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ORIGINAL ARTICLE

Energy efficiency techniques in machining process: a review

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Abstract The paper presents an overview of the state of the art in energy-efficient techniques in the domain of discrete part manufacturing, focusing on the techniques including energy assessment model for machining process and the energy efficiency analysis and evaluation for machine tools, important components, and machining systems. The main motivation is to review the existing works related to reduce energy consumption in machining processes, to discuss the challenges towards energy-efficient manufacturing, and identify the major barriers from both technologies and approaches.

Keywords Manufacturing · Energy efficiency · Energy monitoring · Machining process

1 Introduction

Nowadays, the manufacturing industry has been playing a vital role in the global economy. Unfortunately, manufacturing causes measurable impacts on the environment due to substantial amounts of energy consumption because it consumes both renewable and nonrenewable materials (e.g., metals, fossil oil-derived materials, and water), as well as significant amounts of energy, which results in substantial stress on the unsustainable use of natural resources. Also, manufacturing releases solid, liquid, and gaseous waste streams that can result in damage to the environment. Improving the energy efficiency in machining systems could yield significant reduction in the environmental impact of consumer products. Therefore, energy saving has become a worldwide hot issue in manufacturing sectors, and energy-efficient machining system will be very promising in metal-working industry in the future.

Currently, machining remains to be one of the most important techniques for manufacturing, and it has been widely used in manufacturing industries. It also represents a major demand for energy. Thus, reducing the energy consumption in machining process could significantly improve the environmental performance of manufacturing processes. Although the mechanics of machining has received considerable attention and development, the energy analysis for machining process is a relatively new issue. Energy efficiency issues have been given much more attentions in recent years [1, 2]

To keep energy efficiently used, energy information from machining process shall be obtained to assist process planning or lifecycle analysis. It is commonly believed that with wide application of machining systems, the manufacture of most steel products has become reliant more heavily on the energy-efficient techniques. The acceleration of industrialization has caused a rapid increase of demand for steel products placing heavy burdens on energy supply and the environment. To satisfy the ever increasing demand in the market and competition in the manufacturing industry, machinery product manufacturers are facing the challenges to improve the productivity with reduced energy consumption.

The motivations of this paper focuses on reviewing the existing techniques related to energy efficiency issues for machining processes, discussing the future challenges towards energy-efficient manufacturing, and identifying the major barriers from both approaches and technologies. In the rest of this paper, Section 2 introduces modeling techniques for the energy requirements in machining process. Energy monitoring techniques of machining systems are discussed in Section 3. The issue to energy efficiency-based reconfiguration for machining systems is described in Section 4, followed by challenges towards energy-efficient manufacturing is presented in Section 5. Section 6 draws the summary and final concluding remarks.

2 Energy modeling techniques for machining process

Efforts related to the model of energy consumption of machine tools have been studied by several authors [3–5]. According to the existing research results, the methodologies

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of energy-efficient modeling of machining systems can be divided into three different levels: machine tool level, component level, and system level.

2.1 Energy consumption model of machine tools

Since the energy consumption during the use phase of a machine tool leads to a significant environmental impact, a lot of efforts in both theoretical researches and practice have been performed towards this target in the machine tool industry. Past work has characterized machining energy usage solely based on the specific cutting energy. Although this approach is useful in understanding the fundamentals of chip formation [6], it excludes important elements of machine operation in characterizing the total energy consumption of a machine tool during machining.

Modern machine tools rely on electricity as power source. The major power consumption components of a machine tool are spindle and servo-driven motors. Their power usages are both highly dependent on cutting resistance. The overall energy consumption of a machine tool comes from the base load and from the dynamic forces. That is most of the power usages are dependent on its cutting resistance during machining. Other energy demands come from a hydraulic unit, cutting oil pumps, cooling devices, and peripheral devices such as a controller unit. The multicomponent energy consumption makes the estimation of energy consumption of a machine tool very complex, and the energy loss of each component is difficult to be characterized.

The issue of energy efficiency of machine tools is first presented by Filippi and Ippolito in [3]. In their study, the operating data, involved in various operations, were collected from ten different numerically controlled (NC) machine tools, and their analysis results showed that the energy required of machine tools during machining is significantly greater than the theoretical energy required in chip formation. In other words, the installed power was never fully exploited, and the mean power was quite less than half the power available. The reason is that the productive time accounts for less than 60 % of the total time spent on the automatic machine tool during machining.

