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A method for predicting the energy consumption of the main driving system of a machine tool in a machining process

Fei Liu [a,*], Jun Xie [a], Shuang Liu [b]

[a] State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400030, China
[b] College of Mechanical and Power Engineering, Chongqing University of Science & Technology, Chongqing 401331, China

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ABSTRACT

The machining systems that mainly consist of machine tools are numerous and are used in a wide range of applications in industry, which usually exhibit very low energy efficiency; as a result, they have great potential for energy savings and environmental emissions reduction. To achieve such energy savings, the prediction of the energy consumption of the machining process has great significance. Also, it can provide a decision-support tool for the establishment of an energy consumption quota, the energy-saving optimization of cutting parameters, energy efficiency evaluation, and so on. Although existing researches on the energy consumption prediction of machine tools have been performed, a practical method is still lacking. Therefore, a new method for predicting the energy consumption of the main driving system of a machine tool in a machining process is proposed. First, a machining process is divided into three types of periods: start-up periods, idle periods and cutting periods. Second, the energy consumption prediction models for each type of period and the total prediction model for the machining process are established. Third, by measuring energy consumption data of the start-up and idle processes at discrete speeds, the functions of the fitted curves of the energy consumption of start-up periods and idle periods are obtained, which enables the energy consumption of the start-up period and the idle period at any different speed to be predicted. Fourth, using the cutting power calculated based on the machining parameters and the additional loss coefficients obtained based on the additional loss coefficients equation set, the energy consumption of the cutting periods can be predicted. Finally, the prediction error analysis model is constructed, and the reasons why the error is not big in the prediction are expounded. The results of a case study indicate that the method is practical and has good application prospect.

1. Introduction

The machining systems that mainly consist of machine tools are numerous and are used in a wide range in industries. The total amount of energy consumption by machining systems in the world is extremely high. For example, machining in China involves over 7 million machine tools, whose total power is greater than 70 million kilowatts; this is three times more than the installed capacity of the Three Gorges Dam, which is the largest hydroelectric power station of the world (Hu, 2012).

Hu (2012) also demonstrated that the average energy efficiency of machining process is less than 30%. For example, the energy efficiency of a case described by Gutowski et al. (2009) is only 14.8%. As a result, machining systems have great potential for energy savings. According to the analysis of the environmental emissions of machine tools provided by Gutowski (2009), the CO_2 emissions (calculated by the relevant data of the USA state power grid) corresponding to the annual energy consumption of a 22 kW machine tool (configured with auxiliary assembly) is equal to that of 61 SUV automobiles, which indicates that the potential of environmental emissions reduction of machining systems is also high.

Because the machining systems have great potential for both energy savings and environmental emissions reduction, the research on the energy consumption of machine tools and the machining process has grown rapidly in recent years, with a focus on the following aspects.

(1) Energy efficiency assessment: the US Department of Energy established an Industrial Assessment Center, which is aimed at promoting the energy efficiency of manufacturing processes and at assessing and researching the energy

* Corresponding author. Tel.: +86 23 65104172; fax: +86 23 65105098.
E-mail addresses: fliu@cqu.edu.cn, 13908304060@139.com (F. Liu).

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consumption and energy efficiency of industrial work site (Industrial Assessment Centers (IACS), 2009).

(2) The design of energy-efficient machine tools: the International Standardization Organization (ISO) is drafting the document entitled "Machine Tools — Environmental evaluation of machine tools —Part 1: Design methodology for energy-efficient machine tools" (ISO/TC 39/SC, 2012), which proposes a series of design methods and norms of energy-efficient machine tools.

(3) Promoting the energy efficiency of the machining process: for example, Mori et al. (2011) analyzed the factors that affect the energy consumption of machine tools and proposed methods to reduce the power consumption in machine tool operation. Kong et al. (2011) developed a web-based and application programming interface (API) based process analysis software tools to estimate the energy consumption of a CNC machine tool operation and to evaluate its environmental impact as a first step towards a sustainable manufacturing analysis. Pfefferkorn et al. (2009) examined the flow of energy in thermally assisted machining (TAM) in an attempt to determine the benefits of preheating and some efficiency metrics are suggested and used to study the data that have been collected to date. Liu et al. (2012) proposed a method to achieve the on-site processing energy efficiency. The method will provide support for optimizing the energy efficiency of machining processes.

