Title:

Determination of Workpiece Postures for 3-Axis Machining Using Milling Simulation Results

Authors:
Masatomo Inui, masatomo.inui.az@vc.ibaraki.ac.jp, Ibaraki University
Sunao Kawai, 24nm427t@vc.ibaraki.ac.jp, Ibaraki University
Nobuyuki Umezu, nobuyuki.umezu.cs@vc.ibaraki.ac.jp, Ibaraki University

Keywords:
Workpiece Posture Determination, Cutting Simulation, Machining Cost Estimation, Process Planning

DOI: 10.14733/cadconfP.2024.23-27

Introduction:

A new business model for manufacturing small quantities of machine parts is gaining popularity, in which parts are ordered online for machining and delivered quickly (e.g., MISUMI's Meviy system in Japan). After a CAD model of the part is uploaded according to a specified procedure, an estimate of the time and price required for machining is displayed, and if it meets the requirements, the order is placed immediately. The processed parts are sent by courier service to the specified date, time, and location for delivery (Fig. 1).

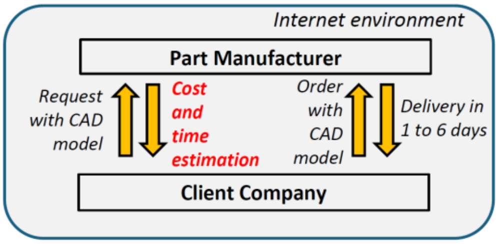


Fig. 1: Online machine part manufacturing business.

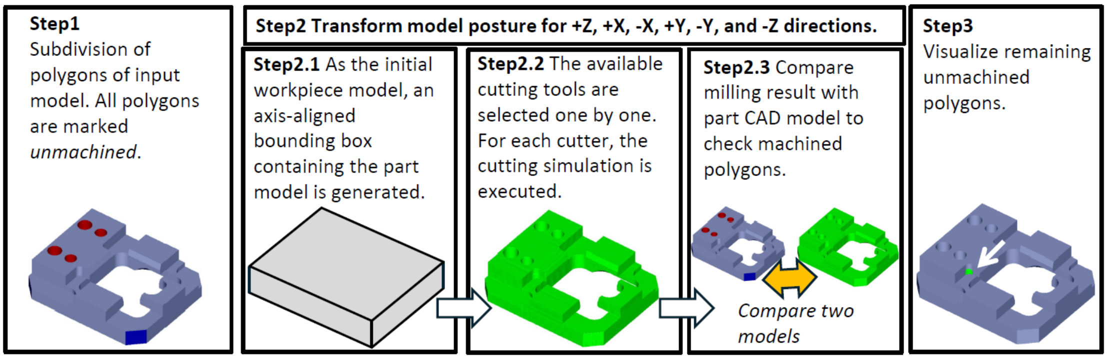
In this type of parts manufacturing, available machining methods are limited to cutting, and the tools used and workpiece mounting methods for machining are also limited to standard ones. Therefore, it is necessary to quickly determine if the uploaded CAD model can be machined with the available tools and specified mounting methods. The number of mounting changes of the workpiece, the type of tooling used, and the necessary machining time should also be determined in the shortest possible time to estimate the costs accurately.

Our laboratory has developed a software system that determines whether a given CAD model is machinable [1, 2]. This method repeatedly simulates cutting operations using prepared tools. If there are any shapes detected that cannot be removed, the system determines that the part is difficult to machine; otherwise, the part is recognized as machinable. In this paper, we extend this method and report on the realization of a software system that estimates the number of times a workpiece needs to be mounted for posture changes. Using this software, computational experiments were conducted on 20-part models to verify the effectiveness of the method.