Draganescu et al. constructed an experimental data-based statistic model by using response surface methodology to estimate machine-tool efficiency and energy consumption in cutting process [7]. In this model, the energy consumption in machining process was expressed as a function of cutting power, machine-tool efficiency, and the rate of material removal. Dahmus and Gutowski proposed an experimental scheme to monitor the energy consumption of machine tools [8]. They assumed that the overall energy consumption of a machine relied on three main activities: constant start-up operations, run-time operations, and cutting operations. It was concluded that the energy consumption in cutting operation takes up very little percentages of the overall energy consumption of the entire machine tool, which relies on the machine's automation level.

Noting that differences of the power demand of a machine in the periods between operating with load and load-free operating, Gutowski et al. [9] proposed a mathematical model for the calculation of energy consumption of machine tools.

According to the mathematical model introduced by Gutowski et al., the electrical power requirement P during machining is estimated by

$$P = P_0 + k \cdot \nu \tag{1}$$

Where P is the power consumption of the machine during machining, P_0 is the power required of the machine during operating with free-load, which usually is called as "base power demand," k is a coefficient that reflects the energy amount required per cubic meters (Ws/mm^3) for cutting operation, and ν is the cutting rate (MRR) in (mm^3/s).

As shown in Eq. (1), the overall power consumption during machining is dependent on not only the base power demand but also the power required for cutting operation. Thus, the total power required during machining can be divided into two parts, namely the idle power (P_0) and the cutting power ($k \cdot \nu$). The idle power is the base power demand or power required for non-major components that support the machine tools, such as power to start up the computer, the hydraulic unit, cutting oil pumps, coolant pump, and peripheral devices like the controller unit, etc.

Furthermore, the power consumption in machining process E can be determined by converting the power Eq. (1) into the power Eq. (2) as follows:

$$E = (P_0 + k \cdot \nu) \cdot \Delta t \tag{2}$$

Where Δt is the time spent on machining operation in seconds. From Eq. (2), it can be noted that P_0 dominates the direct power consumption in machining process.

Following on the work of Gutowski et al. [9], an evaluation approach from electrical energy use was proposed by explicit modeling of the machine tool states, workpiece machinability, and the impact of cutting variables [10]. This model was used to track the visibility and process dependence of energy so that the energy consumed by machine modules, auxiliary units, and machine codes in machining process could be obtained. According to their conclusion, actual cutting energy only accounts for 15–25 % of the total energy consumption on the sophisticated computer NC machine tools. That is, the existing theoretical approaches would not accommodate to calculate the energy requirements of modern NC machine tools. The recent studies show that most of energy efficiency techniques for machining process focus on online energy monitoring by directly measuring cutting power with torque sensors or dynamometers or by monitoring power consumption for system components, such as the spindle, drive motors, etc. [8–10].

Assessing the energy efficiency of a machine tool would be very difficult if the energy required on all its support components were taken into consideration. These components include hydraulic unit, cutting oil pumps, cooling devices, and peripheral devices such as a controller unit, etc., and their energy-efficient modeling techniques will be discussed in the following section.

2.2 Energy required model for peripheral components or subsystems

The total energy consumption of a machine tool could be divided into two parts: the first part is the energy consumed by its major components, i.e., spindle rotation and servo-driven axis motion; the second is the energy consumed by its support components in operating process. Practically, on sophisticated NC machines, the support components consume more than 30 % percentages of total energy consumption.

Therefore, to reduce the energy consumption of a machine, the energy consumption of its support components, especially those deriving from base load, idle periods and periphery maintenance (control and lubrication), and peripheral systems (e.g., room lighting and air conditioning) must be first taken into consideration. For example, the distribution of energy consumption of the support components on a machining center in three-shift operation state is given in Fig. 1. It can be seen that the coolant supply to the machine tool is one of the components with the highest energy consumption during machining. In there, the energy demand is between 20 and 33 % depending on the machining method [11].

