Journal of Cleaner Production 191 (2018) 57–66

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A novel method for energy efficiency evaluation to support efficient machine tool selection

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ARTICLE INFO

Article history:
Received 24 January 2018
Received in revised form
21 March 2018
Accepted 22 April 2018
Available online 23 April 2018

Keywords:
Energy efficiency
Machine tools
Machine tool selection
Procurement

ABSTRACT

Increasing energy price and emission limitations are new challenges faced by manufacturers; above half of their energy consumption is attributed to the electricity consumption of machine tools (MT), highlighting the need for manufacturers to select highly efficient MT. However, due to the unavailability of cutting tests and limited information in procurement stage, it is difficult to apply existing methods to evaluate the energy efficiency of MT options to support efficient MT selection. To address this problem, an energy efficiency model characterizing the relationship among energy efficiency, MT-related factors and workpiece-related factors is established to bridge the knowledge gap and a novel method without any cutting tests is developed including three steps: (i) modelling MT-related factors of each MT option; (ii) modelling workpiece-related factors of expected tasks; (iii) energy efficiency calculation and comparison. Furthermore, a selection example of gear-hobbing machine illustrates the application of the proposed method, reducing 2.88E+06 kJ energy consumption per selected MT per year. This study enables manufacturers to select MT for energy efficiency maximisation with the consideration of expected tasks in procurement stage.

1. Introduction

Manufacturing industry plays an indispensable role in the global economy and over one third of global energy consumption has been consumed in this sector (Jin et al., 2017). Accordingly, an increasing number of environmental directives and targets (e.g. European Directive, 2012/27/EU (Directive, 2012), EU 20/20/20 target (da Graça Carvalho, 2012)) push forward the topic of energy efficiency in order to save resources and to gain control of the drivers of global warming such as CO_2 emissions (Zhao et al., 2017). Driven by the combination of increasingly environmental, political and economic pressures, and also increasing energy and resource prices, the demand for manufacturers to improve energy efficiency and adverse environmental impacts is now more urgent than ever (Albertelli, 2017; Duflou et al., 2012; Liu et al., 2017a).

In manufacturing industry, machine tools (MT), such as machining centre and hobbing machine, are the key equipment in manufacturing companies, and operation of these MT consumes a substantial amount of energy (Diaz-Elsayed et al., 2015; Vijayaraghavan and Dornfeld, 2010). According to statistics from the U.S energy information administration, the electricity consumed by MT has accounted for above 50% of the total manufacturing electricity consumption (Energy Information Administration, 2011). Thus, improving the energy efficiency of machine tools has been one of the most important energy-saving strategies for manufacturers (Hu et al., 2017; Mori et al., 2011). Furthermore, a case study conducted by HE et al. has shown that a 42% reduction in energy consumption for machining the same workpiece can be achieved by altering the MT selection scheme (He et al., 2015). Therefore, an optional solution for manufacturers to improve the energy efficiency as well as reduce energy consumption is to purchase highly efficient MT which can perform their tasks efficiently.

Energy efficiency evaluation of each MT option is one of essential steps towards efficient MT selection, which provides a key support for procurement decision-making. To evaluate the energy efficiency of MT, methods based on experiments have been popular in previous studies (Behrendt et al., 2012; Gutowski et al., 2007; Kara and Li, 2011; Peng et al., 2014). For example, Japanese Standards Association published the series JIS TS B 0024 on energy efficiency evaluation using reference parts (Association, 2010a, b, c, d); Giacone (Giacone and Mancò, 2012), Peng (Peng et al., 2014)

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https://doi.org/10.1016/j.jclepro.2018.04.204
0959-6526/

Nomenclature

MT	Machine Tools
W	Workpiece
EW	Expected workpieces
E	Energy consumption
P	Electric power
J	Total number of process step
F	Energy efficiency factors
L	Number of workpiece expected to machine
I	Total number of process option
M	Number of MT options
S	Speed set
t	Time
e	Expecting-coefficient
x	Probability coefficient
n	Speed of spindle system
k	Key state of spindle motor

Subscripts

s	Standby state of MT
su	Start-up state of MT
u	Unloading state of MT
c	Cutting state of MT
j	Serial number of process step
l	Serial number of Expected task
m	Serial number of options
b	The best option of machine tool

