COMPUTING FOR GREEN MACHINING
Recent Results and Research Perspectives

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Abstract: We present our vision of research for the development of green machine tools focused on information technology issues. We present first what are the characteristics of a green machine tool, its life cycle aspects and the related environmental considerations. We proceed afterwards with needed research in the area of modeling, optimization and associated planning, controlling and scheduling software tools at the process, process planning, machine tool life cycle, factory and manufacturing network level. Finally we present some of our recent advances related to energy consumption modeling in milling.

1 INTRODUCTION

Our objective in this paper is to present a research agenda for green machine tools focused on information technology issues. Some work has been reported in the literature (Munoz, Sheng, 1995, Dornkudwar, et al, 1998, Srinivasan, Sheng, 1999a-b, Akbari, et al, 2001, Dahmus, Gutowski, 2004, Jayal, Balaji, 2007, Narita et al, 2006, Zhigang et al 2008 etc.) considering green machining issues; however, in most cases the focus has been limited at the process and process planning level. We wish to present a broader perspective that also includes system level considerations (several machine tools or distributed manufacturing) as well total life cycle coverage. In the last section we present some of our recent work related to this research agenda.

Basically, in the normal course of machining several environmental discharges occur in solid, liquid or gaseous state as a result of the interaction between the tool, workpiece and the cutting fluid, whereas the machine tool system accommodating the process draws a specific amount of power related to machining and non-machining activities.

Generally, research studies are focused on the cutting energy in machining systems, that is, the amount of energy required to remove a specific amount of material. However, from the point of view of green manufacturing the energy consumption should be considered systematically for the whole machine tool system and not limited solely to the cutting energy which represents just a variable amount highly dependent on process parameters.

2 BACKGROUND

2.1 What is a Machine Tool System?

We will focus our presentation on green machining.

We consider all systems (see Figure 1) that are participating in the delivery of the machining function, i.e. not only the main machining system with its spindle and feed axes subsystems but also

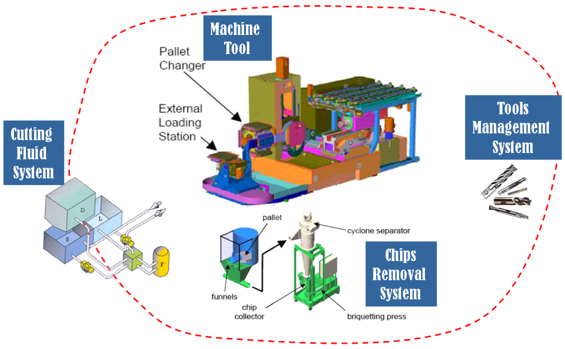

Figure 1: A Machine Tool System (MTS).

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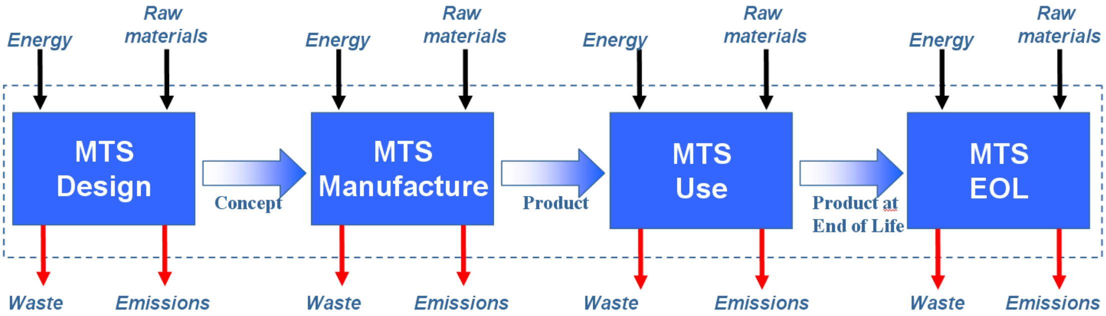

Figure 2: The life cycle of a Machine Tool System (MTS).

the auxiliary systems such as the cutting fluid, chip removal and tool management systems. This is important since the energy consumption and associated environmental impacts are also strongly dependent on the auxiliary systems.