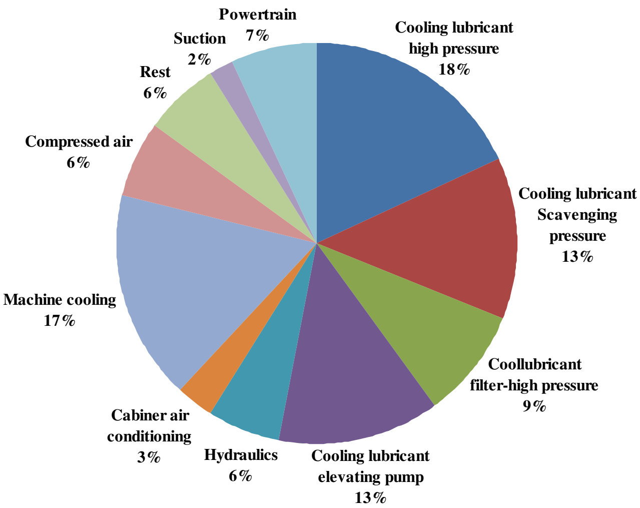

Fig. 1 Annual energy consumption of support components in three-shift operation

Since there are many support components or peripheral devices related to the energy requirement of a machine tool, it leads to a complex procedure required for the construction of the energy consumption model. At present, fewer efforts were made to assess the energy efficiency of machine tools by theoretical model. Thus, the actual energy consumed by machine tools during machining is significantly greater than the theoretical energy required in chip formation.

To determine the energy consumption in machining process, the additional energy consumed by the peripheral components like coolant pumps, various control units, computers, etc. should be considered. Therefore, the overall energy consumption in machining process could be defined as

$$E_{\text{total}} = E_{\text{process}} + E_{\text{peripherals}} \tag{3}$$

Where E_{process} is the energy required for the physics process, and $E_{\text{peripherals}}$ is an additional energy consumed by other support components (e.g., computer, coolant pump, etc.).

The process energy could be estimated for a specific cutting process, which is highly dependent on the mechanics of the process, e.g., the geometry shape and material of the cutters, the size and material of the workpiece, the operating environment of the machine tool, etc. That is, E_{process} depends on the process parameters.

The additional energy consumed by peripheral components $E_{\text{peripherals}}$ could be further divided into two parts. One part is the energy consumption due to the machine's load, i.e., the energy consumption of the machine tool during operating with load. Another part, called as the elementary energy, is the necessary energy consumed regardless whether or not the machine is machining. It could be formulated as

$$E_{\text{peripherals}} = E_{\text{elementary}} + E_{\text{load}} \tag{4}$$

The elementary energy $E_{\text{elementary}}$ is dependent on the specific type machine tool used; the energy E_{load} is dependent on the machining operation and varies with cutting resistance. In order to determine the elementary energy required of a specific type machine tool in a given operating condition, a "standardized start-up procedure" is usually defined to calculate the energy required during idle mode, which is independent on the size of the machine and actual material processing. For example, the elementary energy of a grinding machine consists of the coolant pump energy and the standby energy (i.e., the energy consumed from the various electronics, the control unit, etc.). In this case, E_{load} relies on part characteristics (e.g., its weight, material, and size), cutting parameters, and the properties of cutters.

To estimate energy consumption of support components in a machining system, a discrete event modeling approach was introduced to model energy usage [12]. More components are being considered by this approach, so a more complete energy profile can be obtained.

Other studies provided in literature focused on seeking different monitoring approaches to determine the energy consumption caused by machine tools and the various peripheral devices. Oda et al. reviewed advances in energy-efficient techniques for machining process [13] and described a study on reducing the energy consumption in manufacturing lines by machining process improvement. Note that coolant-related equipment consumed approximately 54 % of the overall energy; their study focused on the coolant consumption of pumps.

