Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Technological requirements of profile machining

PARK Sangchul†, CHUNG Yunchan

(*Department of Industrial Information & Systems Engineering, Ajou University, Suwon 443-749, Korea*)

†E-mail: scpark@ajou.ac.kr

Received Mar. 29, 2006; revision accepted June 3, 2006

Abstract: The term 'profile machining' is used to refer to the milling of vertical surfaces described by profile curves. Profile machining requires higher precision (1/1000 mm) than regular 3D machining (1/100 mm) with the erosion of sharp vertices should being especially avoided. Although, profile machining is very essential for making trimming and flange dies, it seldom brought into focus. This paper addresses the technological requirements of profile machining including machining width and depth control, minimizing toolware, and protecting sharp vertices. Issues of controller alarms are also addressed.

Key words: Profile machining, Technological requirements, Protecting sharp vertices
doi:10.1631/jzus.2006.A1461 **Document code:** A **CLC number:** R733.7

INTRODUCTION

Many products, from automotive body panels to television consoles, are designed with sculptured surfaces, and all rely on sculptured surface machining technology for the production of the dies and moulds used in manufacturing. Since the quality of machining is no better than the quality of its tool path, generating an accurate tool path in an efficient manner has been investigated by numerous researchers. Profile machining refers to the milling vertical surfaces described by profile curves (generally 3D curves), and it has different technological requirements from those of sculptured surface machining. Although, profile machining is very essential for making trimming and flange dies, there has been very little work on the technological requirements of profile machining.

In the case of profile machining, the required machining accuracy is much higher than regular sculptured surface machining. It is also important to observe that profile machining is not a 2D machining operation, because it has to machine 3D profile curves. In other words, the z-values of profile tool-path should be continuously changing according to the given profile curve. To meet these requirements, die makers use cutter radius compensation of NC controllers (also called cutter diameter compensation) for profile machining.

Fig.1 shows the concept of profile machining. For profile machining, the NC programmer gives the original profile curves (without offsetting) to the machining operator, as shown in Fig.1a. Actually, the NC programmer does not know the cutter radius at this stage. When the machining operator (at the shop floor) gets the profile curves, he needs to determine the proper cutter and measure the exact cutter radius (Fig.1b). Then, the machining operator enters the cutter radius to the machine controller for the cutter radius compensation.

While sculptured surface machining has received significant amount of attention from many researchers, profile machining has been rarely brought into focus. Curve offsetting (Park and Chung, 2003; Choi and Park, 1999; Shin *et al*., 2003), curve approximation (Schonherr, 1993; Yeung and Walton, 1994; Shin *et al.*, 1995) and cutting load analysis (Bae *et al*., 2003; Geoffrey, 1975) can be referred to as profile machining related work but most machinists focus on certain geometric issues rather than the technological requirements of profile machining. The objective of this paper is to identify important technological requirements of profile machining, and

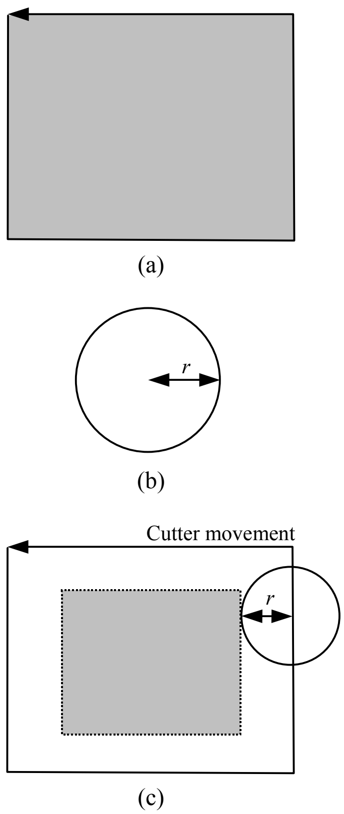

Fig.1 The concept of profile machining. (a) Profile curve (top view); (b) Cutter selection at the shop floor; (c) Input the cutter radius to the machine controller for profile machining (cutter radius compensation)

discuss some of the remedies for satisfying the technological requirements. In this paper, the term 'profile machining' refers to the 3D profile machining using cutter radius compensation of NC controllers.

