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Energy consumption characteristics in finish hard milling

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ABSTRACT

Energy consumption becomes a serious concern for manufacturing industry because it produces a huge amount of greenhouse gas emissions. Previous research has focused on the relationship between energy consumption and process conditions at the machine tool and spindle levels. However, little has been done to investigate the energy consumption in actual material removal at the process level. In this study, power profile and energy consumption at the process level as well as machine tool and spindle levels were characterized in hard milling. A new concept at the process level, net cutting specific energy, has been defined to investigate the energy consumed by the actual material removal. The relationship between cutting conditions and energy consumption at each level has been established. The results indicate that net cutting specific energy cannot be predicted by the traditional model. A new power regression model has been developed to predict net cutting specific energy at the process level.

1. Energy consumption and classification in machining

Energy consumption becomes a serious concern for manufacturing companies because of the considerable costs and environmental impact. In fact, more than 20% of the operating cost throughout the entire life of a machine tool is from electrical energy consumption [1]. In US, nearly 80% of the energy used to operate machine tools comes from electricity produced from fossil fuels, which generates a considerable amount of greenhouse gas such as CO_2 [2].

Energy consumption of a machine tool can be evaluated at different levels: machine, spindle, and process levels, see Fig. 1. At the machine level, the energy consumed by the whole machine tool (e.g. control systems, cooling and lubrications units, drive systems, spindle motor, manufacturing process, etc.) is considered. Understanding the relationship between energy consumption and machining conditions at this level is practical for improving the overall energy efficiency of machine tools. The problem of analyzing energy consumption at this level is that the consumed energy is machine tool dependent. Comparing different manufacturing processes or even same process that uses different machine tools is not practical.

At the spindle level, the energy consumed by the spindle motor is considered. The electricity consumed by the spindle motor rotates the cutting tool in milling. It has been reported that the spindle can consume more than 15% of the total energy [3]. Energy consumption at this level is useful in analyzing spindle motor efficiency. However, the problem is analogous to that of the machine. The spindle energy is dependent on a specific motor which varies with machines.

At the process level, only the energy consumed by the actual material removal is included and is independent of the machine tool. Although energy consumption at process level is usually less than 15% of the machine energy consumption in machining a part, it does not mean the energy consumption at tool tip is not important for the environment impact since the supportive energy consumption at the machining level represents a large fraction of the huge energy consumption. On the other hand, energy consumption at the process level governs chip formation and surface generation. Therefore, energy consumption at the process level is more related to cutting mechanics than the energy consumption at the machine or spindle level. Several recent studies [4,5] have suggested that energy consumption at the process level can be used to predict surface integrity of a machined part. Sealy et al. [4] investigated the relationship between energy consumption at process level and surface integrity. It was found that net cutting specific energy (specific energy at process level) can be an effective process signature for surface integrity. The terminology of "specific cutting energy" in the literature is ambiguous as whether to use the consumed energy at process (net cutting) or machine level has never clearly defined. In this study, the new terminology "net cutting specific energy" is proposed and clearly defined. A process window

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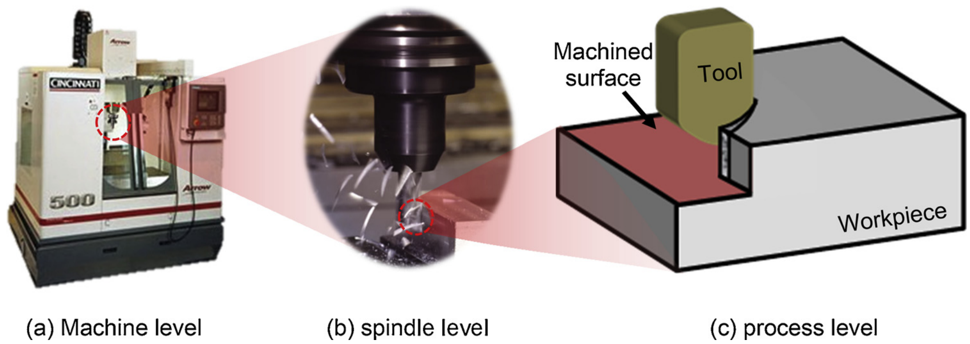

Fig. 1. Energy consumption classification.

exists to optimize energy consumption without sacrificing surface integrity. Buchkremer and Klocke [5] studied the material modification during machining from the energy perspective. The results indicated that surface integrity could be predicted with the mechanical and thermal energy input into the machined surface during a cutting process. Therefore, a thorough study of energy consumption at the process level is critical to understand and optimize a cutting process.

