Review

Energy consumption model and energy efficiency of machine tools: a comprehensive literature review

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ABSTRACT

To cope with the serious situations such as rising energy price, the global resource depletion and climate warming, improving energy efficiency in manufacturing becomes an inevitable trend for energy conservation, emissions reduction and sustainability. As the basis energy consumed device in manufacturing system, machine tools' energy consumption modeling and energy efficiency evaluation are the prerequisite for energy-saving in manufacturing. A comprehensive literature review is needed because some related concepts are not clear and the precision of models still need to be promoted in this field. Firstly, the connotation of energy efficiency for machine tools was discussed. It was pointed out that specific energy consumption referred to the mapping relationship between energy consumption and the processing parameters, which reflected the energy efficiency of machine tools from the perspective of effective input and output. Secondly, design, scheduling management, optimization and environment assessment of machine tools were introduced based on energy efficiency. Thirdly, the existing energy consumption models were classified into three categories in this work: 1) the linear type of cutting energy consumption model based on material remove rate, 2) detailed parameter type of cutting energy consumption correlation models and 3) process oriented machining energy consumption model. Finally, conclusions were drawn for the future study in two major points: 1) the accuracy of current energy consumption models could be improved through introducing the correlation analysis of machine tools, parts, tools and processing condition, 2) more scientific evaluation index system is required for the assessment and test of machining tools' energy efficiency.

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1. Introduction

The energy yearbook published by the U.S. energy information administration in 2012 showed that industrial electricity consumption accounted for 31% of the total electricity consumption, manufacturing electricity consumption accounted for 90% of the industrial electricity consumption, and machine tools electricity consumption occupied 75% of manufacturing electricity consumption (EIA, 2011), as shown in Fig. 1. As an important part of national industry, manufacturing consumes a large amount of energy and resources in product manufacturing process and leads to serious environmental emissions (Zhai et al., 2014; Du et al., 2015).

Machine tools are the basic energy consumption devices in manufacturing (Liu et al., 2013). The emission caused by machine tools using electricity can not be neglected. Gutowski (2013) pointed out that the CO_2 emissions of a numerical control machine tool with main shaft power in 22 kW operating one year was equivalent to the emissions of 61 SUV cars. Machine tools have been regarded as one of the regulatory priority categories in the European Union's *Eco-design Directive2009/125/E* (EPTA, 2007). That puts the pressure on manufacturer to make the machine meeting the eco-design directive and carbon emission standard.

The International Organization for Standardization drafted the standard "environmental evaluation of machine tools" in 2010 (ISO14955-1, 2014). It focused on energy consumption test procedure of metal cutting and design methodology for energy-efficient machine tools. Predictably, the energy consumption index will be one of the machine tools product indexes in the future. Growing energy demand and rising energy prices force manufacturing to seek for high energy efficiency and low cost solutions. Meanwhile,

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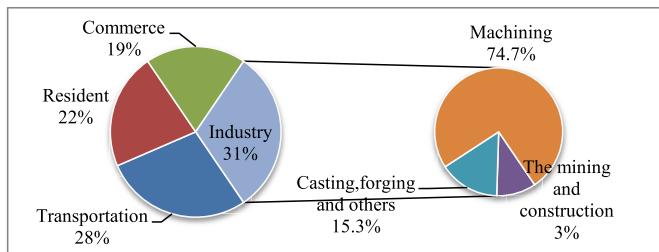
Fig. 1. Electricity consumption proportion of various fields in the United States.

serious environmental pollutions and severe environmental legislations drive both academia and enterprises to attach great importance to energy efficiency problems of manufacturing process and machine tools (Anderberg et al., 2009; Enrico and Andrea, 2013; Trianni et al., 2014). For seldom seeing comprehensive review in this field, this research was written to discuss connotation of energy efficiency and characteristics of the existing energy consumption models of machine tools. In addition, design, scheduling and assessment methods to optimize energy efficiency and study trends of this field were also discussed.

2. Methods

This comprehensive literature review was to reveal the current state of academic insight into the energy consumption model and energy efficiency of machine tools, carried out with methods like meta-analysis and meta-ethnography. Meta-analysis refers to summarizing the results of quantitative studies and finding the effect of a particular variable through various analytical tests, while meta-ethnography is to obtain interpretative synthesis of qualitative research (Bryman and Bell, 2011).