CUTTER RADIUS COMPENSATION FOR DIE AND MOULD MACHINING

Most NC machines provide the functionality of cutter radius compensation because of the following benefits: (1) The NC programmer does not have to know the available cutters at the shop floor; (2) It allows the machining operator to choose from a set of available cutters at the shop floor. For the machining accuracy of profile machining, it is very important to know the exact cutter radius. The required machining accuracy is higher than sculptured surface machining, because profile-machined surfaces should be assembled tightly with other parts. In automotive die making, NC programmers use CAM systems to prepare NC data (also called NC program), consisting of commands to control NC machine. But when they make NC programs, it is very difficult to know the exact cutter radius of the available cutter at the shop floor. Although we assume that it is possible to know the exact cutter radius during preparation of the NC program, the cutter might not be available when it is machined because cutters are easily broken, worn and have to be re-grinded. This is why NC controllers support the cutter radius compensation features to allow a machining operator to choose from a range of cutter sizes.

At run time, the NC controller offsets the profile curve (programmed path from NC programmers) to compensate the cutter radius. Since NC controllers have only very simple offset functionalities, they offset the profile curve segment by segment as the cutter machines by following the profile curve. The offset algorithm adopted in NC controller is much simpler than that of a CAM system. It considers at most 3 to 5 segments (linear or circular) in advance. When the NC controller processes complex profiles, it could make self-intersections in the offset path (cutter center path) as shown in Fig.2 (Fanuc Ltd., 1993). Self-intersection might cause many serious problems including over-cuts, cutter collisions, and controller alarms stopping the machining operation.

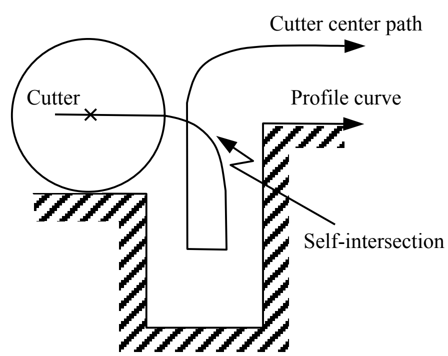

Fig.2 Self-intersection

To avoid the self-intersections of the compensated tool-path (cutter center path), it is necessary to simplify the profile curve before giving it to the NC controller. Fig.3a shows an example of a complicated profile curve, which cannot be offset (compensated) by a regular NC controller. Let us assume that we know the maximum cutter radius (R) which can be used for the profile machining. Then we can simplify the profile curve by two times of offsetting, outward and inward with the same offset distance R, as shown in Fig.3b and Fig.3c. As a result, we obtain a simplified profile curve (Fig.3d) guaranteeing that it makes no self-intersections as long as the cutter radius for the compensation is smaller than R (maximum cutter radius). In this way, the profile curves should be processed to simpler curves, so that NC controllers can compensate the cutter radius without making errors and failures. CAM systems that support profile machining using cutter radius compensation make rounds at each concave corner, which makes controller alarms and over-cuts. The size of rounds should be greater than the largest radius of cutter that a machining operator will use for the machining at the shop floor.

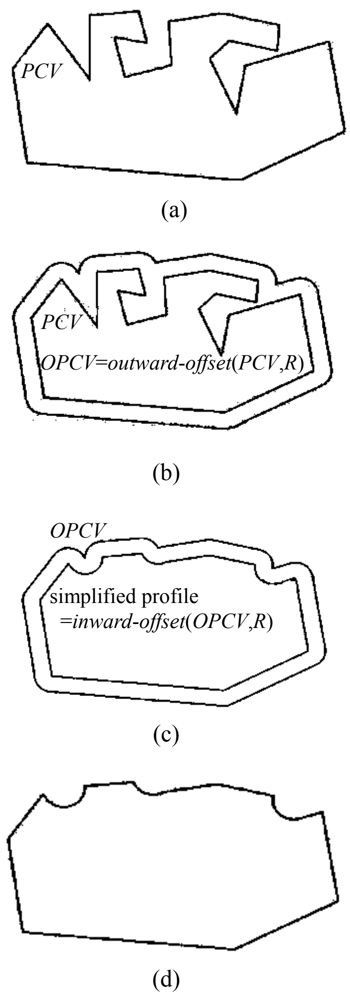

Fig.3 Simplifying a profile curve. (a) A complicated profile curve; (b) Compute *OPCV* by outward offsetting of the profile curve; (c) Compute simplified profile by inward offsetting of *OPCV*; (d) Simplified profile

