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Embodied Energy in Dry Cutting under Consumption of Tool and Materials

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Abstract

Machining is energy and material intensive, and as a result, creates a significant environmental impact. With the drive for sustainable manufacturing, machining industry is under the increasing pressure from government regulations to reduce the consumption of energy and materials and the related emissions. The fossil fuels dominated energy source in U.S. manufacturing coupled with the high embodied energy of cutting tools and work materials make machining generate substantial 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. A thorough investigation to quantify the energy consumption in machining processes is essential to reduce the environmental impact. This study focuses on the total energy consumption in hard milling of tool steels. Tool material consumption through wear progression is inevitable in hard milling. As tool life is very short in hard milling due to the high hardness of hardened work materials, the consumption of embodied energy of cutting tools is very high. Similarly, the embodied energy of removed work material is consumed since the removed work material is converted into chips. However, very few studies have determined the consumption of cutting tool and work material on total specific energy consumption. This study investigated the total energy consumption in hard milling including machine energy and the embodied energy of cutting tool and work material. The results show that a higher material removal rate (MRR) results in less total energy consumption. The embodied energy of cutting tool and work material has a significant effect on the total energy consumption of hard milling. The contribution of cutting tool and work material consumption should be accounted when assessing the environmental impact of a cutting process at the manufacturing phase.

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Keywords: Energy consumption; specific energy; resource utlilizaiton; sustainable manufcaturing; enviromental impact

1. Introduction

Manufacturing is energy intensive, and as a result, increases manufacturing cost and creates significant environmental impact. In the U.S. alone, more than two thirds of industrial energy use is consumed by manufacturing [1]. Machining is an important manufacturing process cluster. Abele et al. reported that more than 20% of the operating cost throughout the life of a machine tool is from electrical energy consumption [2]. Furthermore, nearly 80% of the energy consumed by manufacturing is produced from fossil fuels [1]. As a result, the consumption of electrical energy from fossil fuel generates GHG emissions, e.g., CO_2, NO_x, and CH_4. The increasing concentrations of GHG cause global warming and climate change, which becomes a significant global environmental issue. With the drive for sustainable manufacturing, machining industry is under increasing pressure from government regulations to reduce energy consumption and related emissions. Thus, a quantitative investigation on energy consumption in machining is of great importance.

Total energy consumption has been used as a methodology to assess life cycle environmental impacts of commodity production. The total energy consumption of a product represents the direct energy and indirect energy use throughout the life cycle. The comparison of total energy and

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other indicators (e.g., eco-indicator, climate footprint, and environmental priority strategy) shows that total energy consumption has the lowest data requirement while provides similar results, thus total energy consumption can be used to as an effective screening indicator for environmental performance [3]. The concept of total energy consumption can also be used to evaluate the environmental performance of a manufacturing process. The total energy consumption for a unit manufacturing process includes not only the direct energy consumption of the process, but also the indirect energy due to material consumption. For a machining process, besides the energy consumption by machine tool, the embodied energy of cutting inserts and work material also contributes to the total energy consumption and, therefore, environmental impact at the manufacturing phase. Manufacturing of cutting inserts usually involves high temperature sintering and is very energy intensive. Since cutting inserts used in machining are consumables, when a cutting insert reaches tool life criterion, the cutting insert is usually discarded and the associated embodied energy is consumed. Similarly, the embodied energy of work material is consumed since removed work material is converted into chips. Dahmus and Gutowski proposed a qualitative discussion to evaluate the effects of a cutting tool and work material consumption on the environmental impact of machining [4]. Narita et al. studied the emissions in milling of cast iron (FC250) [5]. Emissions produced by the machine tool energy consumption, cutting fluids, 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 embodied energy consumption of the cutting tool. However, very few studies have quantitatively assessed the effects of embodied energy due to the consumption of cutting tool and work material on total energy consumption at the machining phase.

This study focuses on hard milling which is widely used in semi-finishing or finishing molds/dies. Hard milling can be conducted without using of cutting fluids, thus the dry cutting generates less waste and has better process sustainability [6]. In order to achieve a favorable surface integrity, material removal rate (MRR) in hard milling is relatively small. The small MRR in hard milling is expected to result in low energy efficiency. A thorough investigation of energy consumption in hard milling is needed. As tool life is short in hard milling due to the high hardness of work materials, the consumption of embodied energy of cutting tools is very high. A quantitative study is very necessary to evaluate the impact of embodied energy of cutting tools and work material on total energy consumption from the viewpoint of machining system.

The objectives of this study are twofold: (a) investigate the effect of tool wear progression in hard milling on machine tool energy consumption; and (b) determine the total energy consumption including embodied energy of the consumed cutting tool and work material.

2. Energy Consumption in Machining

2.1. Material and energy flow in dry cutting

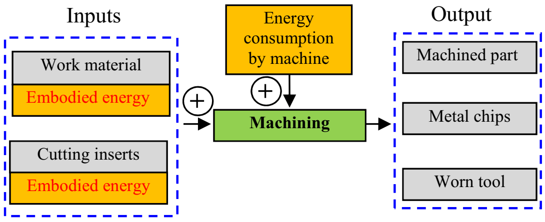

Fig. 1 Energy and material flow in dry cutting.

The material and energy flow in dry cutting is shown in Fig. 1. The energy consumption in machining has been investigated extensively. Most of the previous studies only focus on the energy consumption of machine tool. However, very few studies have considered the effect of embodied energy of input materials. In this study, the total energy consumption was investigated from the perspective of machining system. During machining, the removed material is converted into chips. The embodied energy of the removed work material (i.e., the energy consumed to fabricate work material) is consumed. Tool wear is inevitable and when cutting tool wear reaches a criterion, cutting inserts are discarded. The embodied energy of cutting inserts is also consumed. The total energy consumption at the manufacturing phase can be given by Eq. 1.

$$TEC = E_M + E_T + E_W \tag{1}$$

in which TEC, E_M, E_T, and E_W are the total energy consumption, energy consumption by machine tool, embodied energy of cutting tool, and embodied energy of work material, respevtively.

Similarly, the total specific energy is given by Eq. 2.

$$U_{TEC} = U_M + U_T + U_W \tag{2}$$

in which U_{TEC}, U_M, U_T, and U_W are the specific total energy consumption, specific energy by machine tool, embodied specific energy of cutting tool, and embodied specific energy of work material, respectively.

2.2. Energy consumption by machine tool

Electrical energy is used to drive a machine tool to remove work material. The majority of power demand is actually consumed by the peripheral components of the machine tool, e.g., coolant pump, control system. Gutowski et al showed that the electrical energy requirement for a manufacturing process is inversely proportional to the process rate. Diaz et al [7] and Li et al [8] developed similar analytical models to predict the specific energy of machine tool (Eq. 3).

$$U_M = \frac{C_1}{MRR} + C_0 \tag{3}$$