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Energy driven process planning and machine tool dynamic behavior assessment

Stefano Borgia[b], Marco Leonesio[b], Stefania Pellegrinelli[b], Anna Valente[a*]

[a] University of Southern Switzerland, Institute of Systems and Technologies for Sustainable Production, SUPSI-ISTePS, Manno, 6928, Switzerland
[b] Institute of Industrial Technologies and Automation, National Research Council, ITIA-CNR, Via Bassini 15, Milan, 20133, Italy
*Corresponding author. *E-mail address*: anna.valente@supsi.ch

Abstract

The current work outlines an approach to close the loop between process planning and machine tool dynamic modeling by addressing the problem of energy efficiency across the process design and realization chains, from the process settings and pallet configuration to the machine tool design and usage phases. The proposed closed loop approach consists of an off-line and on-line component enabling the process and equipment dynamic and energy assessment over time. The benefits of the approach have been evaluated against an industrial case study related to the automotive industry.

Keywords: Process Planning, Machine Energy Modeling, STEP-NC.

1. Introduction

Design of a production machine is a very complex activity to be addressed by considering cost, ergonomics, occupied space, operational flexibility, power consumption, etc. Some key machine performance depends on the machine dynamic behavior, especially the ability to remove in a short time a large volume of work piece material (i.e. the “material removal capability”) [1]. In order to reach the optimal tradeoff in dynamic and kinematic performance, the designer acts on numerous design parameters, some of them linked to commercial components, like ball-screws and bearings, others to custom made structures (typically welded steel plates or cast iron). The relationship between those elements and the global machine performance is often very complex. The conception and optimization of the mechanical structure result often to be supported by Finite Element Analysis that allows forecasting the static and dynamic machine compliance with a reasonable accuracy. The gap between this analysis and the real machine capability is usually filled with the designer experience, who must be able, for example, to translate a required machining capability into an equivalent specification on the dynamic compliance. Besides the designer skills, the machining quality often depends upon the decision process developed by the process planner, who has to be tuned the process parameters on to machine characteristics.

Only very recently, the machine design and the process planning is starting addressing the energy efficiency profiling, as a result of the increasing interest towards the development of energy conscious manufacturing [2]. The study of a machine’s energy consumption requires analyses at component level and at system level, as the overall efficiency does not only depend on the performance of individual components (component level), but also on their interaction and the load cycle of the machine (process level and system level). This demands for a holistic approach towards modeling and optimization of energy flows [3]. Once proper models are available, the energy assessment of machine tools is believed to enable a more accurate machine selection process to exploit a certain set of operations.

The current work proposes a machine tool and process planning joint design approach - referred as CLAMP (Closed Loop Approach for energy efficient Machine tool and Process planning) - by explicitly

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addressing the energy efficiency problem in a way the design of the process, the equipment and the production strategies will target the trade-off between productivity and efficiency.

2. Literature review

The energy profiling of machine tools - MT and machining processes has generated a large number of academic and industrial contributions which could be clustered by increasing interaction levels between the MT and the workpiece - WP to be processed. The first set of works deal with the energy consumption associated to the realization of single working features, thus specifically referring the MT behavior while cutting the metal [4-7]. These works deal with only a partial evaluation of the MT energy profile as they only refer to the mechanical energy required to remove the material, without considering machine peripherals and the efficiency of components and subsystems.

A second branch of literature focuses on the energy modeling of MTs by means of the characterization of its operational states (for the basic energy consumption), while the process efficiency is evaluated computing an overall cutting specific energy considering the machine absorption for different combinations of process parameters. Avram and Xirouchakis [8] propose a methodology for estimating the mechanical energy requirements of the spindle and feed axes with respect to 2.5D machining strategies by taking into account steady-state cutting and positioning transients. Balogun and Mativenga [9] propose an extended MT electrical energy states for modeling the direct energy requirements in mechanical machining processes where the energy consumption of MTs is considered with respect to the basic, the ready state and the cutting states. This enables to associate to the realization of a working feature and energy profile that accounts all the MT subcomponents, including kinematic chains (guideways, motors, transmissions, etc.). However, all the above-mentioned models consider the cutting process in an approximated way: for instance, the effect of cutting force/torque dynamics on energy consumption and vibrations occurrence is not taken into account.

The last group of works refers to the machine modeling as a whole by including the static and dynamic features. The manufacturing of a WP can be enriched by energy efficiency information that embraces a realistic cutting force behavior, together with other performance indicators related to vibration occurrence (also due to regenerative chatter); energy consumption and performance indicators can be computed in time while executing a part program in a proper virtual environment, including positioning transients. Leonesio et al. [4] propose an integrated approach between MT and process planning where the MT architecture and performance are tuned on the basis of a set of performance indicators considering energy consumption, associated to static and dynamic components of cutting force. The research advances are concurrently pushed by a strong industrial commitment in the field of energy conscious manufacturing. A large number of MT builder are enriching their solutions with new sensors, controllers and HMI (Human Machine Interfaces) supporting the energy monitoring of the equipment over time [10-11]. New high-efficiency components have started to be adopted, together with more intelligent PLC strategies aimed at deactivating some peripherals when unused. Even if the available portfolio solutions are mainly related to the monitoring phase, this constitutes an interesting proof of the industrial sensitivity to this topic.

Within the MT energy profiling there is still a number of open issues. The current available energy models of MTs mostly consider the MT as a discrete set of operational states. In addition, the available machine energy models are frequently associated to the execution of very simple tasks rather than complex operation chains like a complete pallet execution where also the auxiliary devices and systems are instrumental contributors to the energy assessment. A further poorly addressed topic is that the evaluation of the MT under the energy efficient drivers is not currently linked to the MT design process so that the machine energy performance is not coupled to any design actions for the machine improvement.

The energy optimization drivers can be further exploited under the process planning perspectives by addressing several key questions. The energy efficient process planning is currently exploited by focusing on the execution of single WPs and considering a limited family of machining operations [12-13]. Only in few works the energy drivers are incorporated in the pallet set-up planning and configuration problems [4]. In addition, the energy efficient process planning is still considered as coupled to single MTs. The possibility to conceive the process plan as a distributed network coherently to the network part program (Net-PP) principles [14] constitutes an additional degree of freedom in the energy optimization process, where sub-portion of the pallet can be assigned and processed by different machines operating in the shop-floor coherently to their energy consumption. A further element of improvement for process planning should regard the MT natural degradation process and the related changes in the energy consumption which would require the process settings to be adapted over time and, possibly, the adjustment of the pallet assignment to the machines.

The current work will address a number of the outlined open issues. The rest of the paper is organized