Although, many CAM systems support the tool path generation functionality for the profile machining, most of them only support 2D profile machining, in which the profile curves exist on the xy-plane. They do not support automated or unattended machining processes for complex press dies. For automotive die making the 3D profiling, surely using cutter radius compensation, is useful in outer and inner boundary profiles in drawing, trimming and flange dies. It can also be used in piercing holes, especially in making non-circular type holes.

Some operators in die shops use the tool-paths from 2D profiling features of CAM systems for 3D profiling. In this case they have to control the z-values of the tool while profile machining. Other operators do not use cutter compensation features and have to prepare the exactly same size cutter with the cutter defined in tool-path generation. Operators have to spend much time with care for roughing and semi-finishing. To make the entire die machining processes automated and unattended, sculptured surface machining is not the main obstacle anymore. Profile machining is rising to an important task. This serves as a motivation to summarize the technological requirements of profile machining and implementation issues on tool-path computation.

TECHNOLOGICAL REQUIREMENTS OF PROFILE MACHINING

There are many technological requirements for profile machining as follows.

(1) Collision avoidance. Collision-free machining is a critical requirement for profile machining, and it is a challenging problem. There are many structural and mechanical parts near the boundary profiles especially in trimming and flange dies. Some structural parts are not represented in CAD model, which has geometric shape information for dies, even the shape is simple rather than die surfaces. Recently die makers modelling the structural parts in CAD model are getting common. Another difficulty of collision-free machining is that the parts to be machined are cast faces so the exact shape is unknown in CAD model.

(2) Gouge avoidance. Gouge-free machining is also an important thing. Gouge (i.e. over-cut) could arise easily since the cutter center paths are different from programmed paths. However, many gouge cases in profile machining come from an operator's mistakes. Automated and unattended machining using the tool-paths from CAM systems could remove operators' mistakes.

(3) Alarm avoidance. Alarms of a NC controller are another difficult problem when profiling using cutter radius compensation. Alarm stops the machining operation immediately, and forces the machining operator to check the machine condition.

(4) Sharp vertex protection. Profile machining requires higher precision (1/1000 mm) than regular 3D machining (1/100 mm) and especially the erosion of sharp vertices should be avoided. Fig.4a shows an example of a conventional type tool path for profile machining. Observe that the sharp vertex P_1 is milled by an arc tool-path-element, which seems good enough. However technologically, it is inadequate to use this arc-tool-path-element, because the cutter contacts the sharp vertex (P_1) all along the arc. Due to the oscillations of the machine and the cutter, the sharpness of the corner is destroyed. Though most NC controllers provide cutter radius compensation functionality with a mitered offset option, it is not applicable to the profile machining of curves with global interference, since the controller looks only a few segments ahead. As shown in Fig.4b, mitered offsetting can avoid the vertex erosion problem by replacing the arc with line segments.

(5) Avoiding unbalanced cutter wear. In profiling flat-end-mill has been widely used, and machining operators need to be careful to prevent the unbalanced cutter wear at specific portion of a cutter, as shown in Fig.5.

(6) Keeping down-milling. Fig.6 shows the examples of up-milling and down-milling. One of the key characteristics of up-milling is that the cutter is pulled toward the workpiece (while it tends to be pushed away from the workpiece in down-milling). This phenomenon could lead to a fatal consequence when a slender end-mill is used in up-milling. That is, once the end-mill is pulled toward the workpiece, the cutting-load will be increased, which in turn will pull the cutter further toward the workpiece, and so on. Thus, one of the rules in machining is that up-milling

