The Challenges for CAM Systems and Users in 5-Axis Machining

Robert Endl and Jeffrey Jaje

Sescoi R&D, Department Manager, Neu-Isenburg, Germany and
Sescoi USA, Senior Engineer – Marketing, Southfield, Michigan, USA

Abstract

The use of short cutters is a key feature of 5-axis machining. It significantly reduces the deflection of the tool, results in a better surface quality, prevents reworking and reduces immensely the number of electrode erosions. At the same time there are increasing requirements placed on CAM systems. Collision control and collision avoidance in particular are complex and time consuming tasks. The knowledge of a collision for a given point and tilt angle is important but useless if the collision cannot be avoided. The automated collision avoidance of a cutterpath, while keeping the machine dynamics and the respect of the given limitations, are strong challenges for today's CAM systems.

Although 5-axis milling machines and CAM systems with 5-axis capabilities have existed for many years, it is fairly recent that the two have been useful for the manufacture of Molds and Dies. Challenges facing 5-axis CAM programmers involve more than just making collision free 5-axis CAM cutterpaths. Users must constantly consider surface finishes. They must be aware of machine run-times, and how seemingly small options during programming can make significant differences in actual versus theoretical run times. Programmers must consider not only cutterpath calculation times, but also collision checking calculation times, in relation to all programming times.

1. Introduction

The evolution of CNC-technique and milling began in the 1950's of the 20^{th} century at the MIT (Masschusetts Institue of Technology, USA) when the U.S. Air Force asked for pieces made from full material. First machines were only able to work in three axes. In the 1960's and 1970's the use of IC-techniques (integrated circuits) made the controllers more reliable and smaller up to micro-processor CNCs. Graphical user interfaces at the controller side came in the 1980's plus the first CAM systems arrived which led to much higher productivity and allowed the machining of complex surfaces. Starting with 3-axis machining the CAM-systems were advanced to 3+2-axis and simultaneous 5-axis machining. Today's need of automation for higher productivity leads to strong requests for CAM systems. Especially 5-axis machining, which requires a close cooperation between the CAM-system, the machine kinematics and the controller. The challenges for CAM systems with respect to the technical dependencies and what it means for the user are described in this paper.

Chapter 2 describes the advantages and disadvantages of 3-axis, 3+2-axis and 5-axis machining and shows that 5-axis machining is closely linked to the milling machine's kinematics. Different types of 5-

axis strategies are discussed in chapter 3 followed by a description of collision control and collision avoidance problems in chapter 4. Sescoi's module Auto5 is presented in chapter 5 and gives an automatic solution of calculating a collision free toolpath plus the consideration of the milling machine. How the milling machine is already considered during the calculation process is content of chapter 6. Although 5-axis machining opens new areas and styles of machining the users face new challenges at the same time. How this comes together is content of chapter 7. Examples and case studies are given in chapter 8. A conclusion is given in the last chapter 9.

2. From 3-axis to 5-axis machining

The use of 3-axis toolpaths [2, 3, 5] is sufficient as long as the part is not very deep with respect to the cutter diameter. If the part is very deep and has narrow cavities the usage of pure 3-axis toolpaths is not sufficient for the complete finishing process of the part. Especially, if hard material has to be milled the usage of long cutters results in a bad surface quality and long machining times. Fig.1 shows the situation for a 3-axis toolpath. Here, the minimum tool length must be very long in order to reach all regions of the toolpath vertically.

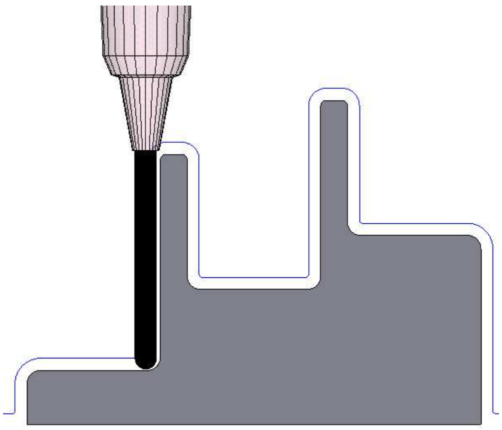

Fig. 1 3-axis toolpath.

