Feed speed fluctuation in simultaneous five-axis machining using an end mill

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Abstract

Machining of free-form surfaces using a five-axis machining centre using end mill is attracting attention. Sudden load fluctuations are not desirable in end milling as this causes scratches or dent on the surface. However, although commercially available high-end CAM (Computer Aided Manufacturing) software controls the load by changing the depth of cut, the current situation is that CAM software does not fully care in how the generated CL (Cutter Location) data and NC (Numerical Control) programs are processed by the NC unit. When surface scratches occur in actual machining, it is extremely difficult to determine whether the problem is in the tool geometry, the geometric accuracy of the machine, or the performance of the CAM software. Unless the cause is identified, it is difficult to make improvements, which is why we hesitate to introduce 5-axis simultaneous machining.

The S-shaped machining test, which was proposed as a performance test for five-axis machining centres, was registered as an ISO standard despite having various problems in each stage of 3D (three dimensional) model generation, machining, and measurement. This test method is more like a CAM software performance test involving software and machine operators than a machine performance test. In this study, a new problem is reported having been discovered by conducting S-shaped machining tests using commercially available CAM software and actual machines. This is a problem that occurs not only in the S-shaped machining test but also in 5-axis simultaneous machining using all end mills. Proposals will be made on how to correct the NC program on site and how to improve the performance of NC units and CAM software.

1 Introduction

Machining of free-form surfaces using a 5-axis machining center using end mill is attracting attention. Especially in the field of die and mold machining, the orientation of the cutting tool can be freely adjusted, so machining can be performed near the outer periphery of the tool, which improves efficiency. On the other hand, however, users continue to use 3-axis controlled machine tools because there is the disadvantage of increased machine costs.
One of the problems with 5-axis machining centres has long been said to be "bad machining accuracy." There are various reasons for this, but one of them was the fact that the motion accuracy of the machine was actually poor. Regarding this problem, there has been a movement to develop and to establish test methods of the machine since the end of the 20th century, and as a result, the ISO has published an accuracy test method. [1-3] However, there is more than one factor that deteriorates machining accuracy. Most machine users use CAM software to create NC programs when using 5-axis controlled machine tools, but many CAM software also exists, ranging from high-end to low-cost, and there is a considerable difference in performance. Also, the workpieces that each software is suitable for are different. Users have to carefully compare the cost and performance of each CAM software before selecting and working with them, but that is actually impossible. Therefore, readily available software are used for processing, resulting in products with poor accuracy.
In this research, as information for users of 5-axis controlled machine tools, the problems of CAM software and NC are introduced, and the careful points in order to aim for higher precision machining are shown. Concretely, the sources that causes fluctuations in the feed speed during side-milling by an end mill are shown, and also countermeasures are shown. Finally, some points to note regarding the processing for the test method recently published in ISO as a reference, is presented.

2 Influence of feed rate fluctuation in the machining using end mill

2.1 Types of machining using end mill

In this research, the accuracy and scratches are considered when end milling a curved surface. In die and mould machining, if there is bad surface roughness or scratches in addition to size accuracy, a lot of time is spent in finishing, so it is desirable to create as smooth a surface as possible only by cutting.
Ball end mills are generally used for curved surface machining, but from the viewpoint of machining efficiency, it is better to be closer to the side than the centre point, and it is best if the side milling can be used. When machining only on the side, only curved surfaces called ruled surfaces can be machined. Recently, from such a point of view, a tool with a shape called a barrel tool has been used.

2.2 The usege of 5-axis control machine tools and problems

2.2.1 Indexing

During machining, only the three linear axes are moved, and the rotary axis is operated intermittently. With this method, it is not necessary to consider the dynamic error of the rotary axis, only the static error. In addition, if the indexing angle is limited, 3-axis compatible CAM software can be used.
As for the problem of machining accuracy, there is a very high probability that steps will occur at different indexing angles.

2.2.2 Simultaneous 5-axis machining

With simultaneous 5-axis machining, the most important problem in curved surface machining accuracy is the accuracy of the spherical surface of the cutting tool. Generally, the positioning accuracy in X, Y, and Z is considered to be about 10 – 30 μm, but there are tools whose spherical accuracy of a ball end mill is worse than that. Recently, ball end mills with better spherical accuracy have become known.
In addition, the rotary axes always operates. Although the position of the tip of the tool relative to the workpiece does not move much, not only the rotary axes but also the linear axes may move significantly in order to change the orientation of the tool, which may also be a problem in terms of necessary energy supplied. Also, the ability of CAM software to generate simultaneous 5-axis cutter locations varies greatly, so it is of great interest to the user which software to use.

