Computers & Graphics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Special Issue on CAD/Graphics 2017

Optimized sequence planning for multi-axis hybrid machining of complex geometries

Li Chen, Ke Xu, Kai Tang*

The Hong Kong University of Science and Technology, Hong Kong

ARTICLE INFO

Article history:
Received 13 June 2017
Revised 10 July 2017
Accepted 11 July 2017
Available online xxx

Keywords:
Hybrid machining
Machinability
Process planning

ABSTRACT

The emerging hybrid machining platform potentiates the manufacturing of complex structures that are previously unmachinable solely by subtractive machining. The essence of such a platform is the alternation incorporating both additive and subtractive process. Multiple alternations are needed to eventually produce a complex model. The planning of the build-up height in each alternation plays a crucial role in the overall process: a large build-up height of partial construction may block the cutter from accessing the in-process part; conversely, frequent alternations will degrade the overall efficiency as well as the surface finish. In order to find a perfect balance, a metric called machinability is proposed to evaluate the subtractive machining feasibility. An efficient algorithm for calculating the machinability under the dynamic obstacle growing environment is then developed accordingly. Based on that, an efficient and deterministic top-down sequential maximization algorithm is presented that is able to minimize the number of alternations while at the same time ensuring a smooth tool path for each subtractive operation. Ample computer simulation examples are given to illustrate the effectiveness of the proposed methodology.

1. Introduction

Traditionally, industrial parts with complex geometries and also high precision requirements are manufactured by a five-axis subtractive machining process out of a raw stock, which is costly and extremely time consuming since up to 80% of material has to be machined off. For instance, for just finish-cut (the final cut), a single large blisk used in aero-engines can take days to machine. The subtractive process is also impaired by the so-called accessibility problem - any area on the workpiece surface must be accessible to the tool so that it is able to contact and remove the excessive material without colliding with other parts of the workpiece or the environment. For a part with slender or curvy features and narrow cavities in between, collision is very likely to occur. This issue also limits the selection of tool and undermines the smoothness of the tool alignment.

On a different note, in some applications, it is required that the tool path follows a specific flow-line direction such that the leftover scallops comply with a specified pattern, e.g., some components in fluid machinery - blisks, impellers and inducers–are required to be machined by a spiral-like tool path. This extra requirement further circumscribes the already limited tool accessible range. To a large extent, the traditional subtractive machining process will no longer be qualified under these requirements.

Additive manufacturing can bypass all the aforementioned issues of the subtractive process. However, current additive manufacturing technologies are limited by their attainable accuracy and surface quality [1,2]. As a result, a part initially additively manufactured always needs a final finish-cutting by five-axis machining, thus still facing the same accessibility issue.

Recently, a new type of machine tool - hybrid machine tool - has emerged in the market that provides an integrated platform of both additive and subtractive processing (see Fig. 1(a)). With the help of this new platform, the additive process and the subtractive process can be integrated into one embodiment [3–5]. It can be anticipated that, with a proper hybrid manufacturing process, a complex component, such as the blisk shown in Fig. 1(b), which originally cannot be machined to realize the desired tool path pattern or is very difficult to be machined at all due to the accessibility constraint, can now be manufactured with high surface quality and authenticity to the specified tool path pattern.

The most challenging issue in hybrid manufacturing is the determination of the alternating sequence $\{A_1, S_1, A_2, S_2, \ldots, A_m, S_m\}$ where A and S stand for additive and subtractive, respectively. As each A_i or S_i requires a new calibration and certain pre-processing of the additive nozzle or the cutting tool, and for each S_i certain residual material must be left underneath the top built contour

* Corresponding author.
E-mail address: mektang@ust.hk (K. Tang).

http://dx.doi.org/10.1016/j.cag.2017.07.018
0097-8493/

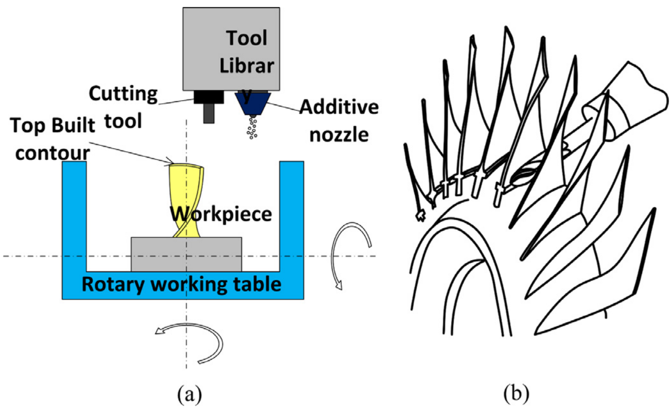

Fig. 1. (a) The typical configuration of a hybrid machine; (b) A blisk of complex shape.

of A_i (see Fig. 1(a)) so that the next build A_{i+1} can start, naturally the number "m" should be as small as possible. However, in the existing literature, to the best of our knowledge, there are no published studies addressing this so called optimal sequence planning problem. In terms of related research, Akula and Karunakaran [6] identified the build direction as an essential parameter in planning a hybrid process. Hu et al. [7] accessed the build direction by taking into account the tool accessibility, the processing time and the number of support structures; users can specify their customized requirements by changing the weights of all these factors. Ruan et al. [8] planned the hybrid process by decomposing the part into non-uniform thickness slices so as to build the part more efficiently. Similarly, a slicing direction is calculated in [9], along which the part is decomposed without overhang features, thus the support structure is avoided. Unfortunately, none of these studies ever mentioned the sequence planning issue when dealing with complex structures. Apart from these works in process planning, other related works in this field mainly concern with the hardware or controller aspects [10–12], which are unfortunately irrelevant to our current issue.

