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Smart tool path generation for 5-axis ball-end milling of sculptured surfaces using process models

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ABSTRACT

Efficient 5-axis milling of free form surfaces required smart parameter selection and tool path generation approaches. Current computer-aided manufacturing (CAM) technology offers limited flexibility and assistance for such purposes, where purely geometrical issues are considered. Consequently, the generated tool path may be off the high-performance milling parameters. In 5-axis milling, the efficient process parameter set usually vary along the tool path due to varying engagement conditions because of inherent reasons. In this paper, a novel approach is proposed for identification of efficient surface milling parameters according to the variation of cutting forces and stability along the tool path, and then continuously implementation of these parameters for smart tool path generation, obeying the geometrical requirements. The proposed approach is applied on representative cases relevant to industrial applications to demonstrate the benefits. It is shown that, use of process simulations in tool path planning and generation offers significant benefits in decreasing the total cycle time in 5-axis milling.

1. Introduction

Sculptured surface machining (SSM) requires 5-axis milling in several industries from medical to aerospace, to overcome geometrical constraints while meeting the quality requirements, where roughing and finishing are the main stages. In roughing, as it is aimed to remove the unwanted volume of material as quickly as possible, the tool faces varying cutter-workpiece engagement boundaries (CWEB), whereas in finishing uniform cutting conditions are preferred for quality. However, excessive cutting force variations in roughing may affect the part in finishing. Consequently, semi-finishing passes may be needed before finishing. In this regard, tool path generation, planning and selection of process parameters is crucial for reduced total cycle time [1]. In some occasions, even though the efficient milling parameters are known, they may not be fully implemented on the process as the CAM system may not allow variable cutting parameters to be implemented.

Tool path generation for 5-axis SSM is a complex task, requiring efficient algorithms [2–4] for CAM systems [5]. Such algorithms have been developed for the last decades to work on faceted data [2], surfaces [3], point clouds [6], and NURBS type of curves [7] to meet various tool path generation requirements in industry. Although being advanced to perform the geometrical calculations for tool path computation, such algorithms consider only the geometry of the cutting tool and workpiece, ignoring physics of metal cutting. As CAM systems are the interfaces between the process planners and the real manufacturing systems, manufacturing industry does not benefit well from the advances in process modelling and simulation as addressed in a recent CIRP keynote paper [8]. Indeed, successful implementation and increased impact of process models in manufacturing industry is achievable by integration of them with CAM systems for parameter selection and tool path planning as discussed by Chen et al. [9], and Altintas and Merdol [10].

Modelling and simulation of milling processes caught high interest in the last decades. In the literature, such efforts started with flat end milling tools, extended to 3-axis ball end milling first and then 5-axis ball end milling. Recently, their integration with the processes caught more importance for increased impact in manufacturing. The first integrated cutting force model was proposed by Altintas and Spence [11] for end milling. They integrated solid modeller based process simulation with tool path generation for end milling processes, where simulated cutting forces and tool deflection are used in feed rate scheduling. Later, Budak and Altintas [12], proposed avoidance of static form errors in peripheral milling through process modelling, where significant accuracy improvements were demonstrated. They simulated form errors along a peripheral milling tool path, and then compensated the tool path by the amount of form errors.

Lee and Altintas [13] proposed the first cutting force model for complex milling tools, i.e. ball end mills, used in 3-axis SSM. They were

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able to consider varying cross-sectional parameters of the tool body in simulation of cutting forces. Later, Weinert et al. [14] took it further for milling of dies and moulds through Z-mapping based process simulation in feed rate scheduling for 3-axis ball end milling. Milfelner and Cus [15] developed a general framework for simulation of cutting forces in 3-axis ball-end milling, where they demonstrated and validated their model on indexable ball end mills. The error margin was less than 10% in most of the cutting experiments. Efforts on modelling of cutting forces in ball-end milling were used to increase performance and accuracy of ball-end milling processes by Kang et al. [16]. They used process simulations in optimization of cutting conditions in 3-axis ball end milling. Budak et al. [17] used cutting force-based feed rate scheduling on 3-axis ball end SSM and showed that cycle time can be significantly reduced.

Process models are used in prediction of chatter-free cutting conditions, as well. Weck et al. [18] proposed milling dynamics based cutting parameter selection in CAM systems. They used time domain simulations to create data sets representing the chatter-free milling conditions. Then, these data sets are used in tool path planning and generation. Although limited to 2½ axis end milling, it was an important step to consider milling dynamics in tool path planning. Later, Budak and Tekeli [19] demonstrated selection of chatter-free cutting parameters in end milling by trade-off between radial depth of cut and axial depth of cut. In the case studies they demonstrated, their conclusion was that 60% of radial depth provides the highest chatter-free material removal rate in end milling operations.