2.3 Influence of feed speed fluctuation

In general, the material that is machined by machine tools is metal, and it is hard to some extent. Deflection occurs when the end mill is pressed to the work piece. As a result, the calculated centre position of the end mill is displaced, resulting in an uncut portion from the calculated machining shape. For this reason, it is well known that at the places where the load on the tool is large, such as concave corners, the deflection of the tool is large, resulting in large machining errors.
In addition, since the end mill tool is cantilevered, machining on the side is efficient, but the stiffness is low. This is a good thing, and even if the machining point of the ball end mill is gradually moved from the side to the tip of the tool, the deflection of the tool will only change gradually, so there will be no steps or dents due to this.
However, there is also curved surface machining that uses only the side of the tool, such as SWARF (Side Wall Axial Relief Feed) machining shown in Fig. 1 [4]. In this case, when the tool feed speed with respect to the workpiece fluctuates, a step occurs due to the fluctuation of the load. Curved surfaces that

can be obtained by SWARF processing are limited to ruled surfaces, so there are not many, but many CAM software support this function.
Simultaneous 5-axis machining enables machining of twisted curved surfaces. Rough machining such as impeller machining can be finished efficiently because the side of the tool can be used widely.

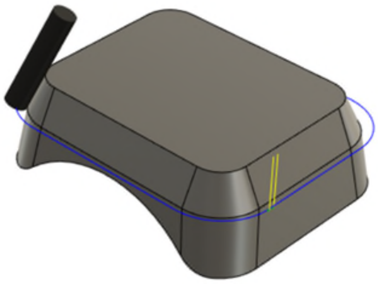


Figure 1: SWARF cutting

3 Example of applying 5-axis SWARF cutting to finishing accuracy test

3.1 Cone frustum cutting

Cone frustum cutting test was established in the NAS standard in the old days [5], and was well known as the only standard for testing the accuracy of 5-axis machining in the 20th century. However, the test method is too ambiguous, so a strict definition was made when introducing 5-axis control and revising the test conditions for machining centres [3].
Also, a method of measuring motion similar to cone frustum cutting without machining was introduced in [2] using a ball bar. In general, machining tests require preparation of a workpiece, machining, and then measurement with a measuring machine such as roundness measuring machine, which is time-consuming. On the other hand, tests using a ball bar are efficient because the results are available immediately after the machine is operated. This is especially advantageous when changing machine settings such as NC parameter tuning.
In a ball bar test, for example, if there is a dent or glitch in the measurement result, it cannot be determined in which part of the inclined cone the dent occurs unless the tool center point moves along the side of the cone at a perfectly constant speed. Therefore, NC programs for ISO 10791-6 AK3, BK3, CK3 [2] inclined cone frustum measurements are generally created using spreadsheet software without using CAM. On the other hand, in machining test with 10791-7 M3 [3], even if the feed speed fluctuates slightly, the load on the tool does not change unless it fluctuates abruptly, so it is common to use CAM for NC programing.

3.2 S-shaped machining test

3.2.1 Overview

S-shaped machining test was proposed in 2012 in ISO meeting as a finished test piece for 5-axis machining centres and had been discussed. It has been changed several times, but it is published in 2020. The final version of S-shaped test specimen in 2020 has a thin wall whose shape is a mirror image of "S" on the base with a maximum dimension of 310 × 210 × 50 mm, as shown in Fig 2.

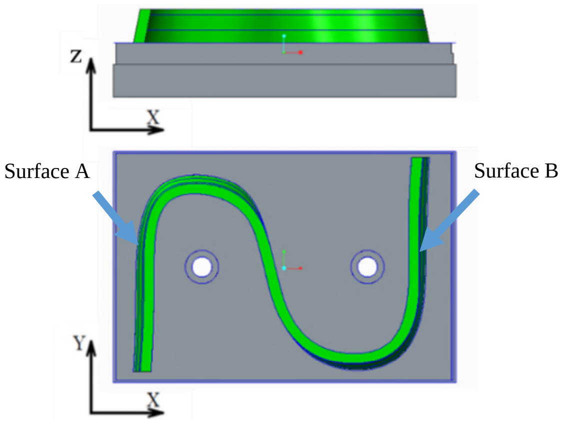


Figure 2: 3D model of S-shaped cutting test piece according to [3]

The S-shaped inclined thin wall of a test piece is machined by simultaneous 5-axis control with a flat end mill, and the shape error of the workpiece is measured and accuracy is evaluated as the machine's accuracy.