Hard milling as a finish machining process is widely used in manufacturing precision tools such as dies/molds. A study on the energy consumption of hard milling is of great interest to precision machining industry. Compared to grinding, hard milling can be conducted without cutting fluids, thus generates less wastes and better sustainability [6]. Relative to conventional cutting, material removal rate (*MRR*) in hard milling is relatively small. In this study, dry milling of hardened tool steel AISI H13 (hard milling) was conducted. The objectives of this paper are to: (1) characterize the characteristics of power consumption profiles in hard milling, (2) evaluate the energy consumption at the machine tool, spindle, and process levels, and (3) establish a relationship between energy consumption and process conditions.

2. Analysis of prior work on energy consumption in machining

The bulk research on energy consumption is limited to the machine level or the spindle level. A unanimous classification of energy consumption has not been defined yet at the early research stage in this area. At the machine level, besides the energy used to actual material removal, additional energy must be provided to power auxiliary equipment such as workpiece handling system, tool changers, control system, and machine lubrication system. It is critical to characterize the energy consumption for each subsystem of a machine tool. Dahmus and Gutowski categorized the energy consumption of a machine tool into three main activities namely "Constant start-up operations", "Run-time operations" and "Material removal operations" [2]. Mori et al. conducted an energy efficiency study for machine tools in end milling and drilling. The machine power consumption was decomposed into constant power consumption in non-cutting state, spindle and servo motor power consumption, power consumption to position workpiece, and power consumption to accelerate/decelerate spindle [7]. Quintana et al. studied the power consumption in a ball end milling process. The power distribution in the rapid traverse stage and effective machining stage were measured and compared. It showed that spindle power was the main factor to influence the machine power consumption [8]. Avram et al. studied the machine energy consumption of a machine tool system in milling. Machine energy consumption was composed of spindle acceleration energy, tool positioning energy, material cutting energy, spindle steady state energy, and spindle deceleration energy [9]. Behrendt et al. developed a systematic method to assess energy use in machining process and validated it in nine machine centers. The machine power consumption included the standby power, component power and machining power [10]. Rajemi et al. investigated the energy footprint in turning. The effects of cutting tool utilization and its embodied energy were considered in selecting optimum cutting conditions to minimize energy footprint [11]. Shao et al. developed a cutting power model associated with process parameters and average flank wear in face milling. Simulation and experiment results showed that the power model could predict the mean cutting power [12].

A machining process involves different states, i.e. idle, air cutting, and cutting states. The power consumption at these states is different. Balogun et al. developed a mathematical model for machine tool electrical energy consumption in milling, where a transitional state between the 'Basic State' and 'Cutting State' was defined as 'Ready State' [13]. Hu et al. developed an on-line energy monitoring system in turning. The machine energy including the constant energy and variable energy in turning was assessed by the on-line energy monitoring system [14].

In recent years, the low energy efficiency and the associated environmental impacts have received increasing attention [15]. The development of analytical models of specific energy is critical for reducing energy consumption in manufacturing. Based on direct energy required at the machine level, a model developed by Gutowski et al. decomposes the energy use into idle and cutting states [16]. The model by Kara and Li characterizes the relationship between energy consumption at the machine level with *MRR* [17]. This model accounts for the machine energy consumption in actual cutting, air cutting, and auxiliary motors via two constants. At the spindle level, the measured energy consumption was used in the model by Diaz et al. to establish the relationship between specific energy and *MRR* [18]. Schlosser et al. proposed a fundamentally different model format based on the unit specific cutting force and an equalizing correction factor [19]. However, the specific cutting energy for this model is also at the spindle level. The model incorporating energy efficiency of the motor by Draganescu et al. is also at the spindle level [20]. Campatelli et al developed a machine tool energy consumption model with special focus on the acceleration/deceleration of axes [21]. The workpiece orientation and cutting toolpath could be optimized to reduce energy consumption. The developed specific energy models could be used for process planning. For example, since specific energy in hard milling can be compared with alternative processes (e.g., grinding), the comparison may provide an evaluation index for production managers to select a suitable process. In addition, the specific energy models can be used for process optimization to reduce energy consumption for a selected process.

These studies have focused on the energy consumption at machine level or spindle motor level. Analyzing energy consumption at these macro-levels leads to a gross oversight of the energy used in actual cutting to generate a new surface. Energy consumption to generate a new surface must be considered since it directly governs the machined surface integrity. Therefore, a thorough study on the relationship between process parameters and energy consumption at each level is needed to better understand the fundamental process-energy consumption relationship.

For a simple orthogonal cutting or turning process, energy consumption at the process level can be conveniently calculated based on