Journal of Materials Processing Technology 229 (2016) 305–312

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Energy consumption and process sustainability of hard milling with tool wear progression

Z.Y. Liu [a], Y.B. Guo [a,*], M.P. Sealy [a], Z.Q. Liu [b]

[a] Department of Mechanical Engineering, The University of Alabama, Tuscaloosa, AL 35487, USA
[b] School of Mechanical Engineering, Shandong University, Jinan 250061, China

ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form
15 September 2015
Accepted 16 September 2015
Available online 21 September 2015

Keywords:
Energy
Emissions
Environmental impact
Machining
Sustainable manufacturing

ABSTRACT

Tool wear progression is inevitable in precision cutting. However, the effect of tool wear on energy consumption at machine, spindle, and process levels is yet to understand. In this study, specific energy in dry milling of AISI H13 was studied at the machine, spindle, and process levels. The effect of process parameters and tool wear progression on energy consumption at each level was investigated. The emissions and environmental impact induced by the machine tool's energy consumption and the cutting tool embodied energy were investigated. The results indicated that tool wear progression only has a predominant influence on energy consumption at the process level but not the machine and spindle levels. However, the cutting tool embodied energy had a significant effect on total specific energy, process emissions, and environmental impact in hard milling. The predictive models have been developed to quantify the relationships between material removal rate and specific energy, emissions, and environmental impact.

1. Introduction

Manufacturing is energy intensive, and as a result, creates a significant manufacturing cost and environmental impact. In the U.S., more than two thirds of industrial energy use is consumed by manufacturing (EIA US, 2011). Machining is an important manufacturing process cluster. Abele et al. (2011) reported that more than 20% of the operating cost throughout the life of a machine tool is from electrical energy consumption. Nearly 80% of the energy consumed by manufacturing is produced from fossil fuels (EIA US, 2011). As a result, a considerable amount of greenhouse gas emissions (GHG) such as CO_2 are produced. With the drive for sustainable development, manufacturing companies are under increasing pressure from government regulations to reduce energy consumption and related emissions. Thus, a quantitative investigation on process energy consumption and emissions in machining is of great importance.

Energy consumption during machining can be investigated at different levels, see Fig. 1. The energy consumption at the machine level should be studied when the goal is to reduce total energy consumption and emissions. The energy consumption at the spindle level is useful in evaluating the energy efficiency of the spindle motor. At the process level, only the energy consumed by the actual material removal is considered. Gutowski et al. (2006) reported that energy consumption by the actual material removal (i.e., at process level) may only account for a small fraction (~15%) of the total energy consumption (i.e., at the machine level). Understanding energy consumption at different levels can help improve energy efficiency and reduce process emissions in machining. Several analytical models of energy consumption at the machine and spindle levels have been developed to analyze energy efficiency in machining. Based on direct energy required at the machine tool level, Gutowski et al. (2006) developed a model which decomposes the energy use into idle and cutting states. Li and Kara (2011) developed a model to characterize the relationship between energy consumption at the machine tool level with material removal rate (MRR). Diaz et al. (2011) developed a model to establish the relationship between specific energy and MRR At the spindle level. Schlosser et al. (2011) proposed a fundamentally different model format based on the unit specific cutting force and an equalizing correction factor.

Energy consumption with a worn tool is higher due to a higher friction force (Yoon et al., 2014). Previous research has been done to investigate the feasibility of using machine tool power to monitor the cutting tool wear. Cuppini et al. (1990) established the relationship between tool wear and cutting power for a turning process. Axinte and Gindy (2004) evaluated the sensitivity of spindle power for tool condition monitoring in milling, drilling, and turning.

* Corresponding author. Fax: +1 205 348 6419.
E-mail address: yguo@eng.ua.edu (Y.B. Guo).