2.3 Energy consumption model for machining system

The goal to reduce the amount of energy required to machine process is to achieve optimum machining condition based on minimum energy consideration. Most studies in literature focus on modeling, measuring, and analyzing energy efficiency of machining systems. Mori et al. presented an energy efficiency solution for machining process by changing cutting conditions, e.g., reducing cycle time [14]. In order to reduce cycle time in their scheme, eight three-axis machining centers are replaced with a five-axis control vertical machining center. Fysikopoulos et al. assessed and compared the amount of energy required of a laser drilling in two subsystems [15]. The first one is “always on,” and the second is “periodically on.” They reported that a common characteristic of almost all machining processes (both conventional and non-conventional ones) is that even when the machine is idle, it is consuming more than 50 % of its maximum power. It is obvious that there is a lot of potential in energy reductions through better design of machine tools (e.g., sharing of common peripherals between different machine tools in a machining system). Giuseppe et al. analyzed the energy varying process in sheet metal forming process based on numerical and experimental results [16] in which two types of aluminum alloys with different sheet thickness values were selected, and the data were obtained by numerically analyzing the sheet metal forming process. To optimize the machining system, two final component geometries were compared to track the varying in energy. Wang et al. proposed an integrated method to evaluate energy efficiency in machining workshop [17]. In their case, the energy profile of machining workshop is respectively analyzed from the machine tool layer, manufacturing unit layer, task layer, and workshop layer so as to reveal the energy performance inside the workshop. Several evaluation indexes were introduced to model and identify the energy flow in each layer, and the evaluation index for each layer is different of which the indexes of machine tool layer focus on the energy breakdown of machine tools, and the indexes of manufacturing unit layer and task layer focus on the energy use of transportation facilities. The energy assessing model of the machining system was defined according to its effective output. The total energy consumption in the machining process was calculated as the sum of instantaneous energy during operating period, i.e., the integral of power function of the time variable. Most of energy-efficient models for machining system are derived from the chip formation theory by analyzing different operation processes or comparing the energy consumptions in different manufacturing activities, etc. According to the chip formation theory, Toenissen analyzed the energy consumptions of a precision machine tool in various types of manufacturing activities, and he carried out empirical analysis for its support components to estimate their energy loss [18]. To control the energy consumption in the decision-making stage of process planning, Srinivasan and Sheng presented a manufacturing feature-based process planning approach [19] in which the traditional process planning procedure is divided into two stages: the macro-planning stage and the micro-planning stage. In micro-planning stage, the operation process, parameters, tooling, and cutting fluids were selected for the individual manufacturing features so that the energy consumption in this stage could be characterized solely by the chip removal energy, while in the macro-planning stage, the interactions between features are examined. In addition, a predictive process model was introduced to obtain process level inventory of process energy, machining time, mass of waste streams (primary scrap and secondary catalysts), and quality parameters in micro-planning stage.

To analyze the potential of a machining system in the aspect of energy-efficient improvement, two types of manufacturing equipments are studied by Devoldere et al. [20]. To estimate the energy required of manufacturing activities, they divided the total time spent on machining process into productive time and nonproductive time. The relation between energy consumptions and loads in a machining system was studied to improve the equipments for the different loads.

3 Energy monitoring techniques for machining process

As mentioned before, to reduce energy consumption of machine tools or machining systems, energy monitor approach needs to be developed to characterize the energy consumed. Although the past studies have quantized the energy consumption of machine tools according to chip formation theory, however, the support components with high energy consumptions on the machining system may be excluded. To accurately determine the energy consumption in machining process, it is necessary to measure the energy consumptions of all components, which include robots, machine tools, and their peripheral components like computers, automatic tool changer, coolant pumps, various control units, etc.

Since there are a number of data sources in a complex machining system, the monitoring of energy consumption in such a system is a challenging issue. A very common approach always is to monitor energy consumed by measuring cutting power with torque sensors or dynamometers. A few studies focused on measuring the power consumption of machine tools as a basis for identifying optimization potentials. Vijayaraghavan and Dornfeld proposed an automatic energy monitoring approach for machine tools by using event stream processing techniques [21]. Pang et al. developed a real-time energy data processing algorithm to identify different operational states to reduce the number of required sensors [22]. The finite-state machines are used to model the operation process, and a framework was developed to classify real-time energy data for energy audit and machine scheduling. The classification procedure is performed by two steps. First, the measured data is processed to remove noise and preserve important features. Then, energy consumption pattern is generated by using the clustering algorithm. Noting that there are variable and constant energy required from various use phases of machinery equipments, Oliver et al. introduced an energy monitoring approach for system components by alternative machining strategies [23] in which the machining operations were divided into two kinds of states: steady state and transient state, and the approach had been successfully used to monitor the energy consumptions of spindle and feed axes. These energy data were estimated from the cutter location data and cutting parameter values extracted from APT files. Hu et al. proposed an online energy monitoring approach for machine tools [24]. The overall energy consumption of a machine tool was divided into constant energy consumption and variable energy consumption. The constant energy consumption of a specific machine tool is obtained in advance and stored in a database. Actually, the constant energy consumption of the machine tool is the base power demand introduced by Gutowski et al. in [9] obtained in the load-free operating state, while the variable energy consumption is derived from cutting power, which is estimated online according to power balance equation and additional load loss function. In addition, an additional load loss function could be identified offline by using input power and cutting power of the machine-tool spindle. Thomas et al. proposed a systematic method for energy-efficient evaluation of machine tools [4]. Several standardized workpieces were used and tested on various type machine tools. A three-step methodology was presented to measure the main groups of power demand by potential users according to the desired detail levels. First, the highly dominant idle power is identified for sole customers of machine tools, and an optimization strategy is evaluated to switch the machine in idle mode. Then, the evaluation is performed to check the effectiveness of specific components like drives, spindles, and coolant pumps. Finally, improvement strategy is given for the machine tool manufacturer to address questioning the overall machine tool concept. After that, the required data can be obtained for energy-efficient evaluation of the machine tool.

