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Critical factors in energy demand modelling for CNC milling and impact of toolpath strategy

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A B S T R A C T

Reducing energy demand in manufacture is an urgent challenge. This challenge is driven by higher consumer demand for manufactured products, increasing electricity and energy prices, volatility and uncertainty in energy supply and national policy. These factors, together with a need to reduce energy consumption derived carbon dioxide emissions, strategically call for energy efficient manufacturing. In manufacturing processes, especially mechanical machining, more than 90% of environmental impact arises from direct electrical energy demand in machine tools. At the machine tool level, the biggest share of the electrical energy associated with mechanical machining is required to bring the machine to a ready state and support non-cutting operations such as spindle torque requirements, auxiliary units and movements. These activities are controlled and related to machine commands such as NC codes. In this paper comprehensive information on energy intensity in machining process, including the influence of tool wear, was studied. Key energy states were identified to build up an energy demand for machining components. The paper defines the essential power constants for a database that can assist energy prediction for any available machines and workpiece materials. The assessment of alternative toolpaths identified major opportunities for energy demand reduction.

1. Introduction

The increase in the population of nation states and the world is promoting higher demand for products. The challenge that arises is how manufacturing industries can cope with increased product demand and sales revenues as well as simultaneously supporting environmental sustainability. Electricity use in manufacturing is one major driver for carbon emissions increase. This is the case because carbon rich energy sources and fossil fuels dominate electrical energy generation (Jeswiet and Kara, 2008). Thus industry needs to be smarter to increase output and productivity while reducing the energy intensity of manufactured products and manufacturing cost.

The manufacturing sector is one of the key growth drivers in many countries and hence a major energy consumer for the world. International Energy Agency (IEA, 2013) reported the world electricity consumption by each sector in 2011, the total figure had reached – 1582 Mtoe (18,396,735 GWh), where industry sector is the highest consumer of electricity with a percentage of 42.6%. This energy consumption represents a high share of environmental burden in the manufacturing sector (Bonvoisin et al., 2013).

Mechanical machining is a technology widely used in manufacturing industries. GardnerResearch (2013) reported the consumption of machine tools from 28 leading manufacturing countries (including China, Germany, Japan, US etc). Total machine tool sales increased in the past ten years and reached $USD 93,205 million in 2012. The European commission identified machine tools in manufacturing as a top three priority for product categories regulated through the EcoDesign directive (EPTA, 2007).

The European Union has set the goal to significantly increase efficiency in the use of resources in all sectors, including industry. In many countries Small to Medium Enterprises (SMES) are significant parts of the economy and need support to manage their energy and environmental footprints. France and the UK have energy efficiency policies for SMEs, while an Industries Assessment Centre in the US was established to improve energy management for SMEs. Implementation of energy efficiency for SMEs in Sweden, Norway, the European Union and India showed potential energy saving of 7–22% on energy bills (Hao, 2011).

Recently, there are more consortia and collaborations around the world working on industrial sustainability. For example, The Sustainability Consortium (TSC®, 2013) is working to develop

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methodologies, tools and strategies for improving sustainability of product and supply networks. However, TSC is currently limited in scope to household and consumer products. Cooperative Effort on Process Emissions in Manufacturing so-called CO_2PE!-Initiative is focussing on manufacturing processes. They are working on a framework of environment footprint with energy consumption and CO_2 emission, developing methodology and identifying opportunity for improvement (CO_2PE!, 2013). The proposed CO_2PE! taxonomy for energy consumption in milling processes is composed of basic energy, idle energy and milling energy. These initiatives do not clarify machine tool design and its complexity, including operations specific tasks done by machine tool axis movements and or defined by CNC codes. Thus a comprehensive methodology and robust energy model will enhance the information on process level energy modelling.

1.1. Energy consumption in machining process

Mechanical machining processes such as turning, milling and drilling are widely used in manufacturing production. Their popularity is due to the capability to fabricate 3D complex geometries to high dimensional accuracy and cost efficiency. The machining process is performed on machine tool centres. Electricity is the main power source for machine tool centres in cutting processes. The energy consumption of machine tools includes the demands for the spindle, axes motion, cutting resistance (workpiece materials, cutting tool and cutting conditions) and others (cutting fluid pump, cooling device, computer controller). Kordonowy (2002) categorised energy consumption for mechanical machining into constant and variable parts. The former, composed of two sub-groups (start-up and run time) depends on machine tool modules (servo motor, computer, spindle, cutting fluid etc), while the latter was influenced by machining and material removal rate. The energy in manufacturing system can be analysed at the unit process level, multi-machine system, factory level and supply-chain level (Duflou et al., 2012). This enables linking the energy demand of machine tools to factory wide performance.