http://dx.doi.org/10.1016/j.jmatprotec.2015.09.032
0924-0136/

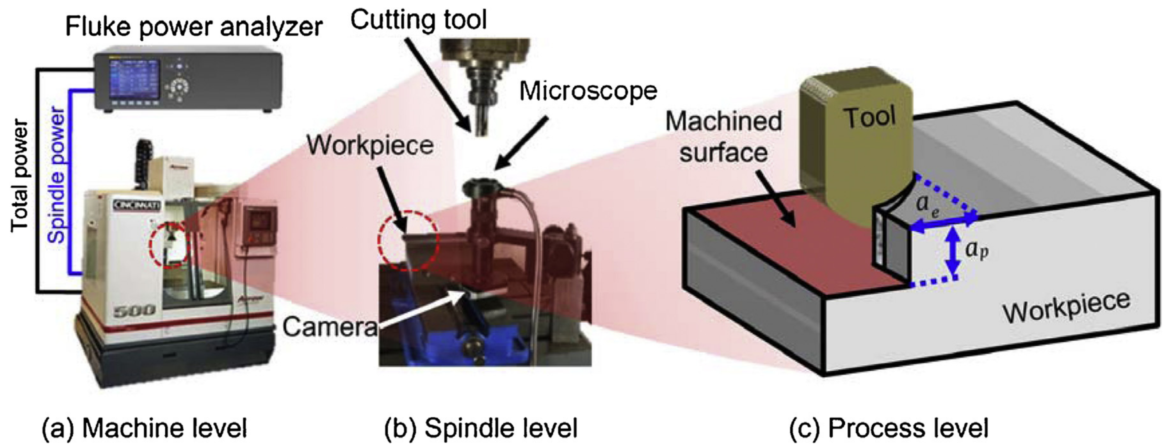

Fig. 1. Energy consumption classification and experimental setup.

However, very little work has been done to investigate the influence of tool wear progression on energy consumption at the process level.

As energy source in manufacturing in the U.S. is dominated by fossil fuels. The consumption of electrical energy from fossil fuel generates GHG emissions, e.g., CO_2, NO_x, and CH_4, etc. The increasing concentrations of GHG cause global warming and climate change, which becomes a significant global environmental issue. The development of a methodology to quantify the relationship between energy consumption and GHG emissions in manufacturing processes is essential to reduce environmental impact. Jeswiet and Kara (2008) developed a simple method to calculate the CO_2 emission for a given manufacturing process. A new concept, carbon emission signature (CES), was proposed based upon the fraction of fossil fuels usage for an electrical power grid. CO_2 emissions are calculated as the product of CES for a power grid and the energy consumption. Previous research has investigated emissions induced by machining processes. Balogun et al. (2013) investigated CO_2 emissions induced by machine tool energy consumption during milling. The effect of different machine tools and geographic locations was considered.

From the viewpoint of machining system, besides energy consumption by machine, spindle, and process during machining, cutting inserts are consumables and contribute to the environmental impact. The manufacture of cutting inserts is very energy intensive. When a cutting insert reaches the tool life criterion, the cutting inserts are discarded and the embodied energy of cutting insert is consumed. Maximizing tool life can reduce the idle time and machine tool energy consumption. Rajemi et al. (2010) investigated the effect of tool life on energy consumption for a turning process. Balogun and Mativenga (2013) developed an energy consumption model considered the energy for tool change by incorporating the tool life. Bhushan (2013) investigated the relationship between power consumption and tool life in a tuning process. Dahmus and Gutowski (2004) proposed qualitative discussions to evaluate the effect of a cutting tool on the environmental impact of machining. Narita et al. (2006) studied the emissions in milling of cast iron (FC250). Emissions produced by the machine tool energy consumption, cutting fluid, cutting tools, metal chips were considered. It was found that CO_2 is the predominant GHG emission. The major sources of GHG emissions in machining were the electrical energy consumption of peripheral devices within the machine tool and the consumption of the cutting tool. However, few studies have assessed the effects of cutting tool consumption on energy consumption, emissions, and environmental impact in machining.

Hard milling is a semi-finish or finish process which has been widely used in mold/die manufacturing. Hard milling can be conducted without the use of cutting fluids, thus generating less waste and having better process sustainability (Klocke et al., 2005). In order to achieve a favorable surface integrity, material removal rate (MRR) in hard milling is relatively small. The small MRR in hard milling results in low energy efficiency. A thorough investigation of energy consumption, emissions, and environmental impact in hard milling is needed. As tool life is very short in hard milling due to the high hardness of work materials, the consumption of cutting tools is very high. A quantitative study is very necessary to evaluate the impact of embodied energy of cutting tools on energy consump-

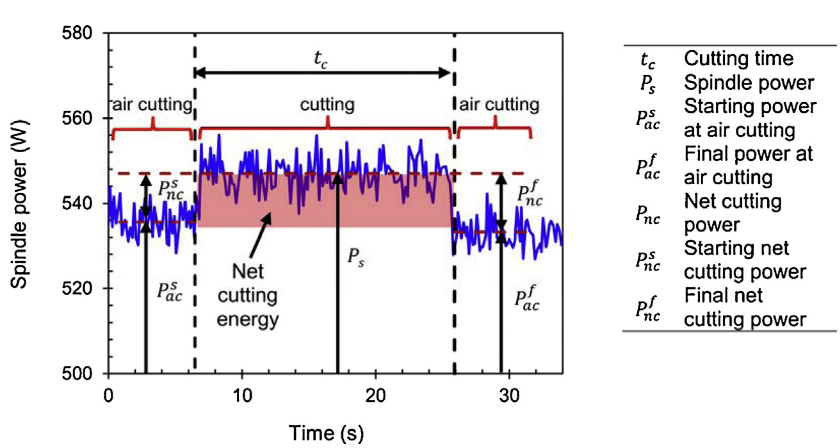

Fig. 2. Energy and power terminology.