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Energy efficiency of state-of-the-art grinding processes

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Abstract

In times of unstable market development due to the energy system transformation and legislative measures concerning the reduction of CO_2 emissions, the manufacturing industry is increasingly aware of the ecological and economical importance of the factor energy. A considerable share of industrial energy and resource consumption can be attributed to machine tools in general and grinding machines in particular. Grinding is an essential technology used for finishing operations of many precision components, especially such made of hard and brittle materials. This work presents an investigation in the energy consumption related to high-performance grinding processes. Grinding tests were performed using different grinding strategies and abrasives including corundum (Al_2O_3) and CBN. In order to identify the dynamic process behavior and energy flows, process parameters were varied and electrical power consumption of the CNC grinding machine, its drive system as well as different peripherals such as cooling lubricant pumps were measured. Specific energy consumption was determined as a function of material removal rate and compared to results of milling and turning processes. The key influence factors on grinding energy efficiency and productivity are depicted. Strategies are evaluated to optimize the overall process performance from an energetic point of view.

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Keywords: Grinding; Machine tool; Energy efficiency; CBN; Cooling lubrication; Sustainable manufacturing; Ecological evaluation

1. Introduction

Grinding is an essential technology especially used for finishing operations of precision components. Especially for hard or brittle materials such as hardened steel and high-performance alloys, high surface quality and dimensional accuracy are difficult or even impossible to realize with other technologies. However, it is a highly energy and resource intensive manufacturing process as it typically requires powerful grinding spindle drive and cooling technologies as well as elaborate auxiliary processes such as grinding fluid processing and mist collection.

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In 2005, U.S. energy consumption due to grinding in manufacturing was estimated to be 17.6 TWh based on assumptions concerning the installed machine capacity and annual production hours [1]. This number may seem overestimated as it corresponds to ca. 1.7% of the total electricity consumption of U.S. industry sector at that time [2]. It is, however, undisputed that the economic and environmental impacts of grinding are substantial. For instance, an LCA investigation of the manufacturing process chain of exemplary engine and powertrain components showed that on average ca. 20% of the resulting global warming potential is attributable to grinding processes [3]. Another study identified that grinding machines had a share of 28% on installed CNC machine tools in the EU-27 in 2009 [4].

When considering the energetic performance of a production system in general and a grinding machine in particular, it is necessary to differentiate between efficiency and effectiveness. Improving the efficiency can be done e.g. by applying new grinding wheel technologies, by utilizing speed-controlled pumps or by employing alternative cooling lubrication technologies in order to reduce the energy demand of a given process. In contrast, an effectiveness approach could make certain process steps obsolete and thus lead to a more drastic decrease in total energy consumption. Different strategies have been identified to reduce energy and resource consumption concerning design and process control of machine tools as well as technological and organizational aspects (cf. [5-10]):

- Selection of the optimal capacity of machine tool and auxiliary systems
- Utilization of more efficient machine tool components (such as drives and pumps)
- Recovery of heat or kinetic energy within the machine tool
- Replacement of integrated by centralized peripherals (or vice versa)
- Selective actuation of non-continuously required devices (such as pumps and ventilators)
- Optimization of process parameters (e.g. by improved design of tool, spindle and machine structure or by utilizing high-performance tool materials) and tool paths
- Optimization of NC-programs and parallelization of processes (e.g. by utilizing multi-spindle machines)
- Alteration of manufacturing technologies (e.g. hybrid processes such as vibration assisted machining)
- Substitution of certain manufacturing technologies (e.g. hard turning instead of grinding or grind-hardening instead of separated hardening and grinding)
- Implementation of automatic machine hibernation during nonproductive times
- Reduction of idle times (e.g. via effective setup and loading strategies as well as production planning measures)

Several studies have been carried out in order to quantify and model the energy demand of machine tools in order to determine their environmental impact [11-13]. These methods were developed for conventional machining processes, essentially taking into consideration constant and process dependent shares of power consumption. In its most rudimentary form, the power consumption of a machine tool is divided in a constant a variable component. Naturally, this is also valid for grinding machines where the (near-)constant share of power consumption ('base load') is attributable to components such as drive electronics, cabinet and machine cooling or hydraulics while the dynamic share is typically mainly caused by axes and spindle drives, cooling lubricant supply or mist separation systems.

The processing time is obviously a key influence factor for the energy demand of machine tools, especially such with high base load. Increasing material removal rates lead to a decrease of primary processing time and thus of overall energy consumption [7, 14, 15]. However, decreasing process times may also lead to a higher share of idle times (especially in the case of suboptimal machine utilization) and therefore to a rebound effect concerning total energy consumption. Furthermore, the approach is limited as product dimensional accuracy and surface quality strongly decrease with increasing material removal rates. Li et al. presented an approach to evaluate the interrelationship among process parameters, specific energy consumption and surface roughness for grinding 100Cr6 (62 HRC) using corundum (Al_2O_3) and CBN grinding wheels [16].

Due to its hardness as well as thermal and chemical stability, CBN is utilized for a wide range of precision grinding processes. It enables a combination of high speed grinding and creep-feed grinding, typically referred to as high performance grinding [17]. Especially when employed on high-performance alloys using high cutting velocities, the high costs of CBN are compensated by increased productivity and tool life compared to other abrasives [18]. However, high-performance grinding processes using CBN pose high demands on the grinding machine concerning issues such as spindle stiffness and cooling, dressing and balancing processes as well as cooling lubrication [19].

Neugebauer et al. presented an approach to drastically increase productivity of a camshaft grinding process by using micro-structured CBN grinding wheels enabling optimal cooling lubricant supply [20]. Compared to standard