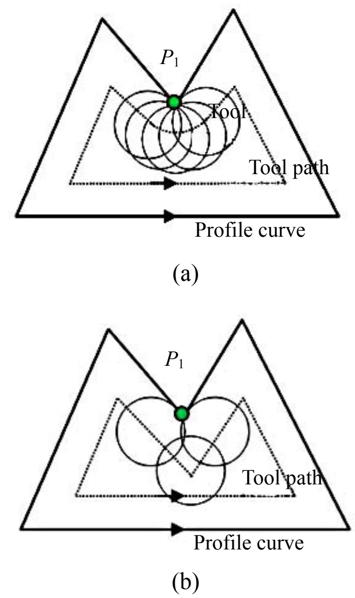

Fig.4 Protecting sharp vertex. (a) Undesirable machining for protecting sharp vertices; (b) Desirable machining for protecting sharp vertices

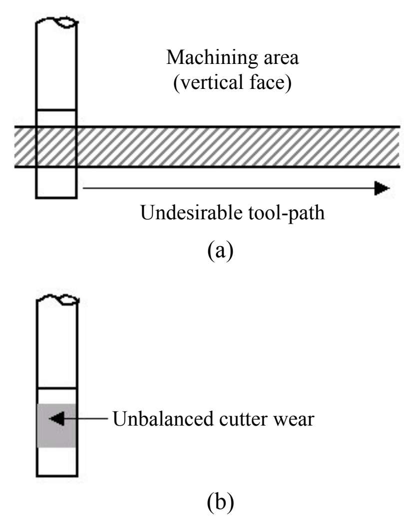

Fig.5 Unbalanced cutter wear
(a) Undesirable tool-path; (b) Unbalanced cutter wear

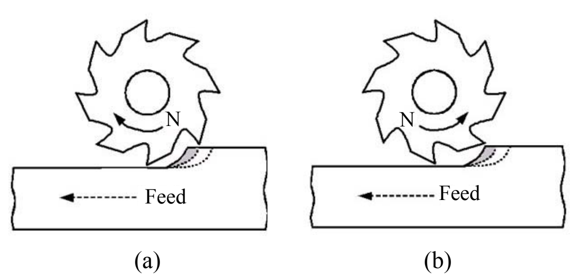

Fig.6 Down-milling (a) and up-milling (b)

with a slender end-mill should be avoided if possible, because it could lead to a gouging, chatter, even cutter breakage. Thus, down-milling is mostly favored in profile machining.

PROCEDURE TO GENERATE TOOL PATH FOR PROFILE MACHINING

Fig.7 shows a procedure to generate tool paths for profile machining and the technological requirements identified previously. The procedure consists of four major steps: (1) Simplification of the profile curves; (2) Collision check with structural parts; (3) *z*-value variation; (4) Tool-path linking. Among these four steps, the first step is the most important because it needs to satisfy three technological requirements, as shown in Fig.7. As already mentioned in the previous section, it is necessary to simplify the profile curves by applying two offsetting operations (outward and inward) consecutively to avoid the gouges and the controller alarms, as shown in Fig.3. To protect the sharp vertex, we need to employ the mitered offsetting approach (Fig.4). As a result, we need to simplify the profile curves with two consecutive offsetting operations with the mitered offsetting policy.

To avoid unbalanced cutter wear, we need to vary the *z*-values of the tool-path, as shown in Fig.8. For the last requirement, keeping down-milling, we need to link the tool-path carefully. As shown in Fig.6, when the cutter rotates clockwise, the wall should be on the right side of the cutting direction for down-milling. Other than the up/down milling, it is also necessary to consider the approach and retraction path geometry, as shown in Fig.9.

