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Evaluating the use phase energy requirements of a machine tool system

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ABSTRACT

This paper has an energy consumption reduction perspective by considering alternative machining strategies and system components interactions translated into variable and constant power flows with respect to various use phase regimes of a machine tool system. The methodology is able to estimate the mechanical energy requirements of the spindle and feed axes with respect to 2.5D machining strategies by taking into account steady-state and transient regimes. In addition, the specific amount of fixed energy drawn by a machine was determined based on a careful monitoring of the energy share amongst the auxiliary equipment that supports the accomplishment of the machining tasks. The numerical results were experimentally validated and the good agreement between them led to the conclusion that the proposed methodology can be used effectively for the calculation of the total energy required by a machine tool system for the milling of a part. This enables a straightforward comparison of different milling part programs with respect to their energy consumption levels.

1. Introduction

A machine tool system (MTS) can be conceived as a collection of equipment needed to perform several steps in order to complete a machining task. The performance of an MTS is highly dependent on the cooperative interactions between the spindle and the feed axes on the one side and the peripheral equipment on the other side. The most general level of such interactions is their energy level, so that they can be thought of as power flows within the entire system. The environmental impact in the use phase of active products such as MTS which generates other products is more important than that from other life cycle phases and resides mainly in the amount of energy consumed (Dahmus and Gutowski, 2004).

Across their entire use phase, the MTSs require various processes and enormous amounts of energy for the act of physically transforming raw materials into finished products. Use processes are performed by executing functions of the MTS. Careful selection of the technology available, intelligent process design and effective integration of the process within the machining system are all areas that can contribute to energy consumption minimization.

2. Energy-related issues in machining

In order to comply with a stricter environmental legislation, the manufacturing community should be able to find solutions to reduce the consumption of resources deployed for the transformation process from input into output. Energy is an essential resource for machining processes and the reduction of its consumption should be motivated not only by the increasing operating expenses of the manufacturing systems but also by a proportional reduction of the production of greenhouse gases. The dependence between the carbon emissions related to the energy available at a power grid and the primary energy source used was discussed by Jeswiet and Kara (2008). They introduced a carbon emission signature (CES) as a simple way to find the carbon emitted during the manufacturing of a part.

One of the first studies identified in the literature addressing the energy efficiency issues in numerically controlled (NC) machine tools was carried out by Filippi and Ippolito (1981). They gathered together data from 10 different NC machine tools involved in various operations. It was concluded that the installed power was never fully exploited because the mean power was quite less than half the power available and due to a rate of 60% of the total time spent as a productive time.

Akbari et al. (2001) provided a qualitative representation of the machine tool standby and cutting energy for alternative machining strategies and summarized the probable effects on the energy consumption caused by running different machining strategies. In another study the cutting energy dissipated as heat and its repartition between workpiece, tool, cutting fluid and environment was quantified for a gear milling process with respect to different cooling/lubrication strategies (Fratila, 2009). Although the transition from conventional to new cooling/lubrication strategies of the

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cutting area results in a significant reduction in solid waste, water usage, global warming potential and acidification an increase in energy use was noticed (Pusavec et al., 2010a). Nevertheless, this difference can be greatly reduced due to the higher productivity and higher performance of sustainable machining alternatives such as cryogenic or high-pressurized cooling/lubrication methods (Pusavec et al., 2010b).

The society awareness about the natural resource depletion and environmental degradation issues led to an increasing interest in exploring new ways to improve the environmental performance by using pollution prevention strategies and environmental management systems. One such technique is the life cycle assessment (LCA) which encompasses all processes and environmental releases across the entire product life cycle. The datasets pertaining to the electricity consumption of various machining processes provide distinct values for different materials (Steiner and Frischknecht, 2007). However, LCA tools usually provide only an average measure over time and location. Furthermore an LCA analysis is only valid as its data and is highly dependent on the completeness and accuracy of the datasets used. Nevertheless an LCA analysis can be also carried out by including accurate data about the power signature of a process derived from machining experiments (Fratila, 2010).