The thin wall of the S-shaped part is formed by a ruled surface defined by two upper and lower spline curves, and is twisted at the centre. The inclination angle of the S-shaped part with respect to the base is always changing, and the maximum inclination angle is about 18°, and the minimum inclination angle is 0°. Therefore, when the S-shaped machining test is performed on 5-axis machining centre, the orientation of the tool axis always changes along the side surface. For this reason, it is said that S-shaped cutting test can inspect the simultaneous multi-axis motion accuracy of 5-axis machining centre under cutting conditions.

This test was finally adopted as an informative annex in ISO10791-7, but many people have pointed out that various problems will arise when it is carried out. The first problem is to create a 3D model from given points of the spline curve. This was solved by giving the 3D model in STEP format. The second problem is evaluating finished results based on factors such as surface smoothness other than positional dimensions. This is a problem deeply relevant to this research. In the end, it was decided to evaluate only positional dimensions, but the smoothness of the surface is still emphasized in exhibitions of machined products. The third problem is the addition of unwanted rotation at the centre of the workpiece. This will be mentioned in detail in the next section. Finally, this workpiece has undercuts that are difficult to measure dimensions.

3.2.2 Singularity

The thin wall of the S-shaped part is twisted, and there is a point perpendicular to the mounting surface (base) near the centre. In this research, this point is called singularity. At this point, the tool orientation is perpendicular to the base. For example, in the case of an inclined rotary table type (trunnion type) 5-axis machining centre equipped with A- and C-axis, A-axis is 0° and C-axis can take an arbitrarily angle.
The presence of this singularity makes it difficult to implement this S-shaped test. In other words, the processing of the singularity here depends on the performance of the CAM software itself and the ability of the operator to handle the software. It has been found that the performance of the post processor does not fully utilize the moving range of the machine's axes and adds unnecessary half-turn motion to the rotary table. [6]
In the model submitted as a draft proposed at the 2015 ISO meeting (Version 3.1), the singularity was one central point. As it was pointed out on the ISO meeting that it might cause unnecessary motion and sudden turning, the 2017 proposal was revised to a section with a certain length rather than one point (Version 4.1) (Fig. 3). However, it has not been verified whether unintended motion or sudden turning has been avoided, and the situation may have deteriorated compared to the model of Version 3.1.

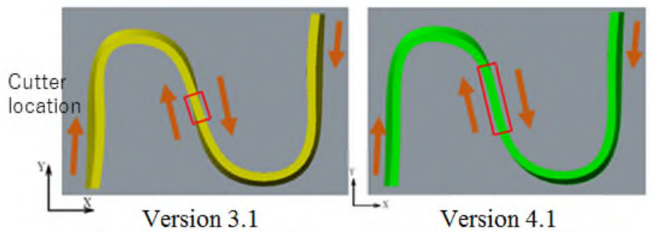


Figure 3: Comparison of model between versions

4 Feed speed fluctuation in S-shaped test

As already mentioned, in the side milling of an end mill, the speed of the tool with respect to the surface of the workpiece becomes important because the tool is machined while deflecting. In other words, where the feed speed of the tool decreases extremely, it will appear as a dent on the wall as the tool's deflection recovers.
The influence of the twist wall existing in the center of the test piece may cause a rapid or unsmooth rotation of the table, but it has only been confirmed on the

NC program. Therefore, in this research, the actual machine tools will be operated with the NC program output by CAM software and investigate how much speed fluctuation is observed in the singularity section.
This S-shaped wall is not symmetrical at the center point. Therefore, the behavior of CAM output is different between Surface A and Surface B (surfaces see Figure 2). Specifically, Surface A has a greater curvature where it enters the singular section, and a smaller curvature where it exits.

4.1 Actual singularity section

First of all, where the singularity section is with the actual model shape, is analysed. There are five points from No. 6 to No. 10 where the upper and lower coordinates are the same as the control points of the 4 spline curves used when creating the S-shaped wall (2 on the A side and 2 on the B side). Figure 4 and Table 1 shows the control points used to create the B-plane targeted this time. The four points from No. 6 to No. 9 are located in a straight line.