One of the most critical constraints in planning an alternating sequence is the aforementioned "accessibility" for subtractive machining. Fig. 2(a) shows a part which is impossible to be manufactured by the traditional machining due to this accessibility constraint. However, with a hybrid process, it is possible to machine the workpiece when it is partially formed, and the interference is thus avoided given the fact that the potential obstacles (parts of the design geometry) have not yet emerged, as illustrated in Fig. 2(b).

It is worth mentioning that past research in the calculation of tool accessible region in multi-axis machining is prosperous. [13] proposed a configuration space method to map the obstacles and machine limit to a 2-D configuration space to give a feasible tool range. Balasubramaniam [14] proposed a visibility based method which captures the tool accessible range in 3-D Cartesian space. Castagnetti et al. proposed a DAO (Domain of Admissible Orientation) concept to optimize the tool path [15]. Gray et al. devised a rolling ball method (RBM) to avoid the global gouging by positioning the tool inside the rolling ball [16]. Wang and Tang [17] came up with a fast algorithm for calculating the accessible region by updating the boundary of the previous one, assuming the region changes smoothly along the tool path. Most of these sampling based algorithms demand a considerable amount of computing power to achieve an acceptable accuracy. To overcome this issue, an alternative planar accessible range of tool orientation was reported in [18] specifically for blisk machining, which would achieve a real-time performance. Liang et al. [19] recently introduced a boundary based method for constructing an accessible range, where each obstacle surface was simplified as a boundary curve. Both performance and accuracy are considerably increased.

To eventually obtain a smooth tool path under the accessibility constraint, various optimization algorithms have been proposed, which can be categorized into two groups - those that work with respect only to the part coordinate system [14,18,20–23] and hence are independent of the machine tool, and those that work in the machine coordinate system [17,24–26] and thus truly reflect the smoothness of the movement of the machine's axes.

Conceivably, if the alternating sequence is more densely layered (i.e., m is large), each layer would have a better accessibility condition, and thus it would be easier to plan the tool orientation to prevent the potential interference while maintain the smoothness of the final tool path. However, as already pointed out, this better accessibility condition is obtained at the cost of significantly increased total manufacturing time and an inferior surface finish (due to dense marks at the interface between A_i and A_{i+1}). Therefore, the main objective of this research is the development of an algorithm that will, for an arbitrary part and a given tool, find the minimum alternating sequence while maintaining sufficient tool accessibility during each subtractive process S_i.

This paper is organized as follows. First, in Section 2, we describe an important algebraic metric called dynamic tool accessible region and its efficient computation which will be used to evaluate the machinability of layers. Afterwards, in Section 3, we present our main result of the top-down sequential maximization, which essentially leads to our final minimization algorithm. In Section 4, several computer simulation examples are given to illustrate the robustness and effectiveness of the proposed approach. Finally, we conclude the paper in Section 5 with some pointers to future research.

2. Machinability and its calculation

2.1. Metric of machinability

As stated earlier, hybrid machining is known for its capability of manufacturing parts with complex shapes or narrow gap features that are basically unmachinable via traditional subtractive machin-

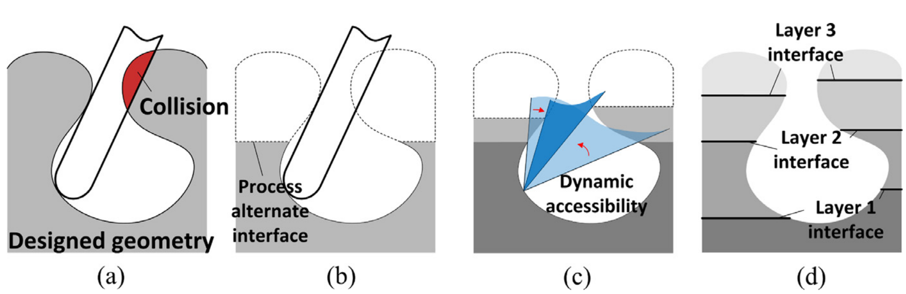

Fig. 2. (a) Collisions in the traditional set up; (b) Collision avoided by an alternating process; (c) Dynamic accessibility; and (d) Alternating process interface.

Please cite this article as: L. Chen et al., Optimized sequence planning for multi-axis hybrid machining of complex geometries, Computers & Graphics (2017), http://dx.doi.org/10.1016/j.cag.2017.07.018