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**Publication Date:**
07-08-2009

**Series:**
Green Manufacturing and Sustainable Manufacturing Partnership

**Publication Info:**
Green Manufacturing and Sustainable Manufacturing Partnership, Laboratory for Manufacturing and Sustainability, UC Berkeley

**Permalink:**
http://escholarship.org/uc/item/794866g5

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# Strategies for Minimum Energy Operation for Precision Machining

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**Abstract**

The development of "green" machine tools will require novel approaches for design, production and operation for energy savings and reduced environmental impact. We describe here work on three projects: i. influence of process parameters on power consumption of end-milling using force and process time models with experimental verification. Process parameters are chosen to minimize process time since power consumed by a machine tool is essentially independent of the load and energy per unit manufactured decreases with process time; ii. KERS (kinetic energy recovery system) for machine design and modeling the integration of a recovery system into a machine tool to calculate the amount of energy that could be recovered, and whether the environmental benefits are significant; and iii. evaluation of interoperability solutions, such as MTConnect, as tools enabling a standardized "plug-and-play" platform to integrate sensors with a unified monitoring scheme to achieve improved energy performance.

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## 1 INTRODUCTION

Manufacturing processes carried out on machine tools are energy intensive. As machine tools have become more advanced, their degree of automation has risen by adding components such as tool change mechanisms or additional axes. Given the general trend of increasing power demand of machine tools the cost that companies have to expend on electrical energy will rise in the future. Furthermore, the external costs on the environment rise, since currently the majority of electrical power is obtained from burning fossil resources. A foreseeable shortage of fossil resources and a growing demand to include the external cost of environmental damage in product prices are likely to increase the cost of electrical energy for companies even further. Therefore, in order to maintain competitiveness and lower costs, companies have to identify ways to decrease the energy consumed during manufacturing for a given product.

Figure 1 shows four approaches to modifying a product life-cycle ranked by the potential impact on a given objective and the depth of analysis of the existing state. This paper applies the idea of product life-cycle modification to the objective of lowering the energy demand of machine tools for a given product. Section 2 summarizes research conducted in which process parameters of end-milling are varied (level 3). Section 3 discusses the potential of installation of kinetic energy recovery systems (KERS) in machine tools. The installation of such devices may be considered a level 1 process redesign of a product life-cycle. Section 4 concludes with a general evaluation of energy monitoring and interoperability standards.

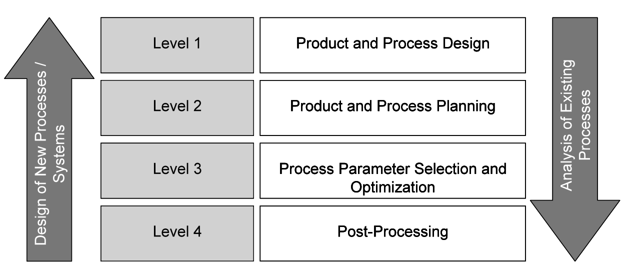


Figure 1: Strategies of green manufacturing

## 2 PROCESS PARAMETER OPTIMIZATION

### 2.1 Theory

The research goal of this project is to analyze the impact of process parameter selection on the energy consumption per part manufactured for an exemplary manufacturing process. End-milling was selected because of its wide use in the industry.

The energy per unit manufactured is determined by both the power demand of the machine tool during machining and the processing time (see Figure 2).

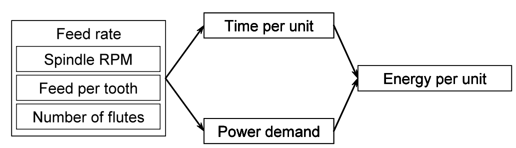


Figure 2: Influence of process parameters on the energy per unit manufactured

The power demand of a machine tool may be divided into a constant and a variable component [1]. The constant power can be attributed to the computer, fans, lighting, etc. of the machine tool. This component of the total power demand is independent of process parameter selection. The variable power demand, though, is dependent on process parameter selection and can be attributed to the spindle or the drives of the table axes.

The processing time per unit manufactured is determined by the feed rate. Cutting conditions at a specific feed rate depend on the selection of the number of revolutions per minute of the spindle, the feed per tooth and the number of flutes.

Figure 3 identifies two opposing effects on the energy per unit manufactured. First, as the feed rate increases the processing time is reduced. Therefore, the contribution of the constant power demand of the machine tool to the energy per unit manufactured decreases. Second, an increase in the feed rate demands more power from the machine tool with or without adjustment of the cutting speed. Depending on which effect prevails, three different machining regions may be found.