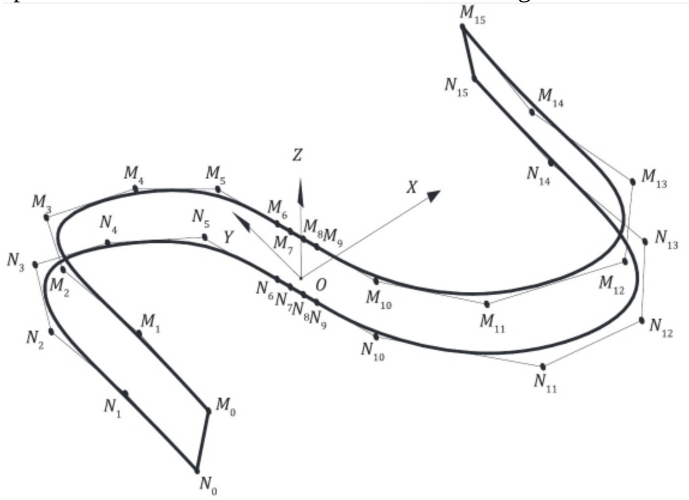


Figure 4: Definition of the ruled surfaces B [3]

The distance between No. 6 and No. 10 is about 62 mm on the XY plane. Since the coordinates shown in Table 1 are control points, the length of 16.5 mm from No. 7 to No. 9 can be reliably treated as a singular section.
In this section, the tilt of A-axis of the 5-axis machining centre becomes almost 0, and the tool becomes perpendicular to the base surface. In addition, any position angle can be taken for the C-axis.
Two types of high-performance CAM software were used in this verification experiment. Since various setting parameters can be selected for each, multiple NC programs were created for one machined surface (Surface B), and the results that seemed to operate most smoothly were examined. When observing the generated NC program, the section where the A-axis became almost 0 was No. 6 to No. 9 in terms of control points.

M_i	POS_X	POS_Y	POS_Z
M_0	−121	−95,5	30
M_1	−117	−29	30
M_2	−121	30	30
M_3	−107	68	30
M_4	−62	67	30
M_5	−31	48	30
M_6	−22	12	30
M_7	−20	4	30
M_8	−18	−4	30
M_9	−16	−12	30
M_{10}	−7	−48	30
M_{11}	26	−88	30
M_{12}	95	−91	30
M_{13}	129	−42	30
M_{14}	118	28	30
M_{15}	125	99,5	30

N_i	POS_X	POS_Y	POS_Z
N_0	−127	−95,5	0
N_1	−124	−29	0
N_2	−128	30	0
N_3	−108	76	0
N_4	−62	74	0
N_5	−33	56	0
N_6	−22	12	0
N_7	−20	4	0
N_8	−18	−4	0
N_9	−16	−12	0
N_{10}	−7	−48	0
N_{11}	30	−95	0
N_{12}	100	−97	0
N_{13}	132	−46	0
N_{14}	127	27	0
N_{15}	131	99,5	0

Table 1: Control points of spline curve composing surface B [3]

4.2 Actual singularity section

Figure 5 shows a monitoring result of the operation of the machine when cutting the surface B with NC program generated by CAM-A. It can be seen that the C-axis rotates about 15° from 86 seconds to 87 seconds. Looking at the tool feed speed in the XY plane at that time, it becomes almost 0 at the start of the C-axis 15° rotation, then moves to the end of the C-axis movement at about 200 mm/min, and the speed in the XY plane becomes 0 again. It is accelerating afterwards.

The C-axis rotation of 15° is commanded in one block in the NC program, and the X- and Y-axis commands on the block are about 3 mm on the distance in the XY plane. Since the “F” command (feed speed command) of the NC program is 1000 mm/min, deceleration during 3 mm there will cause a groove to be cut here.

Let us now consider why the movement in the XY plane is slow. This is because the NC feed rate is calculated by adding the degree of the rotating A-, C-axis in addition to the millimetres of the linear XYZ-axes. That is, since this one block is accompanied by a movement of 15° on the C-axis with respect to the movement of the XY plane of 3 mm, the feed rate of the X-, Y-axis is reduced by that amount. This method of calculating the feed speed has been adopted by many NC unit manufacturers.