It has been suggested that more than 90% of environmental impact from machine tools is due to electrical energy consumption (CECIMO, 2009). This electrical power consumption is the biggest source of environmental impact because carbon dioxide is released when the electricity is generated from carbon rich fuel sources. Hence the energy used in machining process can be used to calculate the associated carbon emission through the carbon emission signature, CES (Jeswiet and Kara, 2008).

The estimation of cutting energy or tip energy in material removal process can be accomplished through the specific cutting energy in chip formation, which is the minimum energy required to remove a certain volume of material (Dahmus and Gutowski, 2004). This depends on the machinability of the material, taking into account the material properties, cutting fluid, cutting tool and cutting conditions. The influence of chip thickness and feedrate on specific cutting energy was reported by Balogun and Mativenga (2014). They suggested that specific energy consumption in roughing processes can be reduced by machining at feedrate greater than the tool edge radius. However in practice, the energy consumed by machining operation is much higher than the specific cutting energy. The machine tool centre is comprised of a variety of functions such as workpiece handling and movement, cutting fluid system, chip removal, tool changing and tool measuring. All of these functions require energy to activate and to support metal cutting by plastic deformation. Table 1 summarizes the mathematical models of energy consumption in machining process from the early work. Gutowski et al. (2006) presented a fundamental model for energy demand in cutting. They reported that the energy required for actual cutting was a very small portion in relation to the total machine tool operation energy. This is due to the dominancy of basic energy (fixed energy) of machine tools. The percentage of actual cutting energy will become even smaller when operating at low production rates (Rajemi et al., 2010).

The energy consumption for machining operation can be reduced by the selection of machine tool centres that have low basic power requirements. However in practice, some industries have limited choice and investment and they would like to use existing resources and machines. Thus improving energy efficiency using existing resources is a prompt solution for industry. Li et al. (2011) proposed that energy demand could be reduced by improving machine tool components (hydraulic system, cooling and lubrication system) and by optimizing machining processes (minimize standby time).

Dietmair and Verl (2009) introduced a methodology and framework for energy consumption minimization of machine or production system. Rajemi et al. (2010) developed a model to select conditions for minimum energy footprint by constraining cutting conditions by an optimum cutting velocity and tool life that satisfied the minimum energy criterion. The energy footprint model in machining a single pass was built by considering power and energy requirements when setting up the machine, doing actual cutting, tool change time and the embodied energy in the cutting tool.

Gutowski et al. (2006) reported that non-cutting operations dominate power demand in machining processes. In additional work, Rajemi et al. (2010) model for energy footprint in machining was extended by including spindle power consumption characteristics (Mativenga and Rajemi, 2011). They showed that power consumption proportionally increased with spindle speed (without cutting load). Their research pointed out that the selection of cutting parameters based on their minimum energy footprint and minimum cost criterion resulted in significant reduction of energy footprint compared to the conditions recommended by cutting tool suppliers. Furthermore, the direct energy model was then developed for milling processes (Balogun and Mativenga, 2013). Several researchers studied the optimization and influence of cutting parameters on power consumption in machining process. For example, in CNC turning of Al alloy SiC composites, the effects of cutting speed, feed rate, depth of cut and tool nose radius were investigated with regards power consumption and tool life (Bhushan, 2013). Yan and Li (2013) studied the influence of spindle speed, feed rate, depth of cut and width of cut in milling process. Campatelli et al. (2014) also evaluated the influence of cutting speed, feed rate, axial and radial depth of cut in milling of carbon steel. They showed that to achieve a lower environmental footprint, material removal rate needs to be increased.

Mori et al. from Mori Seiki Co. Ltd (2011) highlighted two major reasons for power consumption including i) spindle and axes movement and ii) providing cutting force to overcome cutting resistance. By synchronising spindle and axes movement, a control strategy was developed to reduce power consumption. It was suggested that the cutting energy could be reduced by minimized cutting resistance and reduced cutting time. However, is noted here that this optimal cutting condition should not cause any premature tool wear or unacceptable machined quality.

Avram and Xirouchakis (2011) emphasized that energy demand depended on the interaction between spindle and feed, the selection of technology, intelligent process design and effective integration of the process. Kong et al. (2011) evaluated the influence of toolpath on environmental impact by introducing web-based and application program interface (API). Their energy model was comprised of constant part, run-time and cutting stage. Their research showed that the selection of toolpath influences energy consumption. He et al. (2012) presented an energy consumption