Main Idea:

Difficult-to-Machine Shape Detection Using Cutting Simulation

The proposed method uses our previously developed software for detecting difficult-to-machine shapes [1,2]. This software assumes that 3-axis cutting operation is only used as the machining method, and the cutting tools to be used is limited to predefined ones. Information on the available cutters (cutting edge type, cutter shape, shank and holder information) is provided beforehand. As the input data, the polyhedral STL model of a machine part is given. A local coordinate frame is placed to a part model. Cutting operation is carried out by repeatedly changing the posture of the workpiece. It is assumed that the cutting operation is carried out by mounting a workpiece in such a way so that any one of the +X, -X, +Y, -Y, +Z, -Z axes of the model coordinate frame points upwards. After the computation, the detected difficult-to-machine shapes are visualized by painting their corresponding areas on the model surface.



Step1 Subdivision of polygons of input model. All polygons are marked *unmachined*.

Step2 Transform model posture for +Z, +X, -X, +Y, -Y, and -Z directions.

Step2.1 As the initial workpiece model, an axis-aligned bounding box containing the part model is generated.

Step2.2 The available cutting tools are selected one by one. For each cutter, the cutting simulation is executed.

Step2.3 Compare milling result with part CAD model to check machined polygons.

Step3 Visualize remaining unmachined polygons.

Fig. 2: Simulation-based difficult-to-machine shape detection method.

The processing flow of the algorithm is given below (Fig. 2).

Step 1: Each polygon of the input model is examined, and when the length of the longest edge of the polygon is greater than the predetermined length *l*, the polygon is subdivided such that all the edges of the polygon become shorter than *l*. All the polygons are then marked as *unmachined*.

Step 2: The posture of the part model is transformed in an order such that either the +Z, +X, −X, +Y, -Y, and −Z axis directions in the local coordinate frame of the model point upward. For each model posture, the following steps are executed:

Step 2.1: An axis-aligned bounding box containing the part model is generated. This box is considered to be the initial shape of the workpiece.

Step 2.2: The available cutting tools are selected one by one. For each cutter, the following operations are executed:

- The Minkowski sum of the part model and the inverted shape of the selected cutter is computed. A zigzag-type cutter path is generated to machine the entire model based on the Minkowski sum shape.
- The geometric cutting simulation is performed using the obtained cutter path and the tool shape data. The shape model of the workpiece is modified in the simulation process.

Step 2.3: The workpiece shape obtained by the cutting simulation is compared to the part model. If each small polygon of the part model is machined accurately, the mark of the polygon is changed from *unmachined* to *machined*.

Step 3: The polygons with the remaining *unmachined* marks are painted green to highlight the difficult-to-machine shapes in the model surface (Fig. 3).

This software only refers to the shape of the part and does not consider the workpiece shape when generating tool paths. In actual machining, there are cases where machining becomes difficult due to interference between the tool holder and the workpiece, but this software does not consider such cases.

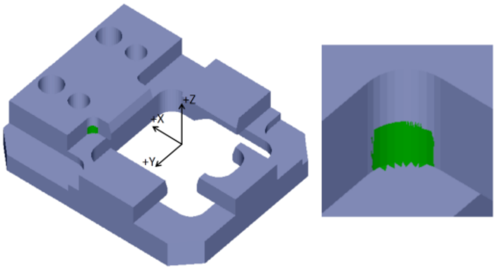
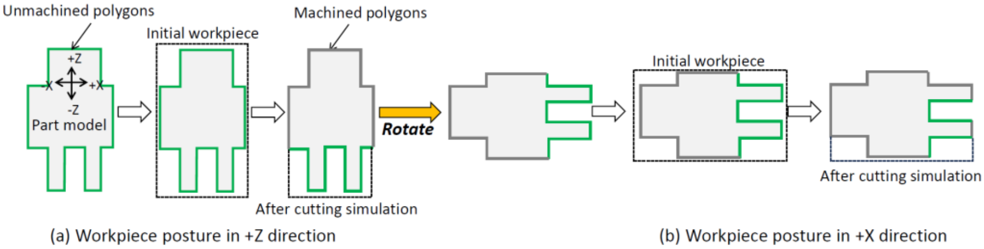


Fig. 3: Detection result of difficult-to-machine shapes using our system.