Regarding the calculation method of the feed rate when accompanied by a rotation axis, there seems to be a method to correct it by NC parameters, but the simplest method is to increase a larger “F” command in this block.

Rather, this 15° rotation on the C-axis is necessary somewhere in the singularity section, so if the C-axis rotate evenly and slowly over several blocks in this section (from No. 6 to No. 9 at the control point), such extreme reductions in the tool feed speed on the XY plane should be eliminated.

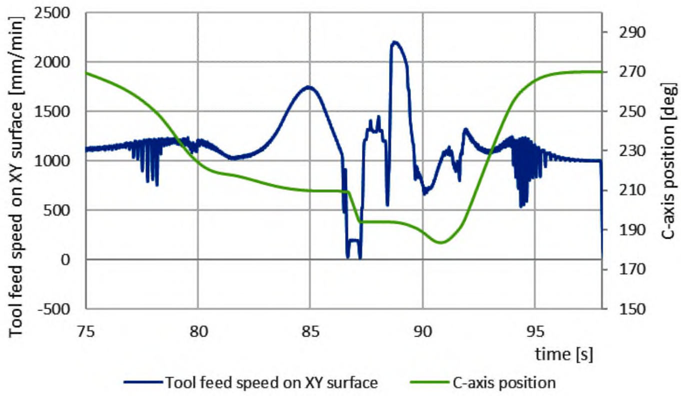
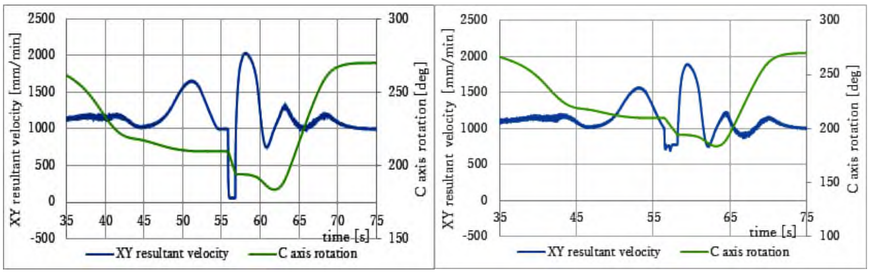


Figure 5: Tool feed speed on XY surface and C-axis position monitored while cutting Surface B of S-curved wall by the NC program generated by CAM-A

Similarly, in the NC program output by the CAM-B software, the C-axis 15° rotation command is also commanded in one block. At this time, the X and Y commands in one block are as small as 1 mm or less, so as a result, the tool feed motion is almost stopped on the XY plane. In Fig. 6(a), from 56 to 57 second, the feed speed in XY plane is decreased to less than 100mm/min, and it may be possible to dig a groove that is clearer than the output result of CAM-A. CAM-B is a well-known software for 5-axis machining function, and the feed speed curve other than the singular point section is actually smoother than CAM-A, but such NC code is output if no measures are taken.

Therefore, the NC code was revised so that the 15° rotation here was evenly distributed to the places where there was no movement command for the C-axis, and operated the machine. As a result, the feed speed on the XY plane decreased slightly from the command speed of 1000 mm/min to about 750 mm/min because the C-axis movement command was included as shown in Fig. 6(b).



(a) original (b) revised

Figure 6: Tool feed speed on XY surface and C-axis position monitored while cutting Surface B of S-curved wall by the NC program generated by CAM-B

5 Conclusions

In the S-shaped cutting test for 5-axis mahining centre, it is necessary to consider the method of commanding the rotary axis at the singular point in the center. The 15° rotation is commanded in one block with small linear axes feed, the tool will move extremely slowly against the wall and will dig a groove. This is a phenomenon that occurs not because of the acceleration/deceleration performance of the machine, but because the command feed speed is distributed differently between the linear axes and the rotary axis.
As a countermeasure, it is effective to gradually distribute the 15° rotation command of the rotation axis to multiple blocks, but this is not automatically created by CAM software at present. Therefore, the performance evaluation of the machine by the S-shaped test is limited to the shape error as described in the ISO document, and the evaluation of the smoothness of the surface should not be performed because it deeply depends on the performance of the CAM system. CAM users should operate their CAM software knowing that feedrate fluctuations will occur, and take steps to add feed speed commands if necessary. Manufacturers of CAM software and manufacturers of NC unit should also make users aware of these problems.

References

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