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An integrated approach to support the joint design of machine tools and process planning

M. Leonesio, L. Molinari Tosatti, S. Pellegrinelli, A. Valente *

Institute of Industrial Technologies and Automation (ITIA), National Research Council of Italy (CNR), Via Bassini 15, 20133 Milano, Italy

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ABSTRACT

The configuration of machine tools and process planning problem are traditionally managed as independent stages, where the process plan is designed by considering a number of machine tool solutions available from catalogue. This strategy presents a number of disadvantages in terms of process results and machine capabilities fully exploitation. The current paper proposes an integrated approach for jointly configuring machine tools and process planning. The approach is structured in 4 major recursive steps that eventually ensure the accomplishment of the best trade-off between the machine tool static and dynamic behaviour, the process quality and the resulting economic efficiency. The benefits of the approach have been evaluated for a test case application in the railway and automotive sectors.

1. Introduction

The design and configuration of machine tools is instrumental for European manufacturing competitiveness [1]. Coherently with the mass customization principles and the traditional European know how in the field of instrumental goods production, machine tools should result from a configuration process tightly related to the analysis of the families of products and process quality requirements rather than being a standard and rigid catalogue equipment. This makes the machine configuration and the process planning as two steps of the same problem where the machine tool geometric and kinematics features influence the accessibility to the workpiece operations along with the fixturing system configuration and the machine dynamic impacts on the final quality and costs of the workpiece.

The relationships between machine tool configuration and process planning have been widely investigated by the scientific literature with reference to the following topics: the evaluation of machine capabilities to statically realize a process plan [2], the execution of a process plan across several resources [3], the energy efficient process planning [4–7] and, finally, evaluation of the impact of machine tool dynamic behaviour on the process planning definition [8]. However, the interest of these works is mostly focused on the impact of a specific machine tool architecture and performance on the process planning problem.

The current paper presents an integrated approach to support the joint design of machine tools and process planning. The proposed approach is structured in four major steps as illustrated in Fig. 1.

The first step consists in the analysis of the workpiece CAD model. The workpiece is analysed according to the STEP standard [9] through the identification of machining feature (geometrical description of the region of the workpiece to be machined), machining operations (selection of cutting tools, machining parameters and strategies) and machining workingsteps (MWS – association between a machining feature and a machining operation). On the basis of a number of alternative MWSs, Step 1 identifies the MWSs that globally better match the production requirements and machine behaviour.

The geometric and technological information related to the family of products together with the data about the production demand and the forecasts about possible product evolutions are utilized in Step 2 related to the machine tool design. The outcome of this step is a domain of general-purpose machine tools that fit the production requirements from both the dynamic and static point of view Steps 1 and 2 are traditionally handled as independent phases as general-purpose machine tools are normally configured with no knowledge of the actual products to machine and the process planning is usually developed starting from an existing machine catalogue.

Step 3 regards the dynamic simulation of the machine tool solutions resulting from Step 2 while executing the MWSs identified in Step 1. The dynamic behaviour of machine tools is evaluated against a number of Key Performance Indicators (KPIs) dealing with the energy consumption, tool wear, surface

* Corresponding author. Tel.: +39 0223699917; fax: +39 0223699941.
E-mail address: anna.valente@itia.cnr.it (A. Valente).

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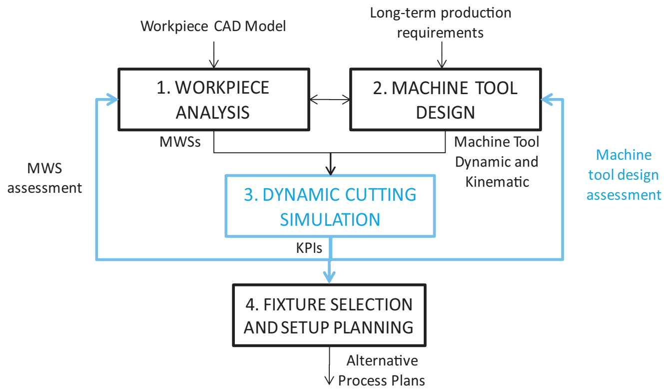

Fig. 1. The integrated approach.

roughness, maximal required spindle power and torque. The KPIs are concurrently relevant to the MWS assessment as they could drive the adjustment of process parameters and to the machine tool design by leading to the tuning of the kinematic and dynamic characteristics.