The current need to improve the energy efficiency of machining processes requires a careful selection of the boundaries of the system to be analysed. For instance the cutting speed employed in a turning process in order to meet the minimum energy criterion is highly dependent on the way the energy footprint related to tool production is accounted for (Rajemi et al., 2010).

A modern machining center can include a wide variety of functions including work handling, lubrication, chip removal, tool changing, etc., all in addition to the basic function of the machine, which is to cut metal by plastic deformation. However, each function is performed with a specific regularity. In order to deal with this aspect Dahmus and Gutowski (2004) carried out an experimental research on machine tool energy consumption and categorized the total energy of the system in three main activities, namely "Constant start-up operations", "Run-time operations " and "Material removal operations". They concluded that the actual cutting energy can be quite small compared with the total energy required by the entire machine tool system during material removal and it is dependent on the automation level of the machine. This conclusion was supported also by another experimental work which addressed the use phase of production machines by following an LCA-like systematic approach (Devoldere et al., 2007).

Herrmann et al. (2009) addressed the energetic consumption of the machine tools and extended the perspective by considering the ecological aspects beyond the economic input and output flows. Moreover a statistical model able to define the dynamics between process parameters and the specific process energy as well as the conversion of the electrical energy into heat and its transfer to the coolant though the pumping process were discussed with the main focus on grinding processes.

Dietmair and Verl (2009) introduced a generic method to model the energy consumption behavior of machines based on a statistical discrete event formulation. The parameter information required to characterize the discrete events can be obtained with a small number of simple measurements or with a degree of uncertainty from the machine and component documentation.

An evaluation system of the environmental burden generated in machining was developed by Narita et al. (2004). Formulated in agreement with the LCA policy the system can estimate the impact generated due to the electric consumption in terms of global warming potential. It was observed that the environmental burden varies under different cutting conditions even though the same product is machined and the electric consumption of the peripheral equipment is the most important amongst the factors evaluated.

3. Research aim and scope

This work proposes an analytical approach for the estimation of the variable mechanical energy requirements of an MTS with experimental verification. The model takes into account the machine tool layout, moving masses and spindle and feed axes specifications, the cutter location data and the cutting force values in end milling as well as the process time calculated based on feed kinematic profiles and command variables control.

The novelty lies in accounting for the energy consumed by the spindle and the feed axes of an MTS with respect to both steady-state and transient regimes. Furthermore, an experimental work is carried out in order to establish the fixed energy share amongst the MTS peripheral equipment components. In this respect the methodology is able to support more environmentally friendly decisions to be taken prior to perform any 2.5D milling operation on a machine tool system.

4. Model structure

The methodology for the estimation of the variable energy requirements of an MTS is implemented into a software tool (GREEM – Global Reasoning for Eco-Evaluation of Machining) based on Visual Basic for Application (VBA) and contains several steps which will be detailed in the following sections.

Step 1: The first step consists in the importing and reading of an automatic programming tool (APT) file which can be generated by CAD/CAM software, e.g. CATIA V5 R15. The APT file is read line by line and the cutter location data together with the spindle speeds and feed rate values corresponding to each milling operation listed in the process plan of a part are extracted and interpreted.

Step 2: At this stage the cutting force components for each milling process are computed by taking into account the effects of the cutter geometrical and machining parameters, namely the number of tool flutes, helix angle, rake angle, side cutting edge angle, feed rate, cutting speed, axial depth of cut, radial depth of cut and the specific cutting pressure for a given tool-workpiece material combination. The cutting force components are calculated by using the mechanistic approach described and programmed according to Rai and Xirouchakis (2008).

Step 3: In this step the load that must be overcome by each motor is estimated. In this respect the main characteristics of the MTS to be used for the milling of the part as well as specific calculation formulas able to predict the mechanical motor torque and the corresponding power during steady-state and transient regimes are provided for the feed axes and the spindle.

Step 4: Finally, the predicted variable mechanical power requirements and the fixed power derived from measurements are integrated with respect to the processing time and provide an overall estimation of the energy required by the entire MTS to complete the machining of a part.

The general overview of the methodology is presented in Fig. 1.

5. Assumptions and considerations

The interpretation of the APT file and the calculation of the power requirements of the feed axes and the spindle of an MTS as