2.2 What is the Life-Cycle of a Machine Tool System?

Before attempting to define what are the green aspects of a machine tool system it is important to consider the entire life cycle of a machine tool system from its design phase to its manufacturing, use and end-of-life (see Figure 2). In each life cycle phase we need to consider the energy and raw materials consumption and the corresponding generated waste and emissions.

However, it is important to mention that the use phase seems to be one of the most important life cycle phases of the machine tool system, where most of the energy consumption and environmental impact is taking place.

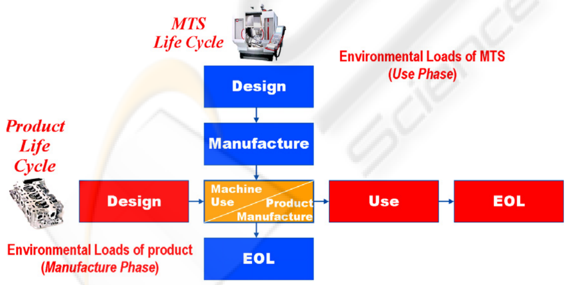

Figure 3: Life cycle crossing of a Machine Tool System.

In that regard it is also important to note that the life cycle of the machine tool is crossing the life cycle of the part that is manufactured i.e. when a part is machined (the machining life cycle phase for the part) a machine tool is used (the use life cycle phase for the machine tool system). This is the well known life cycle crossing problem (Young et al, 1997) of machining, already reported in the literature (see Figure 3). Life cycle crossing implied that we cannot consider the life cycles of the machine tool system and that of the part separately since they are interdependent. For example, a machine tool system that machines a part with a higher quality is greener (if all other aspects are the same) since the life cycle of the part is extended.

2.3 What are the Environmental Considerations?

The environmental objectives for a machine tool system are mainly, as we remarked above, related to its use phase in order to reduce its energy consumption, to reduce (or even better to completely eliminate) the disposal of hazardous substances (such as the disposed cutting fluid), to improve the surrounding air quality (so as to eliminate the corresponding health impacts) and to reduce resource consumption (in addition to energy, such as cutting fluid and other consumables such as cutting fluid filters and tools).

2.4 What is a Green Machine Tool System?

Based on the previous discussions we can mention some desired aspects to achieve the goal of a green machine tool system. A green machine tool system should have reduced installed power for its various motorized equipment in order to reduce the energy consumption. This is especially true since in many cases a far lower power is used to achieve the needed machine task than the installed power capacity. Another aspect of a green machine tool system is the reduction or complete elimination of the hazardous waste and emissions. For example dry machining could be promoted to eliminate the need for using a cutting fluid but this may entail the deterioration of the air quality and the reduction of the life duration of the tool.

3 RESEARCH VISION FOR GREEN MANUFACTURING

3.1 Modeling, Optimization and Software Tools

Our focus is to describe needed research on modeling, optimization and corresponding software tools. In this regard we propose a hierarchy of research issues as illustrated in Figure 4. We propose a hierarchy of research issues in order to facilitate the modeling of a complex manufacturing system by decomposing the system in its components. Each level of the decomposed hierarchy corresponds to a separate physical component which can be modeled stepwise. We will now describe the modeling of each level of the hierarchy.

At the very basic level we need process modeling and optimization methods and tools. For example we need to develop eco-evaluation models for the following alternative processes: dry milling, minimum quantity lubricant (MQL) and high speed milling. These models will allow us to select the holistically best process alternative depending on the specific machining goals. To be able to evaluate a process alternative from the environmental point of view we need to develop models of the corresponding environmental factors, their hierarchy and their dependencies.