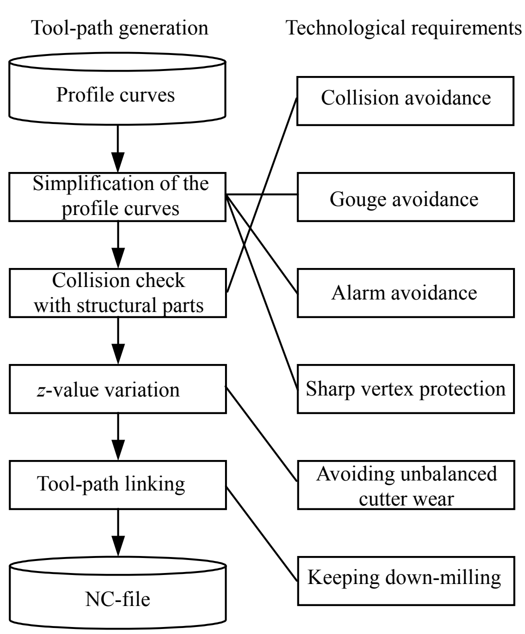

Fig.7 Tool-path generation procedure and the technological requirements

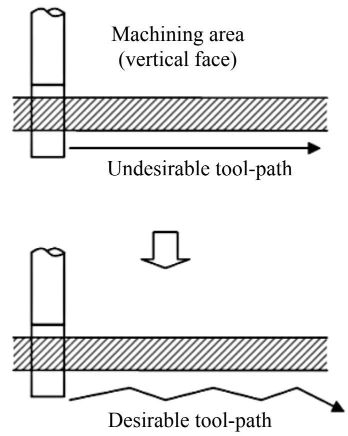

Fig.8 *z*-value variation

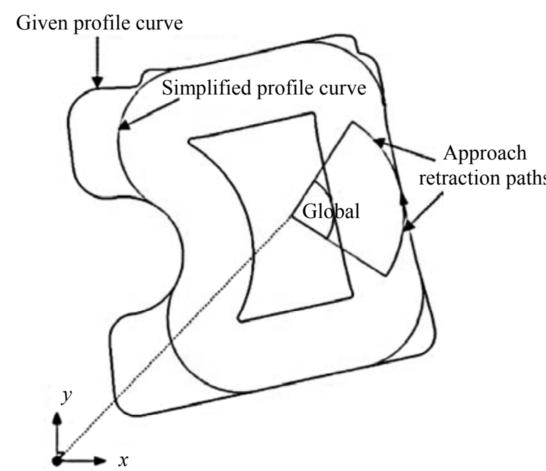

Fig.9 An example of the generated tool-path

CONCLUSION

This paper identifies important technological requirements of profile machining, and discusses some of the remedies for satisfying the technological requirements. Cutter radius compensation is useful feature to mill profile shape in high accuracy but difficult to use and automate. This paper summarizes the technological requirements in machining side and implementation issues on calculating the tool-paths in CAM systems.

Conceptually the final curve obtained by two times of offsetting as shown in Fig.3 does not make self-intersection, which causes an alarm when NC controller compensates cutter radius with the curve. But the simplified curve still might cause NC controller alarms in the real situation. It might come from the floating point errors. In this case, NC-controller raises an alarm when the starting and ending points of two consecutive offset segments are very different (in controller side) and there is no intersection point with the two offset segments. This type of alarming is very often due to an NC-file format supporting only two or three digits below the decimal point.

References

Bae, S.H., Ko, K., Kim, B.H., Choi, B.K., 2003. Automatic feedrate adjustment for pocket machining. *Computer-Aided Design*, **35**(5):495-500. [doi:10.1016/S0010-4485(01)00195-6]

Choi, B.K., Park, S.C., 1999. A pair-wise offset algorithm for 2D point-sequence. *Computer-Aided Design*, **31**(12):735-745. [doi:10.1016/S0010-4485(99)00060-3]

Fanuc Ltd., 1993. Fanuc Series 15-Model B, Maintenance Manual, **1**(2):100.

Geoffrey, B., 1975. Fundamentals of Metal Machining and Machine Tools. McGraw-Hill, p.29-39.

Park, S.C., Chung, Y.C., 2003. Mitered offset for profile machining. *Computer-Aided Design*, **35**(5):501-505. [doi:10.1016/S0010-4485(02)00065-9]

Schonherr, J., 1993. Smooth biarc curves. *Computer-Aided Design*, **25**(6):365-370. [doi:10.1016/0010-4485(93)90031-I]

Shin, H., Jeong, H.M., Kwak, Y.S., 1995. Machining of 2D parametric spline using cutter radius compensation. *IE Interface*, **8**(3):133-139.

Shin, H., Yoo, S.K., Cho, S.K., Chung, W.H., 2003. Directional offset of a spatial curve for practical engineering design. *Lecture Notes in Computer Science*, **2669**:711-720.

Yeung, M.K., Walton, D.J., 1994. Curve fitting with arc spline for NC tool path generation. *Computer-Aided Design*, **26**(11):845-849. [doi:10.1016/0010-4485(94)90099-X]