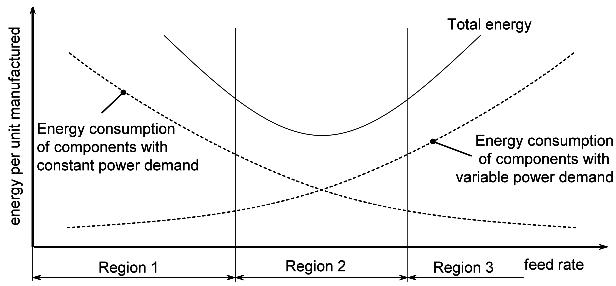


Figure 3: Regions of machining process

The sum of both energy contributions results in a parabolic-total energy plot also shown in Figure 3. In Region 1 the decrease due to a shorter processing time dominates the increased variable power demand. In this region the feed rate will be chosen as fast as technically possible. In Region 2 the energy per unit manufactured is fairly constant, whereas the increase of the variable power demand dominates in Region 3. If the process is located in Region 3, slower feed rates would lead to lower energy per unit manufactured.

## 2.2 Results

Experimental studies were conducted to determine the region of the machining process in Figure 3. Initial experiments (i.) kept the feed per tooth constant by increasing the spindle speed proportionally to the feed rate and (ii.) varied the feed per tooth at a constant spindle speed. Subsequently, the energy per unit manufactured of conventional cutting with a 2-flute uncoated carbide end-mill was compared to the energy per unit manufactured of high speed cutting with a 2- and 4-flute TiN-coated end-mill.

Slot cutting experiments of a low carbon steel (AISI 1030) were conducted on a Mori Seiki NV1500DCG with an 8mm uncoated carbide end-mill and a depth of cut of 2mm to be consistent with [2]. For each process parameter combination, 52 slot cuts were performed in order to study the wear of the tool. The power demand of the machine tool was recorded using a WattNode Modbus power meter via an MTConnect monitoring system (see Section 4).

### 2.2.1 Constant feed per tooth

The initial cutting conditions used a recommended feed per tooth of 0.125mm/tooth and a spindle speed of 800rpm to generate a feed rate of 200mm/min. Figure 4 shows that the energy consumed by the machine tool per unit manufactured decreases over feed rate at a constant feed per tooth of 0.125mm/tooth. However, tool wear increases significantly over feed rate. The tool consistently broke before having cut 52 slots at a feed rate of 500mm/min.

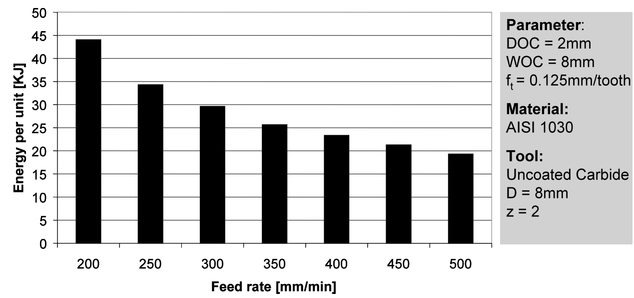


Figure 4: Average energy per unit manufactured versus feed rate

### 2.2.2 Constant spindle speed

The feed per tooth was varied between 0.025mm/tooth (feed rate of 40mm/min) and 0.15mm/tooth (feed rate of 240mm/min). Preliminary studies showed that increasing the feed per tooth beyond 0.15mm/tooth results in tool breakage.

Figure 5 shows that by lowering the feed per tooth (analogous to lowering the feed rate) the energy per unit manufactured increases. However, surface quality improves creating a trade-off between surface quality and energy consumption during machining. Furthermore, the tool wear effectively decreases as the feed rate is reduced since the load on the tool is smaller.

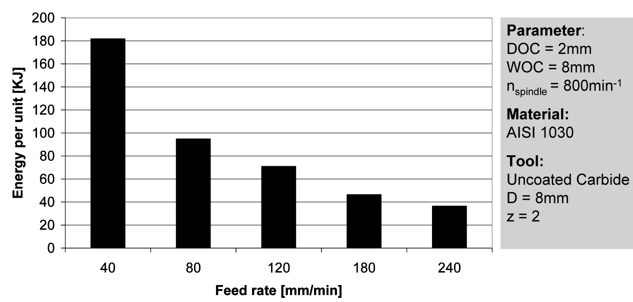


Figure 5: Average energy per unit manufactured versus feed rate at constant spindle speed

### 2.2.3 Conventional versus high-speed machining

High-speed cutting with coated end-mills involves greater cutting speeds at a lower feed per tooth. The feed rate increases since the increase in cutting speed is greater than the decrease in the feed per tooth compared to cutting at conventional speeds. In this study a 4-flute TiN coated end-mill was used and the energy consumed was compared to the 2-flute uncoated end-mill.

