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Development of dynamic energy benchmark for mass production in machining systems for energy management and energy-efficiency improvement

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HIGHLIGHTS

- A new concept of dynamic energy benchmark was proposed in machining systems.
- A method for developing the dynamic energy benchmark was presented.
- The benchmark rating reflecting energy-efficiency level was proposed.
- The benchmark rating system was developed to perform energy-efficiency production.

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ABSTRACT

The energy benchmark has been recognised as an effective analytical methodology and management tool that helps to improve the efficiency and performance of energy utilisation. With a wide distribution and large amount of energy consumption at a low efficiency, machining systems have considerable energy-saving potential. In this study, a new concept of dynamic energy benchmark contributing to energy management and energy-efficiency improvement in machining systems is proposed to overcome deficiencies of previous energy benchmarks. This paper illustrates the concept and connotation of the dynamic energy benchmark and presents a method for developing the dynamic energy benchmark for mass production in machining systems. According to analysis of the energy consumption and the dynamic energy benchmark for machining systems, the dynamic energy benchmark is developed in three steps: (i) the establishment of the database, (ii) the acquisition of the energy consumption and determination of the dynamic energy benchmark, and (iii) the development of a benchmark rating system using the benchmark. Furthermore, a case study involving the establishment of a dynamic energy benchmark for the workpiece in a real machining plant is examined, illustrating the practicability of the proposed method.

1. Introduction

Industrial energy efficiency and potential are primarily analysed through the application of energy indicators and energy benchmarks [1]. The energy benchmark has been recognised as an effective analytical methodology and management tool that contributes to energy management and energy-efficiency improvement in many areas for fulfilling various objectives [2,3]. Numerous methods for developing the energy benchmark have been applied in the steel [4], chemical [5], building [6,7], environment industries [8], among others. The study of the energy benchmark has aroused extensive interest in recent years [9,10], especially in energy-intensive industries such as the manufacturing industry [11].

The International Organisation for Standardization [12], the European Union [13] and the Japanese Standards Association [14] implement numerous energy benchmarks and standards. In China, the Top Quality Control Official and the China National Standardization Management Committee jointly issued several national standards to provide important policy support for establishing the energy benchmark [15]. Moreover, many researchers have proposed some methods for developing the energy benchmark to improve the efficiency and performance of energy utilisation. Jeong developed an integrated energy benchmark that employed district heating to fairly evaluate the building energy efficiency for a

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Nomenclature

A,B,C	curve-fitting coefficient
b_1	load loss coefficient of the mechanical drive system in the first drive link
E	energy consumption
E_B	dynamic energy benchmark of the workpiece
E_{cm}	cutting material energy consumption
E_{gear}	energy consumption of the gear
E_{ke}	kinetic energy of the motor rotor
E_{km}	kinetic energy of the mechanical main drive system
E_{id}	idling energy consumption
E_m	energy of the coupled fields (electromagnetic field)
E_{sb}	standby energy consumption
E_{st}	starting energy consumption
$f(M_j)$	standby power database
$g(n_j)$	starting energy-consumption database
$h(n_j)$	idling power database
M_1, M_2, M_j, M_m	number of the machine tool
N	number of the sample
n_1, n_2, n_j, n_m	spindle speed of the machine tool
N_{cm}	number of cutting material processes
N_{id}	number of idling,
N_{sb}	number of standby
N_{st}	number of starting
P_a	additional load loss
P_{a_0}	additional load loss of the mechanical drive system
P_c	cutting power of the tool
P_{cm}	cutting material power
P_{id}	idling power
P_{id_0}	idling power of the mechanical drive system
P_{Le}	power loss of the main motor
P_{sb}	standby power
t_{cm}	cutting material time
t_{id}	idling time
t_{sb}	standby time
α	load loss coefficient
η_{BR}	benchmark rating of the machined workpiece
$\varphi(n)$	load loss coefficient database
ERD	energy-related data
EUD	energy-unrelated data

multi-family housing complex [16]. Spiering proposed an energy-efficiency benchmark for injection-moulding processes and examined how the production factor energy, as applied to manufacturing, can be an impulse for parallel improvements regarding energy [17]. Wang presented an energy-efficiency benchmark methodology and benchmark indicators owing to the lack of a system of energy-efficiency indicators and a standard benchmark system [9].

The U.S. Energy Information Administration published an energy yearbook in 2012 showing that energy consumption in the mechanical manufacturing industry accounted for 74.7% of the total energy consumption in the manufacturing industry [18,19]. The development of a rational energy benchmark will play a significant role in energy management and energy-efficiency improvement for the mechanical manufacturing industry and the machining system [20]. Nevertheless, there are few effective methods available for developing the energy benchmark in the discrete manufacturing industry and the discrete manufacturing system [21–23]. Numerous surveys have indicated that the machining system consumes a large amount of energy, and the energy efficiency of the machining process was very low: usually less than 30% [24]. Therefore, machining systems have considerable energy-saving potential [25,26].

Currently, the European Commission [27] classifies products such as machine tools and fans as critical for achieving the objective of decreasing the European energy consumption until 2020 by 20% compared to the projections [28]. These critical products must follow eco-design measures, as defined by directive 2009/125/EC [29]. The Japanese Standards Association proposed related studies regarding machine tools using test methods for electric power consumption [14]. Moreover, the International Organisation for Standardization is developing the ISO 14955 series, which deals with the standardization of environmental evaluation and the improvement of machine tools, e.g., Machine tools – Environmental evaluation of machine tools – Part 1: Design methodology for energy-efficient machine tools (ISO 14955 – 1:2014) [12]. The ISO 14955 series lacks a metric for evaluating the design of a machine tool considering the efficiency limit (e.g., the technically achievable efficiency) and the interaction of the components on a percentage scale [30]. Zein highlighted this issue and developed a method for determining energy-efficiency limits [31]. However, a metric for the standardised evaluation of machine tools and mass production has yet been established [30].

Several studies have reported energy benchmarks related to the mechanical manufacturing industry and the machining system. Xiong developed an indicator system, analysed the essential elements and content that should be included in this indicator system, and summarised the methods and steps for establishing an indicator system according to benchmarking demonstrations for energy-intense industries [32]. Liu proposed a method for dividing manufacturing products into a variety of general products and individual special products and presented a strategy for allocating the energy according to the product types [22]. Cai proposed a concept of fine energy consumption allowance of workpieces and the establishment method [1] and formulated a multi-objective energy benchmark for the mechanical manufacturing industry [20], which provided important support for developing an energy benchmark for machining systems. Zhou proposed an energy-consumption model for determining the energy-consumption allowance of a workpiece in a machining system and introduced a modelling method [21]. Hoda proposed a methodology for energy-use analysis and the benchmarking of manufacturing lines, analysed the energy use in manufacturing lines, and introduced the concept of local energy benchmarking [33].

As previously mentioned, most of the extant studies mainly focused on the analysis of the energy consumption and the energy efficiency of machine tools or machining systems (i.e. ISO 149550 series). A missing piece for the completion of the ISO 14955 series is a metric for the standardised evaluation of the energy consumption for the mass production in machining systems. The metric must consider the efficiency of each machining system and the need-oriented utilisation in combination with the other factors while referring to the efficiency limits. A state-of-the-art review reveals that none of the existing metrics are feasible to adequately achieve the goal. Additionally, the ISO 14955 series is not applicable for the energy benchmark for the production of a single workpiece with different machine tools or machining systems. Moreover, the previously proposed energy benchmarks are a static benchmark and are essentially a simple numerical value interpreted as a relationship between one produced object and a