Selection of Necessary Workpiece Postures

In our study, a simple Z-map model was used to record the results of the geometric cutting simulation. Because the Z-map model cannot change its posture, the box-like workpiece model is re-created whenever the model posture changes in the +Z, +X, −X, +Y, -Y, and −Z directions. After the cutting simulation, the part model and the machined workpiece model are compared to check whether each polygon of the part model has been processed accurately. When the removal of the material from the polygon is completed, the *unmachined* mark of the polygon is changed to *machined*, and the cutting result is recorded in the polygons of the model.



(a) Workpiece posture in +Z direction

(b) Workpiece posture in +X direction

Fig. 4: Machinable polygon detection process.

Fig. 4 illustrates this process. As the preparation, all surface polygons of the part model are marked *unmachined* (green color in the figure). In the initial machining, the model is oriented so that its +Z axis points upward. A box-like workpiece shape is defined and the cutter path computation and the cutting simulation are done. By comparing the part model with the machined workpiece model obtained by the simulation, the machining result of each polygon is checked. Its *unmachined* mark is changed to *machined* (gray color) when the material removal for the polygon is completed. The model is then set so that the +X axis points upward. A box-like workpiece is redefined for the model in the new orientation, and the same process is repeated.

In the above software, cutting simulations were repeated while changing the posture of the workpiece in six different directions. For many parts, however, machining can be completed with fewer posture changes. This is illustrated in Fig. 5 and 6 for two-dimensional machining. In this case, up to four posture changes are possible, with each of the +X, -X, +Z, and -Z axis pointing upward, but in reality, machining can be completed with only two workpiece postures as illustrated in Fig. 6. Changing the workpiece posture is a time-consuming process that requires the detaching and remounting the workpiece and the subsequent adjustment of the origin. Therefore, the fewer the number of posture changes, the faster and cheaper machining can be performed.

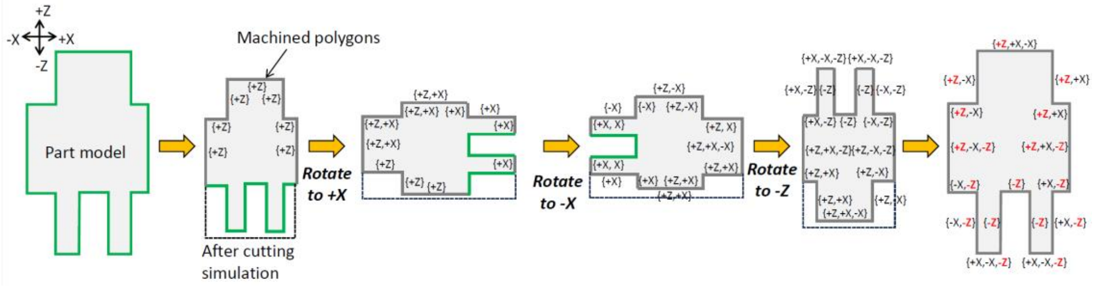


Fig. 5: Recording of workpiece posture information to each machinable polygon.

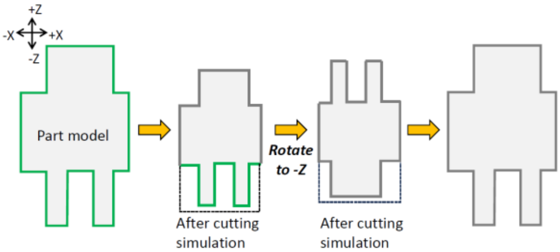


Fig. 6: Detection result of the minimum workpiece posture changes.