The above-mentioned studies are significant, but the studies primarily refer to the actual machining process, and still lack of a method which can be used to predict the energy consumption and energy efficiency of machining process before the actual machining process. The method is significant, because it is capable of providing support to promote energy efficiency, to set the workpiece energy consumption quota, and to optimize the workpiece design and process planning for reducing energy consumption. These significant contributions of the method are based on our research on the energy consumption prediction method of machining processes in recent years.

Some related studies regarding the prediction of energy consumption of the machining process are described below.

Dietmair and Verl (2009) presented a modeling framework for tool machine energy consumption forecasting. A number of examples were presented on the application of the model for energy efficiency optimization.

Kara and Li (2011) presented an empirical approach to develop unit process energy consumption models for material removal processes. The methodology was tested and validated on eight different CNC turning and milling machines. The presented model predicted the energy consumption of machining processes with an accuracy of over 90%.

Diaz et al. (2011) indicated that the machining time dominates the energy demand for high tare machine tools and provided a method for characterizing the specific energy of a machine tool as a function of the process rate. The model allows a product designer to estimate the manufacturing energy consumption of the production parts without measuring the power demand directly at the machine tool during operation.

Diaz et al. (2012) reviewed the accuracy of a specific energy characterization model to predict the electrical energy consumed by a 3-axis milling machine tool during processing. The energy characterization model exhibited good accuracy for the part manufactured under varied material removal rate conditions and highlighted the potential for energy reduction using higher cutting speeds.

Lau et al. (2008) proposed an energy consumption change forecasting system using fuzzy logic. The approach can use to help the manufacturer forecast the energy consumption change in the plant when certain production input factors are varied.

In conclusion, some significant research studies on the energy consumption prediction of machine tools have been performed. However, to enable practical application of the prediction methods, the following problems must be solved. First, the existing research studies mainly refer to energy consumption of a specific machining process, a practical workpiece machining process consisting of the start-up periods, idle periods and cutting periods is not fully considered, which makes it difficult to predict the energy consumption of the entire machining process of a practical workpiece. Second, the present methods of modeling and simulation based on the historical production information and database of energy consumption face difficulties in predicting the energy consumption of new workpieces. Third, the additional load loss in the machining process is very complicated and cannot be neglected, which sometimes is more than 20% of the cutting energy, so the prediction of the additional load loss is a question.

The method proposed in this paper may solve all of the above problems.

The main driving system (MDS) of a machine tool consists of the spindle motor and the mechanical transmission system. The energy consumption of the MDS is the principal part of the energy consumption of a machine tool, and the energy consumption law of the MDS is the most complicated of all energy consumption. Therefore, this paper mainly focuses on the energy consumption prediction of the MDS.

2. The classification of the periods of the energy consumption in the machining processes of a workpiece

Consider the example of the machining process of the workpiece shown in Fig. 1 to analyze the characteristics of the energy consumption of the periods in the machining processes of a workpiece.

The machining process of the workpiece includes the initial cylindrical surface turning at low speed, followed by the head face turning at high speed, and finally cutting off the workpiece at low speed.

The power schematic diagram of the entire machining process is shown in Fig. 2, which reveals that the process of energy consumption consists of three classes of periods.

① start-up period (1)
② idle periods (2) (4) (6) (7) (9) (10) (12)
③ cutting periods (3) (5) (8) (11)

There are different energy consumption characteristics in the three classes of periods. The power process of start-up periods changes sharply and the law of energy consumption is complicated

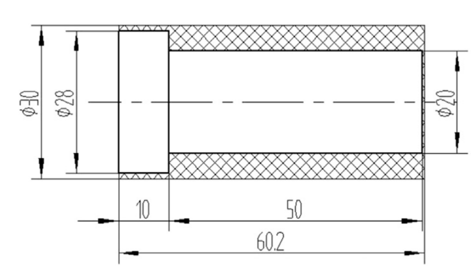

Fig. 1. The blank drawing of the workpiece.