Superscripts

m	Serial number of options
i	Serial number of process option

Greek symbols

α	Load loss coefficient of 1st order
β	Load loss coefficient of 2nd order
η	Energy efficiency

and Schlosser (Schlosser et al., 2011) introduced a method for comparison of machine tools based on a reference process. Advantages of using reference part and process are the testing close to the manufacturing result in practice, the short test time and simplicity of the test method (Schudeleit et al., 2015). But these methods fail to consider the influence of diverse tasks or cutting parameters on energy efficiency, which has been addressed by Gutowski (Gutowski et al., 2007) and Kara (Kara and Li, 2011) by establishing the empirical correlation between the machine tool power consumption and a physical output variable (e.g. material removal rate for a grinding machine or cutting speed for a laser machine) based on cutting experiments. However, it is a challenging job to curry out tests on all MT options using various tasks to build this kind of model; more importantly, this kind of experiments are unavailable in the stage of MT selection since most of MT options normally have not been built before ordering.

Besides methods based on experiments, component-based methods have been proposed. For example, Draganescu developed a method to map the efficiency of a spindle of a milling machine (Draganescu et al., 2003). Similarly, Schudeleit established a component mapping-based approach to describe the power consumption of a MT for any utilization (Schudeleit et al., 2016a). The ISO/DIS 14955 series also provides detailed measuring methods down to the level of MT components as well as test scenarios that can contain the machining of parts (Organization, 2016), but, as reported in (Organization, 2014), it does not suggest a methodology for quantifying the result achieved. Those methods enables to evaluate the energy efficiency of MT component, but neglects considering the dimensioning and utilization resulting from the interaction between all MT components (Schudeleit et al., 2016b). Therefore, Schudeleit presented an effortful approach for a total energy efficiency index based on an evaluation of actual (measured) and reference (best available technique) values for all machine tool components that are collectively responsible for at least 80% of the total power demand in each operation state of a machine tool (Schudeleit et al., 2016b). Paetzold investigated the influence of the different components (spindle, feed, coolants) features and properties on energy consumption and developed a methodology for process-independent energetic assessment of MT (Paetzold et al., 2017). However, these methods neglects the diversity of machining tasks and uncertainty of processing schemes and parameters, which should be considered to evaluate the energy efficiency of MT in procurement stage.

In MT procurement stage, experience rules, such as higher horsepower and lower standby power, have been popular to evaluate the energy efficiency of MT options in MT selection studies (Nguyen et al., 2014; Perçin and Min, 2013; Wu et al., 2016). However, existing studies (Liu et al., 2017c; Salahi and Jafari, 2016; Zhou et al., 2016) indicates that the energy efficiency of MT is determined by the energy performance of its components and the machining tasks of its users, meaning that those experience rules, which do not consider the machining tasks, cannot truly reflect the energy performance of MT. Although a large number of multi-objective decision-making algorithms, such as fuzzy multi-criteria decision making (Önüt et al., 2008), fuzzy analytic hierarchy process (Ayağ and Özdemir, 2006; Samvedi et al., 2012), and fuzzy analytic network process (Ayağ and Özdemir, 2011), have been developed to facilitate purchasing engineers to choose the MT with the best energy performance, they would fail to achieve this goal if they do not have an effective tool to evaluate the energy efficiency of MT options in a relatively precise way. Based on the previous studies on energy demand estimation (Diaz et al., 2011; Gutowski et al., 2006; Hu et al., 2012; Lv et al., 2014), some calculation models of machining efficiency for toolpath selection and process planning during MT use phase have been developed and validated (Edem and Mativenga, 2017; Shin et al., 2017; Xie et al., 2016b). For expamle, Aramcharoen proposed a methodology to predict energy demand in CNC milling machine with 95% accuracy when compared to online monitoring (Aramcharoen and Mativenga, 2014). As proved in their studies, the energy efficiency of MT varies in different process conditions (e.g., different workpiece, process parameters), revealing that the machining efficiency of MT in a single machining scenario cannot serve as the evidence of MT selection for energy efficiency maximisation in whole service phase. Therefore, these calculation models also fail to serve as an effective tool to support MT selection.

The review of the pertinent literature reveals that manufacturers lack tools to evaluate the energy efficiency of MT options to support efficient MT selection. Therefore, the objective of this paper is to establish a novel method, named Potential Efficiency (PE) Method, for energy efficiency evaluation specifically for efficient MT selection. In this novel method, not only the energy performance of MT components but also the machining tasks expected by manufacturers (including machining parameters, workpiece diversity and process uncertainty) are considered to