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Optimal interface surface determination for multi-axis freeform surface machining with both roughing and finishing

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Abstract In the current practice of multi-axis machining of freeform surfaces, the interface surface between the roughing and finishing process is simply an offset surface of the nominal surface. While there have already been attempts at minimizing the machining time by considering the kinematic capacities of the machine tool and/or the physical constraints such as the cutting force, they all target independently at either the finishing or the roughing process alone and are based on the simple premise of an offset interface surface. Conceivably, since the total machining time should count that of both roughing and finishing process and both of them crucially depend on the interface surface, it is natural to ask if, under the same kinematic capacities and the same physical constraints, there is a nontrivial interface surface whose corresponding total machining time will be the minimum among all the possible (infinite) choices of interface surfaces, and this is the motivation behind the work of this paper. Specifically, with respect to the specific type of iso-planar milling for both roughing and finishing, we present a practical algorithm for determining such an optimal interface surface for an arbitrary freeform surface. While the algorithm is proposed for iso-planar milling, it can be easily adapted to other types of milling strategy such as contour milling. Both computer simulation and physical cutting experiments of the proposed method have convincingly demonstrated its advantages over the traditional simple offset method.

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1. Introduction

Multi-axis machining is nowadays widely used in machining freeform surfaces of complicated and high-precision parts, particularly for those large-size parts like blisks of aero-engines and dies and molds in aerospace industry. For a five-axis machine tool, while the two additional rotary axes enable it to possess a larger machining flexibility and achieve a better finish surface quality, its driving ability is often limited due to its complex kinematics and also the relatively poor rigidity of the two rotary tables. On the contrary, in the case of three-axis machining, as the tool axis remains fixed, the three translational axes can endure much higher velocity, acceleration and jerk during the machining. Based on these different characteristics of the two commonly used multi-axis machining types, to machine a freeform surface out of a raw stock, a two-process strategy is often adopted in practice. In the first process (roughing), a large cutter is used and the machining type is three-axis, with the objective of removing most of the material from the raw stock as quick as possible. In the second process (finishing), a five-axis machine tool is used and the cutter is much smaller; this time the primary objective is to achieve a good finish surface quality and to satisfy the specific machining requirements.

Refer to Fig. 1. After the roughing, an intermediate surface S_r is formed so that the volume between the raw stock surface S_0 and S_r has now been removed by means of three-axis machining; this surface will be referred to as the interface surface. After that, in the finishing process, the residual material between this interface surface and the nominal surface S_f will be removed by means of five-axis machining. Obviously, with respect to a fixed type of tool path (e.g., the iso-planar type of tool path, as adopted in this paper), different interface surfaces will result in different machining parameters (such as the depth of cut) for both roughing and finishing process. Because feed rate assignment on a certain tool path crucially depends on these machining parameters (e.g., the depth of cut decides the cutting force which in turn directly affects the maximal feed rate allowed), different interface surfaces will lead to different feed rate schedules for both roughing and finishing and consequently result in different amounts of total machining time.

In this paper, we present an implemented optimization algorithm, together with the accompanying physical cutting experimental results, to address this optimal interface surface determination problem: for an arbitrary freeform surface S_f and the raw stock surface S_0, given a fixed type of tool path (i.e., the iso-planar type), the tools for the three-axis roughing and the five-axis finishing, and the two types of most critical constraints on the feed rate – the kinematic capacities of the machine tool and the maximum deflection cutting force on the cutter, our algorithm aims at finding the best interface surface S_r so that the total machining time of the resultant roughing and finishing process will be minimized. As convincingly confirmed by our physical cutting experiments, such an optimal interface surface often substantially improves the machining efficiency compared with the traditional offset surface.

This paper is organized as follows. In Section 2, a review on the background of this research is given. In Section 3, the iso-planar tool path generation scheme is introduced, and followed by a detailed description of how the in-process workpiece (IPW) is efficiently calculated in the machining process, which determines the cutting force. In Section 4, the optimal feed rate scheduling strategy is given, which considers both the kinematical constraints of the machine tool and the specified deflection cutting force threshold. In Section 5, the construction and optimization algorithm for the interface surface is presented, which is followed by the experimental results and the discussion in Section 6. The paper is concluded in Section 7.

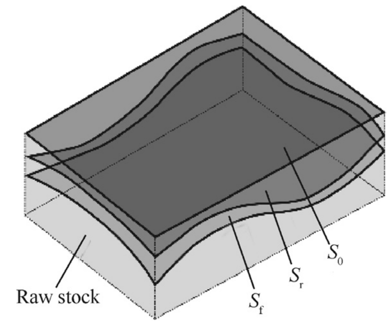

Fig. 1 Illustration of machining stock.

2. Literature review

In the existing works of multi-axis machining of freeform surfaces, much effort has been spent on improving the machining efficiency. In general, they mainly focus on two aspects: one is to reduce the total tool path length with regard to the workpiece itself, and the other is to optimize feed rate for an already generated tool path, so that the tool can move at a higher speed subject to certain physical constraints (such as the maximum cutting force and/or the kinematical limits of the machine tool).

Currently, the most popular types of tool paths in multi-axis machining of freeform surfaces are iso-parametric[1–3], iso-planar[4–7], and iso-scallop height.[8–10] For the iso-parametric and iso-planar type, they inevitably suffer from a common problem of machining redundancy between the cutter contact (CC) curves; in other words, the total length of the tool path is not minimized. Targeting at this issue, the iso-scallop height method as proposed by Suresh and Yang[8] tried to eliminate CC curve redundancy by maintaining a constant scallop height between the neighboring CC curves, and the total tool path length could be reduced in this way. Following this idea, there is a large number of works aiming at further reducing the total tool path length such as by selecting an optimal master cutter path (MCP).[11–14] Nevertheless, in all these works (Refs. 8–14), the tool path is generated in the workpiece coordinate system (WCS), independent of the specific machine tool on which the final physical machining will be executed, and, as always, a constant feed rate is assumed. As a consequence, the machining efficiency is typically not really optimized since the machine tool often has to work at a relatively low feed rate lest its kinematical constraints are violated.

There are also studies on machining efficiency with the kinematical constraints of the machine tool considered. Kim and Sarma[15] introduced a vector field by taking the drives' speed limits into consideration to generate the so called time-optimal MCP. Aimed at maximizing the kinematical