The comprehensive review process included three main steps. Firstly, research theme or question was specified, meanwhile a large number of relevant literature data and appropriate search strategies were selected. Secondly, after reading and critical analysis, the current topics and issues were refined. Thirdly, the findings were synthesized.

2.1. Specifying research question and searching literature data

In the past, compared to high energy consumption of metal smelting and casting industry, attention to energy consumption of machine tools was not enough. Nowadays, as the surge in the number of machine tool equipments and increasingly serious environmental problems, in addition studies find that machining system showed a great potential for energy saving, thus problems of energy efficiency of machine tools have been received the widespread attention at home and abroad (Santos et al., 2011; Shrouf et al., 2014; Camposeco-Negrete et al., 2013; Wang et al., 2015). As a result, the energy efficiency of machine tools was determined as one of the research questions. The initial, the research questions for the systematic review were rather broad: "What is the energy efficiency?" or "How to evaluate the energy efficiency of machine tools, machining system or manufacturing?" or "How to improve the energy efficiency of machine tools?". The search term ("energy efficiency" and "machine tool*" or "machining") was used, where "machine tool*" included "machine tools". Because the machine tool was part of the manufacturing system, the term ("energy efficiency" and "manufactur*") was used, where "manufactur*" included "manufacturing" as well as "manufacture". Then "energy efficiency" was changed to "energy-efficient", "efficient", "energy consumption", and the above search

was repeated. Considering energy saving implied energy efficiency, the search term ("energy*saving" and "machine tool*" or "machining") was also used, where "energy*saving" included "energy-saving". Then "energy saving" was changed to "energy conservation" to repeat again.

After reading some literatures, it was found that energy consumption model of machine tool was the key to solve the problem of energy efficiency, and some studies used the specific energy consumption to evaluating energy efficiency (Wang et al., 2013; Bhushan, 2013; Peng and Xu, 2014; Duflou et al., 2012). Therefore, the energy consumption model of machine tools was determined as the other research question. The search term (("machine tool*" or "machining") and ("energy consumption model*")) was used. Then "energy consumption model*" was changed to "specific energy consumption" and "specific cutting energy". Because some studies would use words such as "cutting force", "power or electricity demand" to express the energy consumption, then these words were used to repeat the search. This step broadened the scope of knowledge about energy efficiency and energy consumption model of machine tools. Literature search was carried out in the Engineering Village, the Web of Science, Elsevier ScienceDirect and Springer Link. Because some researches could not be accessed, Google Scholar was also used to identify conference proceedings and unpublished studies. And some national statistics websites were used for industry statistics information.

2.2. Applying screening criteria and refining the current topics and issues

It is easy to bog into the mire of literature for lacking the screening criteria, although as widely as possible to collect literature data is the responsible attitude of the study. The first criterion applied was to target the mainstream. Literature in famous journals, classics, research reports of full-time department were reading carefully to catch the mainstream direction of this field, and their references needed much attention. The second was to narrow the search range after organizing the literature. In order to accumulate the knowledge, it is necessary to take good reading notes for the important literature. Then the literature researches were classified roughly according to the content through comparing them in common and differences. On the one hand it was found that improving energy efficiency mainly depended on the design and use. Beside the theory, some technologies were also need to evaluate the energy efficiency. On the other hand, it was found that energy consumption models were different in form and application characteristics. In order to further observes, problems were extracted, the search was narrowed and a new round of search was done. For example, the search term ("lightweiging design" and "machine tool*" and "energy efficiency"), ("energy consumption data" and "machine tool*" and "monitoring"), ("energy-saving operation" and "machine tool*"), ("scheduling" and "energy efficiency"), ("energy consumption simulation software") was used and so on.

2.3. Synthesized our findings

It was found that many universities and research institutions including the University of New South Wales, Brunswick Industrial University, University of Stuttgart, the University of California, Seoul national University, Chongqing University, etc. carried out a lot energy efficiency researches on different levels of machining system (such as single/multiple machine system, the workshop/factory, the enterprise/supply chain). However, machine tool, as the basis energy consumed device in manufacturing system, energy efficiency definition of it has not been very clear so far. Therefore,