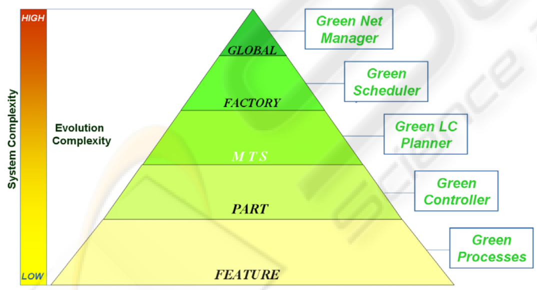

Figure 4: Machine Tool System hierarchy of modeling and optimization methods and tools.

Environmental factors that are of interest for a green machine tool are the air quality, the tool wear, the cutting fluid disposal and the energy consumption during the various machining steps (setup, tool changing, workpiece loading, tool approaching and retracting and machine tool spindle and axes). Additionally, we need to develop measurement and monitoring methods and tools to quantitatively evaluate the magnitude of the environmental factors. Subsequently we need to develop methods and tools to transform the environmental factors into environmental impacts and associated criteria. Finally we need to develop multi-criteria methods and tools to be able to evaluate holistically a machining process across technical, economical and environmental dimensions. This last objective is important since environmental performances cannot be evaluated in isolation but a holistic approach is needed that considers all the performance aspects and dimensions. Some criteria would be conflicting and as a consequence compromise solutions would be sought with the appropriate choice of the criteria weights.

At the next level of needed research, we note the need for the development of process planning modeling and optimization methods and tools. This is the point where the life cycle of the machine tool is crossing with the life cycle of the part. Although quite a few publications treated systematically this issue we consider that we still need to do more research especially with regard to the overall process plan optimization of a part when several processes and machine tools are involved. For example we may be able to reduce the total energy consumption and environmental impact for the grinding of a cylindrical part if we first machine the part by turning with a minimized stock allowance and reduced dimensional tolerances and subsequently perform the final grinding of the part (Denkena et al. , 2005). This beneficial result is expected since it is well known that the specific cutting energy for grinding is much bigger than for turning. On the other hand we need to grind the part to achieve a high quality part surface. Therefore the goal here is to develop overall machining strategies for the manufacture of a part that may involve several machine tools and alternative machining processes. Furthermore, even when restricting ourselves to the use of one machine tool we see the need to develop methods and tools for the green machining of complex parts which require complex toolpaths. This is so since current approaches are in most cases limited to straight toolpath machining and do not consider complex curved toolpaths which generally necessitate the acceleration and deceleration of the machine tool axes movement and therefore may impact in an important manner on the total energy consumption and environmental impact. Therefore, methods and tools are needed to generated appropriate toolpaths to reduce the energy consumption and environmental impacts for geometrically complex parts.

Another important issue in holistic process planning optimization is the evaluation of a process holistically i.e. not only with regard to its part quality, machining time and cost performance but also with regard to the expected energy consumption and environmental impact. It is also desirable to quantify the total cost of a process plan i.e. to include the energy consumption cost and environmental impact reduction or treatment cost. It is important to emphasize here that the needed methods and tools would have to model the entire machine tool system involving the development of holistic mechatronic machine tool models since we need to model not only the cutting process, but also the axes electromechanical feed drives, the spindle system and its cooling subsystem among others. In that sense here we use the term process planning in a broader sense i.e. we include the control aspects that are needed to achieve these goals.

At the next level of the research vision hierarchy we need to consider the development of methods and tools for the modeling and optimization of the life cycle of a machine tool. Therefore we need such eco-evaluation methods and tools for each life cycle phase (design, manufacturing, use, maintenance and end of life) as a prerequisite. These methods and tools would probably have to rely on some experimentally derived databases since it would be very difficult to model all the related complex phenomena analytically. Examples of needed research for the use phase is the need to monitor in real-time the holistic performance of the machine tool. This means we need to also monitor and make transparent to the machine tool user the energy consumption and environmental impact in real-time so that he/she may eventually be aware and/or interfere to improve its energy consumption and environmental performance. The monitoring methods and tools could also provide us with information about the remaining life of the machine tool and its components so that we can optimize its maintenance and end-of-life scenarios. For example on the basis of this information we could develop models and methods of remanufacturing process costs and associated environmental impacts for a used machine tool system. This would be very useful in reducing the uncertainties that are inherent in remanufacturing planning and scheduling due to the arrival of parts with unknown quality and random quantities. As a result this would significantly improve the performance of remanufacturing systems and consequently the recuperation of a great part of the energy and resource already spent to manufacture the machine tool or some of its components.