Table 1 summarizes how the number of flutes ($z$), spindle speed ($n_{spindle}$), feed per tooth ($f_t$), and feed rate ($v_f$) were varied across the three experiments.

Table 1: Summary of conventional versus high-speed cutting parameters

| | Units | Conv. | High-Speed |
|---|---|---|---|
| ***Coating*** | - | - | TiN |
| ***z*** | - | 2 | 4 |
| $n_{spindle}$ | rev/min | 800 | 7334 |
| $f_t$ | mm/tooth | 0.125 | 0.033 |
| $v_f$ | mm/min | 200 | 968 |
| $t_{cut}$ | s | 28.8 | 6.0 |

Figure 6 shows that there is a dramatic decrease in energy as the cutting parameters change from conventional speeds to high-speed values. This decrease in energy per unit manufactured is primarily a result of the decrease in processing time.

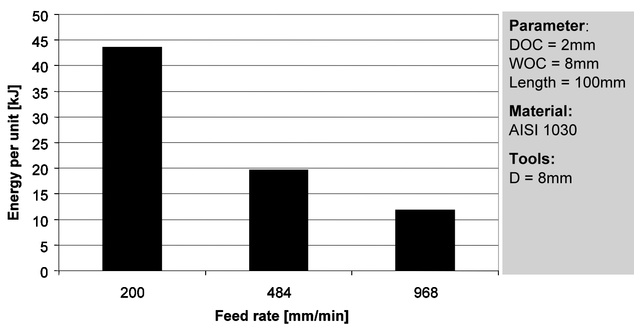


Figure 6: Energy comparison of conventional cutting versus high-speed cutting

Even though the feed rate during high-speed cutting was increased, tool wear reduces significantly after cutting 52 slots compared to the conventional cut (see Figure 7).

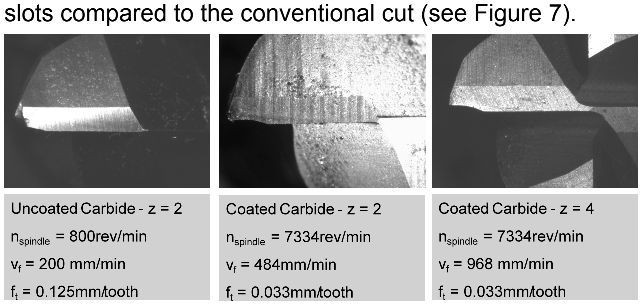


Figure 7: Tool wear comparison after 52 slots

## 3 ENERGY RECOVERY IN MACHINE TOOLS

### 3.1 Background and Method

Aside from taking into consideration process parameter selection as a method of reducing energy consumption in a machine tool, the recovery of energy through the use of a kinetic energy recovery system (KERS) would be a possible method of improving production efficiency within the manufacturing industry.

By creating a computer model of the NV1500DCG's spindle motor and table, evaluations of the possible reductions in power usage were made, as well as the cost benefits such a system could bring. These components were chosen to model since they possess varying levels of kinetic energy during workpiece manufacture. The use of experimental results obtained from the NV1500DCG for the power requirements to drive the spindle at various angular velocities, allowed the computer model results to be refined to better match the behaviour of the actual machine tool.

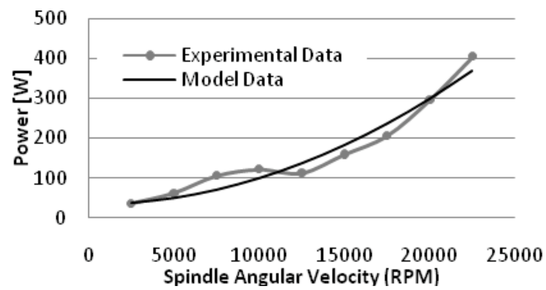


Figure 8: Comparison of experimental and model data

Three possibilities where energy recovery could occur were investigated; when decelerating the spindle to stationary, during air cutting and when decelerating the table mass to stationary. Under optimum cutting conditions it was found that approximately one million deceleration events of the table would be required to recover the same amount of energy that one spindle deceleration event would recover. For this reason, the installation of KERS onto the table drives was dismissed as requiring more effort and resources than the potential benefits.

Investigation of the reduction in energy needed during air cutting using the NV1500DCG's spindle motor (Fanuc αB80S/20000i) concluded that keeping the spindle speed constant would be the most efficient strategy under all cutting speed and air cutting duration conditions. However, models of other motors did show a reduction in energy usage, suggesting that energy recovery during air cutting for some spindles may increase machine efficiency.