In summary, one of promising energy monitoring techniques is the automated monitoring approach. It can significantly decrease the complexity of working with large systems. As contrast, several manual monitoring approaches are available for energy measurement on the equipments with power meters. Since manual monitoring approaches are cumbersome even for simple systems, thus, it is impossible for them to be used in more complex systems.

Nowadays, various digital sampling devices have been widely used in industry for energy monitoring, which can help attaching contextual process-related information to raw energy data. Thus, it is very important to analyze these energy data for making a decision to decrease energy consumption. Also, in order to save energy, reduce cost, and increase reliability, the smart grid technologies are very useful to analyze energy generation, transmission, and delivery. Automated monitoring systems allow better communication of demand data to the grid, enabling smart grid technologies in manufacturing systems.

4 Energy-reducing strategies for machining process

In the existing works, studies of energy efficiency in machining process have been carried out from many aspects. According to the research levels and techniques used in energy-reducing strategies, these efforts can be classified into three groups: approaches by improving functions of machine tools or selecting alterative machine tools for specific tasks; approaches by optimizing machining conditions like cutting parameters, cutter's material, etc..; and approaches by reconfiguring machining systems.

4.1 Improving functions of machine tools for energy efficiency

Since machining processes cause measurable impacts on environment due to substantial amounts of energy consumption, reducing energy consumption is a very critical issue for machining process. To achieve this, the machine tool manufacturers could contribute to this issue by optimizing the functions of machines. For example, micro-factory can be constructed by using smaller machine tools, which reduce not only the space occupied by the machine but also energy consumed in the cutting process [25, 26]. In fact, a conventional milling machine consumes 800 times more energy as much as a micro-milling machine. Oda et al. reported a power saving approach for five-axis machining center by the inclined cutting [10], and the optimum inclined angle for cutting with minimal energy consumption was found out by experiments. In addition, several important conclusions also were obtained by analyzing experimental results. For example, when an inclined surface is being machined, the power consumption in machining process varies with different inclined angles used, and the optimum inclined angle is 15° for ball end milling with lowest power consumption per material removal unit and longest tool life.

Furthermore, reducing energy consumption could be achieved by reconfiguring machine tools, and many efforts have been performed for reconfigurable machine tools [27–29]. The formulation of the reconfigurable machine tool paradigm is based on modularity of the structure, software, and hardware which make it easy to adjust for different demands. Generally, reconfigurable machine tools possess six characteristics: modularity, integrability, customized flexibility, scalability, convertibility, and diagnosability. The modularity of the structure, software, and hardware components allows quickly adjusting the capacity and functionality of the machine to meet different demands.

Since a modular machine tool possesses loose components which can be mixed and matched to function as desired, its assembly is easily reconfigurable to perform single or multiple machining operations on a workpiece [30]. A modular system always includes several different spindles, such as a universal standard spindle, a high-performance spindle, a precision spindle, and a spindle for the multi-use technology with extended axis accuracy. Depending on the application, there are several tool revolver positions and numerous automation options available. Selectable components to achieve energy efficiency include regenerative drives, energy-efficient transformers, power safe functions that switch off auxiliary units in production breaks, aggregate cooling on central circulation, and a frequency-controlled high-pressure pump. For instance, on typical multi-spindle machines, spindles and their drive motors are both located within the machine's spindle drum, thus creating the need to cool the drum and necessitating the consumption of more energy. Coolant supply to machine tools is one of the components with the highest energy consumption during machining. In general, the energy consumption is between 20 and 33 %, depending on the machining method.