It is interesting to note here that the eventual models that we propose to be developed for the life cycle of machine tool system would also serve in benchmarking the machine tool systems and in establishing a holistic rating classifying the machine tools in different categories according to their holistic performance. This would be an answer to the need to develop a green labeling system for machine tools which is rather difficult to achieve given its complex performance which strongly also depends on the way it is used.

At the next step of the hierarchy of needed research we wish to propose the consideration of the modeling and optimization of a factory consisting of several machine tools of different types and the associated infrastructure. There is recently a strong research interest in funding research in the area of the factory of the future and/or the sustainable factory. These are from our point of view related issues. The need is to consider here not only the cycle times, throughput and resource utilization but also the waste streams in solid, liquid and vapor states, for part mixes with different material properties and geometric complexities. Therefore, here we need to develop modeling and simulation methods and tools of the extended factory for planning preventive maintenance and cutting fluid recycling procedures. We need to generate trade-offs between reducing the waste stream output and increasing machine downtime. We also need to develop new methods and tools for holistically planning and scheduling a factory with the incoming arrival of random mixes of various part types with different geometric complexities.

At the next level of the hierarchy of the needed research we need to consider the development of methods and tools for the modeling and optimization of manufacturing networks consisting of several machining suppliers geographically distributed. This involves research issues in evaluating holistically process plan alternatives between local and global manufacturing. It also includes part/product packaging and transportation considerations. Furthermore, methods and tools are needed for the modeling of the organization aspects and the management of global manufacturing networks and green supply chains. This would necessitate the development of decision models for incorporating environmental issues into the problem of supplier evaluation and selection. Furthermore, we need to consider the impact of supply chain management decisions not only on cost, quality, delivery and technology but also on the environment.

3.2 Energy Consumption Modeling in Milling of Prismatic Parts

Electricity, before being consumed, is already burdened with its own environmental ramifications because its production is accompanied by important emissions. Therefore, it can be inferred that any reduction of the energy consumed in machining yields an environmental benefit.

In this regard, we present here some of our recent work on energy consumption modeling for the milling of prismatic parts. This model covers aspects related to process plan optimization by running alternative machining strategies and enable the quantification of the overall energy consumed by the machine tool system with respect to various use phase regimes. This example covers the first two levels in the hierarchy of a machine tool system presented in Figure 4. Furthermore, this example also covers one part of the third level modeling in the manufacturing systems hierarchy: the usage phase of machine tool modeling.

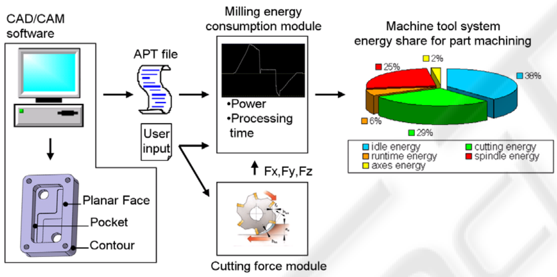

Figure 5: Information flow and software modules for the estimation of the energy consumption.

The complete coverage of all the life cycles of a machine tool is a goal for the future as is the research on the remaining two levels (fourth and fifth).

We consider the milling of a prismatic part such as the one shown in Figure 5.

We will describe the information flow and the software modules needed in order to model the energy consumption during the milling of such a part. The first step is model the three-dimensional geometry of the part with standard commercial Computer-aided design systems. Afterwards, we consider at this stage using the available Computer-aided facilities in standard commercial systems to generate the required toolpath to mill the given part. The output of this modeling would be an APT file in neutral format containing the description of the toolpath and the axes feed speeds and spindle speed. In the future we will consider more general formats such as the STEP format. The APT file is the main input to our software that performs the energy consumption modeling during the milling of the part.