Therefore spindle deceleration to stationary was found to recover the largest amounts of energy in the NV1500DCG. A system was modelled that stored the recovered energy in supercapacitors. This form of energy storage was used mainly for its power density and longer life expectancy than secondary batteries. A supercapacitor bank was then defined that could store the energy from one deceleration event from 20000rpm using a maximum voltage of 1kV and a charge / discharge efficiency of 90%.

An environmental evaluation of multiple workpieces was carried out through the use of a Monte Carlo simulation where tool size selection was based on a normal distribution having a mean cutter diameter of 5mm, and a standard deviation of 2mm in increments of 0.5mm. These values were chosen to simulate high speed machining. 75 parts at each different combination of time to machine a part (varied from two to five minutes) and tools used per part (varied from two to five) where simulated in order to determine trends and magnitudes of expected power savings. 75 parts were simulated and averaged at each combination to lessen the effect that the pseudorandom nature in which the tools were selected would have on results.

### 3.2 Results

A supercapacitor bank made up of 400 350F supercapacitors connected in series, for a cost of $7200 was defined [3]. The overall recovery efficiency of the system, as defined by equation 1, was found to be roughly 74% for most angular velocities.

$$\eta_{recovery} = \frac{\text{Total Energy Supplied Back To Motor}}{\text{Total Kinetic Energy Of Spindle}} \quad (1)$$

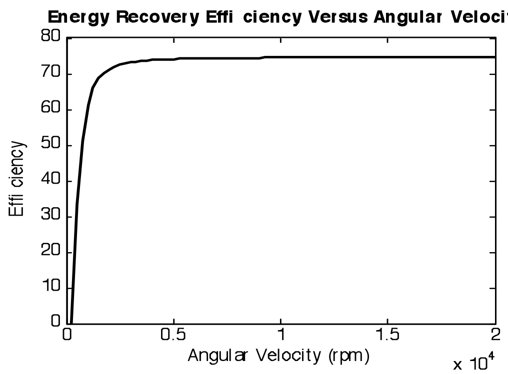

Figure 9: Recovery efficiency

The results for the environmental analysis show that power savings between 5 and 25% for the whole machine could be expected with a KERS under the simulated conditions (see Figure 10)

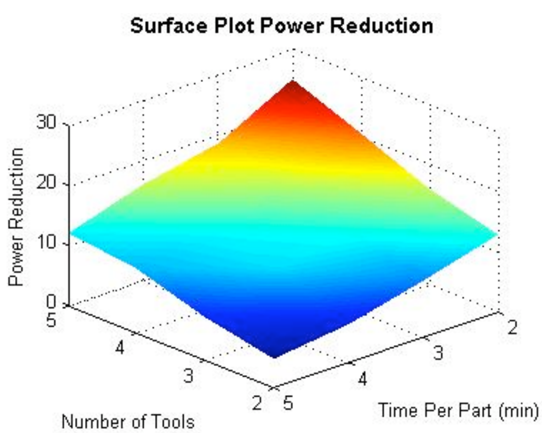

Figure 10: Expected power savings

A simulation of a single part that used three tools (5mm, 2.5mm and 4mm) and had a part time of 2 minutes was completed to evaluate the potential power savings and cost reduction. A power saving of 20.41% was determined with a decrease in energy of 49.6kJ per part. A full breakdown of power usage within the NV1500DCG with and without KERS is shown in Figure 11.

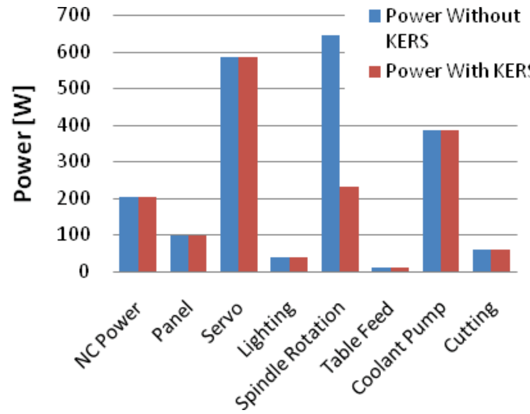

Figure 11: Power usage with and without KERS. Power data compared to data presented by [2]

A cost evaluation over a 500000 cycle lifetime of the supercapacitors as defined by the manufacturer, gave an allowable system cost of $162 using modern day energy prices. This suggests that a KERS system defined using a maximum angular velocity of 20000rpm is not a cost effective solution to increasing process efficiency. Either energy prices must increase or the cost of supercapacitors must decrease for this solution to be implemented.

