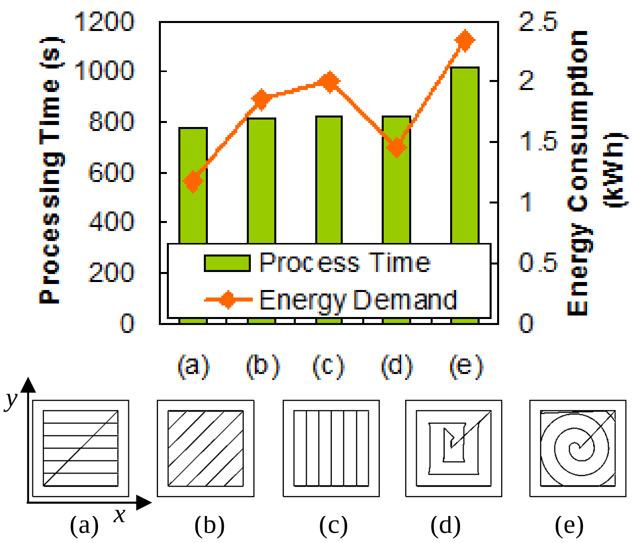

Figure 4: Processing time and energy consumption of various tool paths.

Since part features can be manufactured in a number ways because of tool path flexibility, a pilot analysis was performed on 5 NC codes to produce a 100 × 100 × 40 mm pocket with a 20mm diameter flat end mill (for rough cutting) and a 10mm diameter flat end mill (for finishing). These results are presented in Fig. 4 and show that moving principally in the y-direction requires more energy due to the design of the Mori Seiki NV1500DCG – more mass is in motion since the x-axis is carried by the y-axis and two drive motors are utilized versus only one for the x-axis. These results also highlight that longer tool paths generally result in larger energy consumption due to the direct correlation between processing time and energy as described in the previous section.

7. 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. An opportunity to realize power savings of up to 25% was also presented in the KERS analysis implemented on a machine tool's spindle. Transitioning from design changes to operational changes, process parameter selection strategies were 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.

Acknowledgement

This work was supported in part by Mori Seiki, the Digital Technology Laboratory (DTL), the Machine Tool Technologies Research Foundation (MTTRF), and other industrial partners of the Laboratory for Manufacturing and Sustainability (LMAS). The authors would like to thank the UC Berkeley Mechanical Engineering Department's Student Machine Shop, Kalman Manufacturing in Morgan Hill, CA, and Ellison Technologies for providing valuable insight and advice.

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