The first step of the energy modeling software consists in extracting the detailed toolpath and speeds information from the APT-file. Afterwards this becomes an input to our milling energy consumption module. This module contains detailed formulas for the estimation of the power requirements and motion times of the feed axes and of the spindle with respect to steady state and accelerating and decelerating regimes. Furthermore, input from the user to this module is information about the machine tool characteristics such as its architectural layout, the moving masses of the axes the friction coefficient in the guideways, the types of the spindle bearings and the maximum feed rate.

We also need input data about the cutting tool, the workpiece and its material, necessary for the computation of the cutting force components used for the estimation of the cutting power. Finally we need data about the auxiliary equipment and their nominal installed power.

We show in Figure 6 some of our results of the milling energy consumption for the planar face feature of the modeled part, machined under wet conditions and by removing the same amount of material at two different cutting speeds.

In addition to the energy estimated for the spindle and axes along the path followed by the tool for the machining of the planar face with respect to both steady state and transient regimes, these graphical representations report also the energy consumed by the auxiliary equipment of the monitored machine tool, such as the cutting fluid pump, the air conditioner of the electrical cabinet, the hydraulic pump and the tool changer. The energy consumed by the minimum quantity lubrication (MQL) system is represented only for the sake of comparison with its counterpart alternative (i.e. cutting fluid pump).

The main conclusions which can be drawn from the analysis of the MTS energy share for the machining of the planar face at low and high speed levels are as follows:

(i) for both conditions the power required for the idle state of the machine generates the highest energy consumption

(ii) the transient non-cutting movements of the feed axes do not show appreciable energy consumption; the acceleration of the

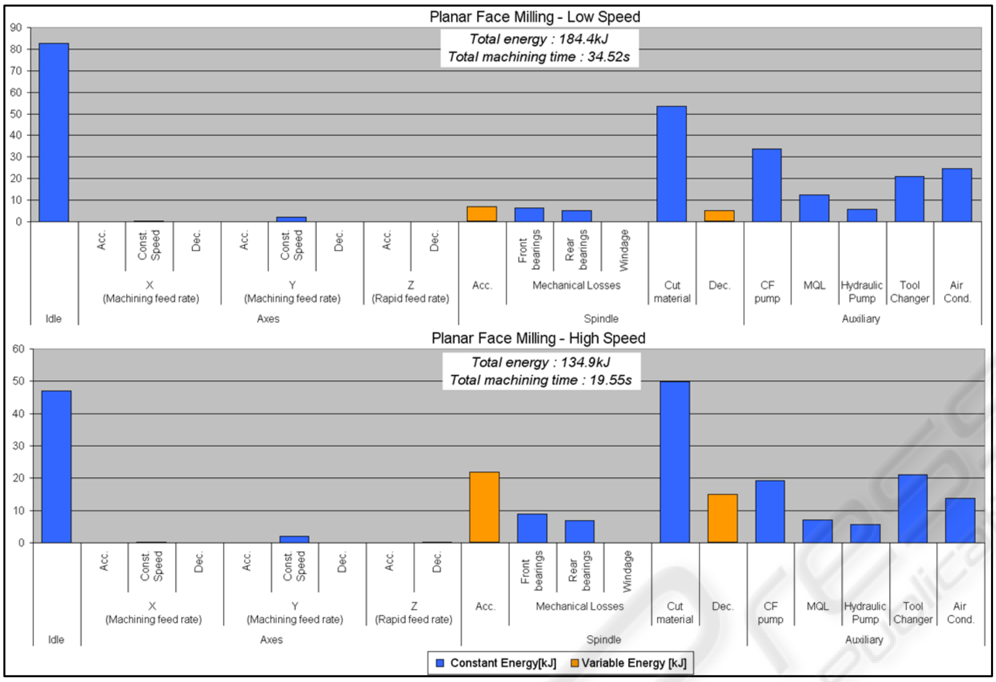

Figure 6: Machine Tool System consumed energy (kJ) for planar face milling (low speed vs. high speed).