## 4 ENERGY MONITORING AND INTEROPERABILITY

Due to the growing complexity of manufacturing, any substantial improvements in the manufacturing process require a holistic approach [4]. Despite this trend, the majority of prior literature, while significant in contribution, has been limited by its focus on process level improvements rather than the systemic approach necessary to fully capture the complex nature of energy flow in a machine tool [1]. Through understanding of the energy behavior at the system level is necessary to develop sustainable manufacturing systems [1].

Given the diverse sources and mechanisms of energy consumption in machine tools, robust metrology tools for energy inevitably require the use of multi-sensor systems. While representing a new paradigm of process monitoring, multi-sensor systems face several technical challenges including: (i) the development of effective down-sampling techniques to reduce the large information flow from the sensors in the system to those signals of greatest importance, (ii) the reduction in training and setup time required for the system to function, and (iii) the lack of commonly adopted sensor codes and protocols to successfully integrate several sensor types into a unified monitoring scheme [5], [6]. Overcoming these challenges requires standardization. Standardization allows communication within the monitoring scheme to occur in a common language which provides both better access to relevant information from sensors enabling effective down-sampling techniques [7]. Furthermore, standardization provides for common interfaces within the monitoring system which greatly decrease the developmental time and effort required to implement any sensor system [4].

To achieve standardization in machine tools, interoperability solutions are required. One such interoperability solution is MTConnect. MTConnect is a data exchange standard based on XML (see [7] for more information). To test its effectiveness, we have used MTConnect to successfully integrate thermal sensors, controller data (including x, y, z position, speed, feed, power status, and NC program information), and a WattNode power meter into a unified monitoring platform for a Mori Seiki NV1500DCG mill center (see Figure 12). The work presented in Section 3 used this MTConnect "test-bed" to monitor and record power consumption wirelessly even though the experiments conducted did not require all of the available data sources. This was still the ideal choice, though, since MTConnect provided a time stamp to match the recorded data to the process via the NC code. As Figures 4-6 display, the use of MTConnect offers a suitable and effective means of monitoring several data sources and gleaning relevant information to improve the energy performance of our machine tool.

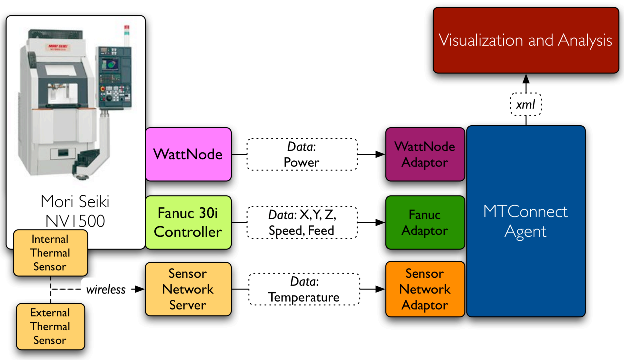


Figure 12: Unified monitoring scheme using MTConnect

## 5 CONCLUSION

High-speed cutting resulted in smaller energies per unit manufactured compared to a machining operation at conventional cutting speeds. Since the decrease in the processing time had a greater impact on the energy demand per unit manufactured than the increase in power demanded. Also, a reduction in tool wear was observed on TiN-coated end-mills after the predefined number of slot cuts compared to conventional cutting. Therefore, it can be concluded that high-speed cutting is more energy efficient than cutting at conventional speeds.

The installation of KERS into machine tools is expected to reduce average power consumption by up to 25% depending on workpiece geometry and machining time. The energy efficiency of the system is highly part specific and it is advised that a KERS should be custom defined for each machine tool once the main workpiece to be manufactured has been determined. Using current day energy and supercapacitor prices it was found that a KERS defined using the machine tools maximum cutting speed would not be an economically viable method of increasing machine efficiency.

A unified monitoring scheme provides the system approach required to fully capture the effects of the inherently complex nature of energy flow. Unified monitoring schemes are enabled by interoperability solutions such as MTConnect that allow for the standardization needed to more easily and effectively integrate various disparate elements and allow for an effective means to easily glean the relevant information from sampled data.

Through all three approaches discussed, energy efficiency for precision manufacturing can become more easily realizable, providing invaluable benefits to the environment and potentially large monetary rewards to those who adopt these and other green techniques.

## 6 ACKNOWLEDGMENTS

MTConnect™ is supported by the Association for Manufacturing Technology (AMT). For additional information refer to www.MTConnect.org. Research in the Laboratory for Manufacturing and Sustainability is supported by the Machine Tool Technology Research Foundation. Special thanks to Will Sobel of SystemInsights for providing Modbus agents for the WattNode.

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