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Methodology for process-independent energetic assessment of machine tools

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Abstract

Energy-labels draw users' attention to energy efficiency and thus they force the manufacturers to reduce the energy consumption of their products. This paper focuses on the large variety of metal-cutting machine tools, representing a challenge to find an evaluation basis for a unique energy-label. For this reason, the process-independent energy consumption has been compared to machine tool features and properties. The data-base contains measured values and has been extended by values from literature. Concerning a large number of various machining centers for milling operations, the statistical analysis shows the influence of the different machine tool features and properties on energy consumption. Finally, an evaluation basis is presented and the applicability on energy-labels is discussed.

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1. Introduction

Growing populations and higher global living standards lead to an increased demand for consumer and industrial goods. Machine tools play an important role in the production of these goods. In order to cover the increased demand, more machine tools are needed. The high number of machines in use is associated with a high consumption

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of electrical energy. This consumption stands for more than 95% of the environmental impact of a machine tool [1]. Furthermore, energy as a global resource will become expensive and rare, in particular, if the objective is sustainability. Moreover, the long-term trend of highly automated production intensifies the energy consumption, e.g. due to the expanding use of powerful CNC-machining centers with numerous peripheral units [2]. All these aspects demonstrate the need for highly energy-efficient machine tools. Thus, the European directive 2009/125/EC for "Ecodesign of Energy-related Products (ErP)" [3] as well as energy-efficiency standards and regulations deal with this topic, e.g. ISO 14955-1 introduces a design methodology for energy-efficient machine tools. Nevertheless, another very important step on the long path toward energy-efficient machine tools consists in labeling of machine tools with regard to their energy consumption. Energy-labels draw machine tools users interest on energy saving aspects. Thus, the labels also force the manufacturers of machine tools to reduce the energy consumption of their products [4]. In [4], Herrmann et al. pointed out that reference cutting processes should be defined for assessing energy efficiency based on already known parameters. However, the challenge consists in defining a unique evaluation basis for the large variety of over 400 types of metal-cutting machine tools [1].

The energy consumption and efficiency of machine tools has been addressed by various publications in the past years, as referred by Zhang [5]. Nevertheless, this topic also drew interest in the past due to the lower energy availability and to a reduction in the manufacturing costs [2, 6–9]. The authors mostly focused on measurement, analysis, simulation and prediction of the energy consumption with the aim of reducing it during the utilization phase. In particular, Gutowski et al. [10] suggested the assessment of the power consumption P as a function of the idle power, the material removal rate (MRR) and a constant from the physics of the process. This function can be rearranged for computation of the specific electrical exergy which is equivalent to the specific energy consumption per removed material volume (SEC), which is further inverse proportional to MRR. In [11], Li analyzed empirical data for the SEC using the ANOVA and regression analyses. He obtained a prediction model that equals to the rearranged equation for the specific electrical exergy as mentioned above. Furthermore, Yang statistically evaluated a significantly dependence of MRR on the cutting speed, the depth of cut and the feed rate [12]. Alternatively, Degner introduced the theoretically specific cutting energy W_{th} for cutting processes.as a ratio of the cutting power (P_c) and the MRR [8]. After some mathematical manipulation, W_{th} is proportional to the specific cutting force k_c supplemented with diverse correction factors K in accordance with the cutting force model by Kienzle [13].

Approaches for assessing the energy efficiency based on process parameters imply a clear definition of one or more reference processes. Thus, various reference work pieces and test-conditions are treated in standards [14–16]. The new ISO/DIS 14955-2 provides detailed measuring methods down to the level of machine tool components as well as test scenarios that can contain the machining of parts. In this context, Schudeleit et al. [17] present an effortful approach for a total energy efficiency index based on an evaluation of actual (measured) and reference (best available technique) values for all machine tool components that are collectively responsible for at least 80% of the total power demand in each operation state of a machine tool. The evaluation is made in the operation state "processing" with maximum spindle power considering the lowest estimated SEC.

The European project eco2cut [18] developed an approach for benchmarking machine tools consisting of a process-dependent part, based on a test work piece, as well as a process-independent part, based on component tests, including spindle and axes movements. Machines and components are assessed by using average values obtained from measurements of other machines. This approach is naturally associated with a high effort. Kaufeld [19] proposes a testing cycle including movements of all axes and the spindle as well as tool change sequences for a process-independent indicator for energy efficiency (EE), but the approach is not justified in detail.

Literature shows the complexity of the topic related to assessing the energy consumption of machine tools. It is obvious that many parameters and impact factors have to be considered. Therefore, detailed evaluation models and effortful experimental setups have been developed to date. However, the assessment of a process-dependent energy efficiency such as SEC includes the need for universally accepted reference processes and test work pieces, which represents a huge challenge regarding the large variety of metal-cutting processes and machine tools [1]. A process-independent energy label for machine tools could avoid the issue of reference processes and, thus, it could make assessments of energy efficiency significantly easier. Therefore, the approach presented in this paper aims at a unique energy label for machine tools and is based on a process-independent energy indicator that is very simple to measure. Hence, the energy label of a machine tool in accordance with this approach is very easy to perform and thus appropriate for wide use.