Coolant supply to machine tools is one of the components with the highest energy consumption during machining. As shown in Fig. 2, there are a variety of ways to lower energy required for coolant supply to machine tools, one of the primary ways to save energy for coolant supply is to decrease the cooling lubricant requirement while maintaining a maximum cooling and lubricating effect. These approaches include minimum quantity lubrication, direct oil drop supply system, increase of life cycle of lubricants, and so on. Another one is to prevent the energy loss of coolant supply system by improving flow ways of lubricants or the properties of cooling lubricants, such as optimized pipe dimension for coolant lubricant supply, high-pressure jet-assisted machining, vegetable oils as lubricants, cooling lubricants without mineral oil, etc. The existing technologies for energy-efficient cooling lubricant supply are outlined as follows [11].

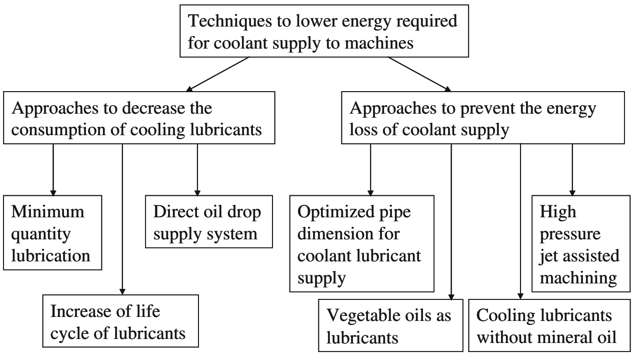

Fig. 2 Approaches to lower energy required for coolant supply to machine tools

Minimum quantity lubrication (MQL): MQL uses a through-tool oil mist tailored to provide just the right volume for ideal lubricity at the interface of the tool and work surface. Since no transferring, recycling, and pressurizing coolants and their accompanying costs for coolant supply, filtration and mist collection equipment are required, and the use and maintenance of lubricant circulation systems consume high amounts of material and energy. Therefore, lower energy consumption could be achieved in machining process.

Optimized pipe dimension for coolant lubricant supply: The pumping medium is responsible for pressure loss through development of friction on pipe walls. The pressure loss from the pipe diameter should be compensated for by the pump. Enlarging the pipe diameter could decrease the pressure loss and the energy required by the pump.

High-pressure jet-assisted machining: High-pressure jet-assisted machining uses the mechanical and thermal properties of a high-pressure jet of water or emulsion directed into the cutting zone. In contrast to conventional machining, it delivers small flow rates of common lubricants under high pressure (up to 300 MPa) to penetrate closer to the shear zone at which the highest temperatures occur. Thus, the consumption of cutting fluids is lowered, and machining performance is increased.

Direct oil drop supply system: The system can supply a very small oil drop directly to the cutting edge without making oil mist. Comparing with the conventional minimum quantity lubrication, the occurrence of oil mist is abandoned and the consumption of lubricants is reduced. Additionally, direct oil drop supply system shows almost same machining performance as compared to MQL technique.

Vegetable oils as lubricants: The beneficial aspects of vegetable oil as lubricants are its biodegradability and non-toxicity, which are not exhibited by conventional mineral oils.

Furthermore, under the reformulation of additives, chemical and genetic modification, vegetable oils (e.g., canola oil, coconut oil, olive oil, palm oil, soybean oil, etc.) may substantially substitute petroleum-based lubrication fluids in the long run.

Cooling lubricants without mineral oil: Concepts to replace mineral oils in cooling lubricants use biopolymer solutions, which offer similar properties to those of conventional cooling lubricants. These sustainable materials save up to 90 % of energy use for production compared to oil-based lubricants. Efficient usage of cooling lubricants actually results in cost savings throughout the lifetime of the machine tool.

Increase of life cycle of lubricants: The life cycle of lubricant is improved through the independent lubricant structures, and the energy consumption is reduced. Use of closed loop recovery of used cooling lubricants could reduce the consumption of cooling lubricant. There are numerous industrial solutions available, which are largely related to peripheral filters and units, or centralizing the cooling lubricants supply system.

4.2 Optimizing machining conditions for energy efficiency

Several methods to improve machining conditions for reducing energy consumption were increasingly developed and applied in recent years [31–34]. To assess the energy consumption during machining, one must understand the different factors that affect energy consumed in the process, of which the cutting parameters are most important factors. Generally, energy consumption would be reduced if suitable cutting parameters were selected during machining.