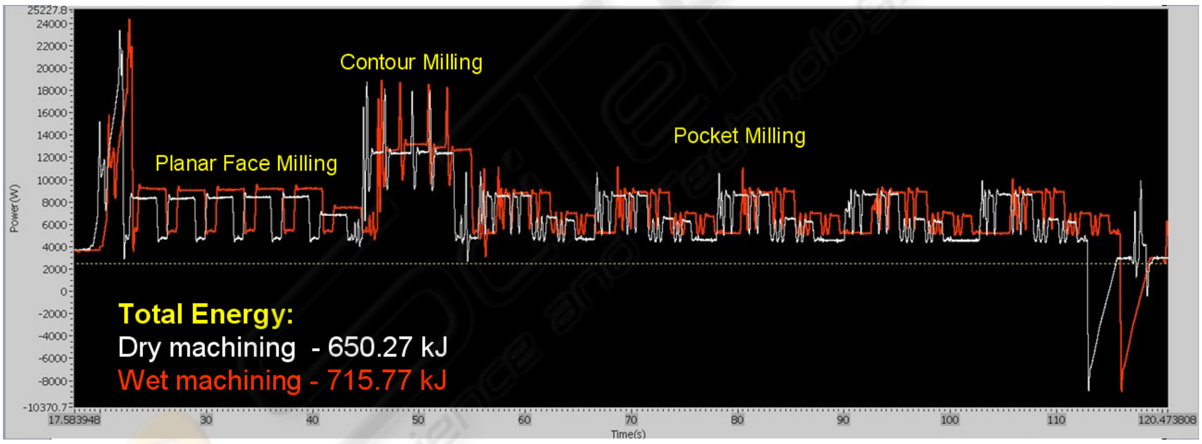

Figure 7: Machine Tool System energy consumption (kJ) for part milling (wet vs. dry machining).

Spindle consumes more energy as the cutting speed increases but it is assumed to be performed only once at the beginning of the machining of the milling features of the part and an important amount of this energy can be recovered by electrical braking during spindle deceleration

(ii) The energy consumed to overcome the mechanical losses of the spindle is proportional with the speed

(iv) The low spindle speed level employed for the machining of the planar face proved to be 36.7 % more energy demanding than the machining in a higher speed range

If several auxiliary components are used in parallel during the use phase, the energy required to fulfill the auxiliary functions of the machining system can easily become dominant.

Figure 7 shows the difference between the energy consumed during the milling of the features depicted in Figure 5 by employing the same cutting parameters under dry and wet conditions. The difference mainly stems from the energy required to run the cutting fluid pump.

4 CONCLUSIONS

We have presented a research vision for the development of methods and software tools to support the design and operation of machine tools while reducing their energy consumption and environmental impacts. We presented this vision as a hierarchy of modeling problems to be resolved starting from the process level, to the process planning level, to the machine tool life cycle, to the sustainable factory and finally to the machining network management. Besides this vision we briefly presented support the design and operation of machine tools while reducing their energy consumption and environmental impacts. We presented this vision as a hierarchy of modeling problems to be resolved starting from the process level, to the process planning level, to the machine tool life cycle, to the sustainable factory and finally to the machining network management. Besides this vision we briefly presented some of our recent work on energy consumption modeling in milling of prismatic parts. This modeling allows comparing process plans with regard to their cutting parameters and the selected machine tools. Furthermore, it allows identifying the most important components of energy consumption in the machine tool so that we can focus in their optimal design and use.

In this paper we discussed some of our recent research relative to the first two levels in the hierarchy of the machine tool system presented in Figure 4 and a part of the third level. The complete coverage of all the life cycles of a machine tool (third level) is a goal for the future as is the research on the remaining two levels (fourth and fifth).

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