Tool path pattern is an important level in design of milling processes, which affects how the machine tool would move throughout the tool path. In one of the early studies Feng and Su [20] presented a concurrent optimization approach for finishing of 3D-plane surface using ball-end mills. They put feed rate, tool path direction and step over in the focus of optimization. A mechanistic cutting force model was used in order to account the effect of feed rate on the cutting forces and hence the dimensional tolerances. Effect of tool path pattern on the cycle time was previously studied for high speed pocket milling operations by Monreal and Rodriguez [21]. They discussed the effect of feed rate direction in zig-zag tool path pattern and successfully captured the discrepancy between the theoretical cycle time and the actual one at high feed rates. Manav et al. [22] presented an approach in optimization of 3-axis milling of complex sculptured surface machining, based on multi-criteria such as cutting forces, cycle time and scallop height. They identified the feed directions and step over according to force-scallop height cycle time-minimal approach. However, this study was limited to 3-axis milling and the selection of cutting depth was out of scope. In one of the early studies Vosniakos and Papapanagiotou [23] proposed a process planning approach for convex pockets, i.e. without islands, i.e. 2 ½ axis milling. Their approach was based on a hybrid contouring, where clearing enough space for staircasing was aimed at the contouring step, based on the offset of the contour. Then, staircasing was applied based on the parametrisation and orientation of the tool path. Hsieh and Chu [24] used Particle Swarm Optimization method for optimization of tool path planning in 5-axis milling of ruled surfaces, where machining errors were used as the objective function. In their approach, they relaxed the problem by providing a tolerance band on the constraint of tool-workpiece contact. Then, they compromised between cutter radius and cutter locations. They achieved significantly less errors in tool path planning for 5-axis flank milling type of processes.

In ball-end milling, scallop height is an important criterion in tool path generation in terms of step over value. Especially in semi-finishing and finishing stages the surface is aimed to be generated having a scallop height value lower than the tolerance. In this regard, the tool path length and hence the cycle time depends on the required scallop height. In order to achieve minimum cycle time, generation of tool path for constant scallop height has been an important research topic. In one of the highlighted studies Feng and Li [25] proposed an approach for efficient generation of tool paths in 3-axis ball-end milling of sculptured surfaces. They aimed to keep the scallop height constant throughout the machine surface so that redundant segments of the tool path can be minimized for decreased cycle time. They demonstrated that the same specified machining accuracy can be achieved by shorter tool paths by constant scallop height generation.

Efforts on modelling of 5-axis SSM have gained momentum for the last decades. Budak et al. [26] proposed the first analytical model for simulation of cutting forces and stability limits. The effects of lead and tilt angles on CWEB were included in the process model, enabling the simulation of cutting forces and stability for almost any configuration of 5-axis milling. They demonstrated the use of cutting force simulations in feed rate scheduling and selection of lead, tilt angles for improved stability. Recently, Koike et al. [27] determined the cutting sequence in thin-wall milling according to the static deflections. In another relatively recent study, Budak et al. [28] proposed use of process models in tool path optimization of thin-walled parts such as turbine blades, where the cutting depth is adjusted considering the dynamics of in process workpiece in isoparametric milling tool paths. It was demonstrated that the cycle time can be significantly improved when the cutting parameters are selected considering the process mechanics and dynamics.

In 5-axis milling, selection of tool posture is challenging issue due to the nonlinear relation of process outputs to the tool axis through both the process geometry and mechanics. In the literature, process simulations were used in tool posture selection based on mechanics and dynamics of 5-axis SSM, which is a good insight to the process planners for improved cutting conditions. Layegh et al. [29] used process simulations to account cutting forces, part vibration, and surface quality in determination of preferable tool postures in 5-axis milling processes. However, this was not for a continuous tool path. Later, Tunc et al. [30] proposed a comprehensive approach to account cutting forces, stability and machine tool motion for tool axis selection along a continuous 5-axis milling tool path. They demonstrated that, tool postures could be optimized along a tool path to have level cutting forces, stable cutting depth and as well as smoother machine tool motion. However, they did not cover tool path generation or planning, which is another substantial area of process development.

In 5-axis SSM, contrary to 2½-axis flat end milling, the preferred cutting conditions vary along the path due to the free form surface of the part geometry. Hence, they need to be identified and implemented continuously along the tool path. For instance, stability limit may change due to varying CWEB as the cutting tool progresses along the path, but CAM packages usually allow setting constant cutting depth. Similarly, as discussed in this section the research on integration of process models and tool path generation methods is relatively limited. However, identifying a pre-surface for uniform stability or cutting forces would provide decreased cycle time and improved process quality. In the literature, 5-axis SSM process simulations are mostly used for feed rate scheduling, spindle speed variation and tool orientation optimization as summarized in the previous paragraphs. However, in some cases adjustment of tool path according to the stability limits or cutting forces may be more beneficial especially if the tool axis cannot be modified due to geometrical constraints or if spindle speed variation is not allowed at the CNC controller. However, use of process simulations for tool path planning and generation would further increase milling productivity. For such a purpose, in this paper, as the first time in the literature, an automatic tool path modification approach is proposed for smart 5-axis SSM. Process simulations are used (i) to determine the pre-surface of any desired milling stage and (ii) to modify any pre-finish tool path. Preferable cutting parameters are identified by process simulations considering the interaction between