The last step of the approach concerns the selection of one or more fixtures and the definition of workpiece orientations as well as the association of the operations to a given orientation (workpiece setup) [10,11]. The outcome of this phase is the generation of alternative process plans feasible from the workpiece quality requirements [12]. Production time and costs are investigated and optimized on the basis of the MWS KPIs.

The following section of this work will provide the reader with a more comprehensive description of each step of the proposed approach (from Sections 2 to 6). Section 7 will present an industrial test case considered to evaluate the approach benefits. Section 8 will outline the conclusions and future work.

2. Workpiece analysis

The workpiece analysis is the first activity in feature-based process planning [13] and aims at defining the operations that are necessary for the complete machining of the workpiece. As stated in Section 1, the workpiece analysis is based on the STEP-NC standard, leading to the definition of the machining feature (geometric description of the region to be machined), machining operations (strategy of machining) and machining workingstep (association between a feature and an operation). As a region can be machined on the basis of alternative strategies in terms of cutting tools, machining parameters or tool path, the same feature can be realized by alternative operations and, consequently, alternative MWSs. The complete realization of a workpiece implies the identification of the technological constraints among the MWSs to be executed. The proposed approach considers two different kinds of technological constraints: precedence and tolerance constraints [14]. Precedence constraints impose an order of execution between two MWSs whereas tolerance constraints require the execution of two MWSs in the same setup to ensure the accomplishment of quality requirements. On the basis of these technological constraints, a network of operations can be built by taking into account the precedence constraints and the alternative strategies to process a specific feature. This network will be employed during the last step of the approach dealing with the fixture selection and setup planning.

3. Machine tool design

The configuration of the machine tool is an extremely articulated process that, coherently with the proposed approach, starts from the collection of data about the family of products to be processed. These data include the geometrical and technological characteristics of products synthesized in the workpiece analysis step along with the production volumes.

The configuration process involves the identification of the minimum set of machine tool requirements that accomplish the process constraints (such as the minimum working cube, the number of axes, the spindle orientation and power). On the basis of this minimum set, other types of constraints can be taken into account such as the productivity, the reliability, the available budget, the energy efficiency as well as the machine global size (in the case it should be integrated in a predefined shop-floor). In the case the demand is expected to be variable over time, additional evaluations can be done with regard to the customization of the machine flexibility degree to match the forecasted changes.

All this information leads to the identification of a domain of alternative machine solutions characterized by different architectures, performance and costs. At this stage, the machine design process requires the evaluation of machine performance while executing the process. The analysis of machine–process dynamic interactions enables the evaluation of the machine criticalities and possible improvements.

The next section outlines the dynamic cutting simulation as a means to assess the machine tool design and the workpiece analysis as part of the process plan.

4. Dynamic cutting simulation

In the metal cutting strategy, the objective of decreasing manufacturing time and costs is strictly connected to the need for ensuring the requested level of quality. The quality can concern directly the workpiece geometrical properties, or it may refer to the process, for instance, its efficiency in terms of energy consumption.

The workpiece quality is affected by all the phenomena that determine an undesired displacement of the tool with respect to the nominal path. A comprehensive assessment of workpiece quality entails an analysis of four major categories of phenomena: thermal deformations of machines and parts; volumetric positioning errors of the tool tip; dynamic interaction among machine, process and workpiece; trajectories errors due to CNC and/or feed drives performance. Due to the high demanding performance in terms of material removal rate (MRR), the modelling and minimization of vibrations, either forced or caused by chatter instability, represents a major limitation for improving productivity and part quality in metal removal processes. Vibrations occurrence has several negative effects: poor surface quality, out of tolerances, excessive noise, disproportionate tool wear, spindle damage, reduced MRR to preserve surface quality, waste of materials, waste of energy and, consequently, environmental impact in terms of materials and energy [15]. Besides the surface quality and the violation of tolerances, the other effects deal with process quality and have a direct impact of the overall production efficiency. The key for evaluating the level and the effects of vibrations onset is the so-called dynamic cutting process simulation, able to couple the forces originating from the material removal with the relative dynamic and static response between tool tip and workpiece [16]. While the simulation of single processes or machine characteristics is state of the art, the integration of process and the machine tool modelling in the simulations is particularly innovative. The interactions between machine tool, the workpiece and the process surely represent a great challenge as their modelling must be evaluated to address the forced vibrations onset and regenerative chatter instability. The discontinuous cutting forces produced by the machining process excite the tool tip causing a chip section modulation