Chen et al. developed a heuristic algorithm to determine optimal cutting parameters with specified constraints [32], which include the maximum tangential force to tool breakage, the maximum feed rate, the maximum depth of cut, etc. Following the work of Chen et al., Hinduja and Sandiford described a procedure to determine the optimum pair of tools that can machine a milling feature [33] in which determination of optimal cutting parameters is based on the minimum cost criterion. Lee and Tarng [34] proposed a machining model for optimization of multistage turning operations based on polynomial networks. First, they constructed a polynomial network to determine the optimal cutting parameters. Then, the relationships between cutting parameters and cutting performance like surface roughness, cutting force, and tool life are determined by using the polynomial network. Finally, optimal cutting parameters are obtained based on maximum production rate or minimum production cost. By establishing a tool life equation from experimental data and the adhesion wear model, Choudhury and Appa proposed an approach for optimization of turning cutting parameters to improve the cutting tool life [35] in which the optimal cutting tool life is obtained by using a constant metal removal rate throughout the cutting process, and the experimental results show that the cutting tool life is increased up to 30 % by using the optimal cutting parameters. Unfortunately, the energy efficiency in machining process never is considered in these studies above.

Considering that the machining time is an important variable to energy-efficient assessment, the energy efficiency of a machining system could be evaluated by using machining time as evaluation criterion. Nafis et al. [36] developed a genetic algorithm for optimization of end milling cutting parameters in which the shortest machining time is defined as a major evaluation criterion for optimization of cutting parameters. Other constraints include maximum allowable cutting force, machine power, available rotational speed, and required surface finish.

Mesquita et al. [37] proposed an approach for optimization of turning cutting parameters coupled with computer-aided process planning. Both minimum production cost and machining time for machining are defined as constraints to determine optimal cutting parameters.

Rajemi et al. proposed a minimum energy criterion for optimization of turning cutting parameters [38], and several important conclusions were obtained as following: (1) different types of workpiece requires diverse energy consumptions during machining, and the energy footprint is dependent on the properties of the workpiece materials. For example, tougher material-like titanium alloy requires higher energy in machining process compared with other materials like aluminum and steel; (2) more than 50 % of the overall energy was consumed in non-cutting operations in terms of distribution of energy. One of the solutions to reduce energy consumption in non-cutting operation is using less power spindles. Alternatively, the time spent on non-cutting operation could be minimized by optimizing process planning to reduce the energy waste. Since non-cutting operations consumed most of the energy, keeping machines powered up but not cutting would contribute to energy waste; (3) the energy consumed in removing the same volume of workpiece material could be reduced by using higher cutting speed. Thus, high speed machining could be a strategy to reduce total energy consumption during machining. Therefore, it could be concluded that selecting suitable machines and machining conditions could reduce energy usage in machining process.

4.3 Reconfiguration of machining systems for energy efficiency

In the last years, the improvement of functionality and performance of machining systems has been the primary objective with a secondary concern on energy consumption. However, as energy costs have been rising in recent years, energy efficiency has become an important criterion to design for. Reconfigurations of machine tools or machining systems are based on modular hardware and software. They could quickly change in capacity or functionality to accommodate and make a rapid response for more frequent and unpredictable market changes.

Nowadays, many researchers pay attention to the issue of reconfiguration of machining systems [39–41], but less effort is made to take into energy efficiency consideration. Techniques to reconfigure machine tools and machining system can be traced to 1999.

In a reconfigurable machining system, of which many components are typically modular (e.g., machines, axes of motion, controls, and tooling) [27], and the machines can be reconfigured to meet various requirements. The flexibility of the reconfigurable machining system allows manufactures to change the functionality and kinematics of the equipment to meet new requirements and amendments at any time.

Reconfigurable machine architectures are an emerging technology that offers promising advantages, such as increased flexibility and reduced time-to-market for machine tool applications. However, to meet the strong energy budget constraints, the existing approaches of reconfigurable machine tools need to be improved to take into energy efficiency consideration. For this purpose, first, one needs to identify not only the location of energy loss on the machine tool but also which components, parameter settings, or specific topologies are responsible for the energy loss. Then, he or she should seek improved approaches to reduce the identified energy loss and optimize the machine design towards energy efficiency. These approaches include evaluating the overall effect after replacing a component by a more efficient one, evaluating different topologies (with or without energy storing elements, machines with central, or distributed actuation) and optimizing cutting parameters with respect to energy efficiency.