We have developed a technique to determine the minimum number of workpiece postures by extending our software to detect difficult-to-machine shapes. In the conventional software, a cutting simulation is performed for each workpiece posture, and then each surface polygon of the part model is checked and recorded to determine whether machining the polygon is complete or not. The recording method is modified in our new software to include the workpiece posture information for each polygon that is determined to be machinable at a certain workpiece posture. In Fig. 5, a cutting simulation is performed for each workpiece posture in the +Z, +X, -X, and -Z axis, and the polygons for which machining is completed are recorded with the workpiece posture information at that time. After the cutting simulations, we can see that machining can be completed in only two workpiece postures for +Z and -Z axes by examining the record (see the rightmost figure in Fig. 6).

The following is a brief description of the implementation method. In conventional software, only *machined* or *unmachined* status is recorded for each small polygon. The new implementation expands this recording area to record the *machined* (= 1) or *unmachined* (= 0) status for each of the +X, -X, +Y, -Y, +Z, and -Z workpiece postures for each polygon. At the initialization of Step 1, an *unmachined* mark (0) is recorded for the six postures for all polygons. In Step 2.3, the machined/unmachined status of each polygon is checked, and if it is machined, the area corresponding to the workpiece posture of that polygon is set to 1. The processing in Step 3 is also changed to accommodate the new recording method. For each polygon, the six recording areas corresponding to the workpiece postures are checked, and if even one area is found that is set to 1, the polygon is determined to be machinable. If a polygon has a 0 in all the recording areas, it is judged to be unmachined, i.e., difficult-to-machine polygon.

Finally, based on the data recorded in the polygons, the following algorithm is used to determine the required combination of workpiece postures.

Step 1: Examine all the small polygons and extract polygons that have zeros recorded in all six recording areas. These polygons are excluded from further processing because they are difficult to machine in any postures.

Step 2: For each combination of the 6 workpiece postures (1 posture: 6, 2 posture combination: 15, 3 posture combination: 20, 4 posture combination: 15, 5 posture combination: 6), the following operations are performed.

- For all polygons, examine the recording area corresponding to the given posture combination. If a 1 is recorded for any of the recording areas, the polygon can be processed for the given posture combination. If all polygons can be machined, the workpiece posture combination is recorded as the required workpiece postures.

Step 3: The smallest combination of the recorded workpiece postures is output as the solution.

Since there are only 62 (= 6 + 15 + 20 + 15 + 6) possible combinations when all combinations are examined, it requires only a small increase in processing time compared to the conventional method.

Computational Experiments

The described algorithm was implemented using C++ in VisualStudio 2017 environment to detect difficult-to-machine shapes for 20-part models provided by a company while simultaneously calculating the minimum combination of workpiece postures required. The increase in computation time due to the additional processing was negligible (tens of milliseconds). Cutting simulations were then performed using only the obtained combinations of workpiece postures, and the machining results obtained were compared with those obtained when cutting simulations were performed with all six postures using the conventional method. The results were in perfect agreement for 20 cases, validating the effectiveness of the proposed method.

Conclusions:

This paper describes software that determines the minimum combination of necessary workpiece postures by extending the technology for detecting difficult-to-machine shapes using the cutting simulation. Computational experiments were conducted on several part models using the developed software, and it was confirmed that appropriate combinations of workpiece postures could be obtained. The time required for the newly added processing is negligible.

Finally, future enhancements to the method are described. (1) In the current system, the required posture is selected from six predefined postures. This method should be extended to automatically determine the candidate workpiece postures based on the part geometry without the predefined ones. This problem is similar to the determination of the necessary spindle directions in the 3+2 axis machining [3]. (2) The number of tools used in the machining also has a significant impact on the machining costs. Current software performs machining simulations using all available tools, some of which do not contribute to workpiece removal. It is necessary to develop software that determines the necessary tool combinations. (3) Our software does not consider the influence of workpiece shape in the machining. To improve the accuracy of detecting difficult-to-machine shapes and determining the necessary workpiece postures, it is necessary to implement an algorithm that takes the workpiece shape into account in the solution.

Masatomo Inui, https://orcid.org/0000-0002-1496-7680
Sunao Kawai, https://orcid.org/0009-0001-3934-7701
Nobuyuki Umezu, https://orcid.org/0000-0002-7873-7833

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