The objective of reconfiguring machine tools or machining systems is not to develop a new, more energy-efficient components, although the evaluation results will lead towards new insights for optimizing the design of new components with respect to the energy efficiency attribute. For instance, replacement by more energy-efficient components if the energy losses are concentrated in one component; use of a more energy-efficient concept if multiple components are to be changed and a new trade-off is to be made. The reconfigurable machining system can easily change configuration by using reconfigurable machine tools, and energy efficiency assessment of the reconfigurable machine tools s are the same with that of the traditional ones. Therefore, it is very prospective to study energy efficiency techniques for reconfigurable machining system.

5 Challenges towards energy-efficient manufacturing

Productivity or actual throughput is frequently advocated to evaluate energy consumption per workpiece output in manufacturing industries. However, since there are a vast number of energy consumption equipments or devices in modern machining system, the assessment of energy consumption in such a machining system still is a challenging issue. The issues toward energy efficiency assessment in machining process are outlined as follows:

1. Existing works for energy efficiency assessment focused on simple machining process, such turning, milling, and grinding. It is necessary to study energy efficiency for various types of machine tools, major components, and reconfigurable components so that energy efficiency techniques could be applied on advanced machining systems like flexible manufacturing system, reconfigurable machining systems, etc.
2. Study energy consumption map for various machining processes, and it could be used as a standard for the improvements of mechanical configuration and structure of machine tools to reduce the non-cutting energy in machining process. Construct different energy budgets that could be used to improve the existing energy assessment model of machine tools.
3. Construct energy assessment models for various machining processes, and they will be helpful in providing support for machining scheme selection, energy saving discovery, and energy quota allocation in plant.
4. Studies of reconfigurable machining systems started from around 10 years ago, and it will be one of the important issues in manufacturing field in the next decade. Its main task has been seeking a rapid and cost-effective method to deal with the short life cycle of the products and change in customer demand of quantity and type of the product. However, the issues of energy efficiency have rarely been given much attention. To make this new design methodology take into energy efficiency consideration, techniques to assess the energy efficiencies for important components, machine tools, and machining systems should be widely studied. The issues include studies of energy efficiency for different-type reconfigurable components, reconfigurable machine tools, and reconfiguration of machining systems.
5. Study alternative approach to decrease the time required in machining process for improving energy efficiency, and it can be achieved by shortening process chain. Technologically, energy-efficient high speed cutting performance has been realized, although high-performance machining leads to higher abrasive wear of deployed tools, which should be included into the ecological assessment and evaluation of high speed cutting.

In short, energy efficiency should be added as an extend criteria into the existing optimal techniques in machining systems, and energy assessment could be performed by using resource models. In addition, the synergy between minimum cost and minimum energy solutions could be obtained in manufacturing industries.

6 Conclusion

This paper presented an overview of current advances in energy efficiency techniques for machining systems. The literature review indicated that despite decades of research on optimization of machining system in productivity and cost, little efforts have been performed by taking into consideration energy efficiency. However, energy efficiency issues in manufacturing systems have been given much more attention in recent years.

Techniques for energy efficiency modeling, evaluating, and analyzing for machine tools and manufacturing systems have been reported. Energy savings can be achieved by improvement of machining systems and use of online energy monitoring in machining processes. Techniques for optimizing machining processes focused on process level activities and their improvements to reduce energy waste, which include optimizing material use and cutting parameters, reducing cutting fluid consumption and cutting energy.

Actually, enough work has not been performed on energy-efficient techniques from process level activity. However, rising energy costs has made the energy efficiency a key topic—particularly in the manufacturing industry. It is very important to rapidly design, construct, or reconfigure a manufacturing system with energy and cost savings for modern manufacturing companies to keep the competitive ability in increasing global competition. It is very necessary to develop energy-efficient techniques to reduce energy waste by predicting the behavior and performance of machining systems, optimizing mechanical configurations and structure in design, and selecting optimal cutting parameters.

Finally, in this review, the shortcomings or limitedness in the existing approaches were analyzed to identify the major barriers from technology. Moreover, the significant improvement potential towards energy efficiency in machining process was presented, and some challenges are identified and summarized in this area.

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