For that reason the spindle is tilted in a way that a specific region of the part can be machined with a shorter tool. The process of setting a constant angle to the spindle is well known as 3+2-axis machining. For complex parts it is common that dozens of views need to be defined in order to fully cover the whole part. The resulting toolpaths must overlap leading to not only an overhead in machining time, but also difficulty in blending perfectly the different machining views. At the same time the number of lead-in and out movements increase dramatically which results in surface quality problems and more tool movements. Finally, programming this way is quite difficult for the user and often the sum of all views does not cover the whole geometry. Fig.2 shows four views for the part yet there is still a region not covered in the centre of the part. This region would again need additional views or it must be eroded. Summarizing, it is clear that the part can be machined with a shorter cutter but for an additional price. Many overlapping views need to be defined which in return lead to surface quality problems due to a higher number of lead-in movements and machine blending. The programming is time consuming, needs manual interaction and is an error-prone process.

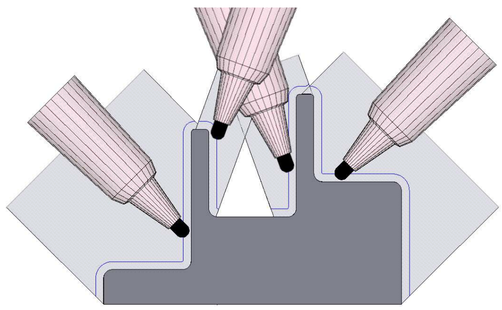

Fig.2 3+2-axis toolpath.

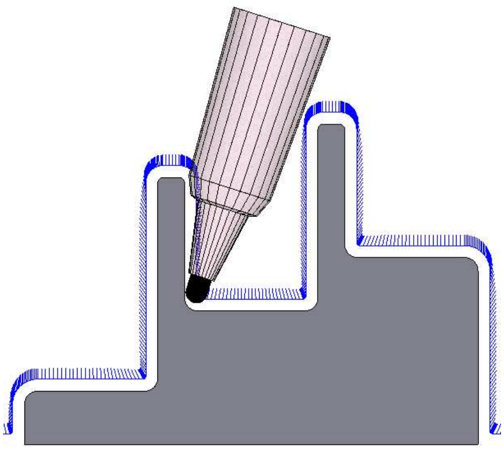

Fig.3 5-axis toolpath.

In order to overcome the drawbacks of 3+2-axis machining new strategies for simultaneous 5-axis toolpaths have been developed [1, 3, 10]. Simultaneous 5-axis machining incorporates the 3 linear axes as well as 2 rotational axes at the same time. It solves all the problems of 3+2-axis machining. The cutter can be very short, no overlapping views need to be generated, the probability of missing an area is much smaller and the machining can be performed continuously without additional lead-ins and lead-outs (Fig.3).

However, in 5-axis machining the problems of 3+2-axis machining are not removed, they have been shifted from the programmer to the CAM-system. This sounds reasonable and has many advantages for the user. The CAM-system WorkNC (Sescoi) has even developed 5-axis “push-button” strategies which generate a fully automatic collision free toolpath. Today’s users have this option but real life is more complex. A 5-axis toolpath which runs very well on a specific machine may run worse on another machine. The reasons for this are manifold and reach from machine kinematics properties to controller settings. Hence, the machine itself needs to be taken into consideration **during** the programming [7, 11, 12]. Thus it is important for the programmer to know in advance which machine will be used to cut the part.

Fig.4 The 5-axis machines Auerbach IA 5 B and DMC 75V.

A toolpath which is collision free with respect to the cutter and holder needs not necessarily be machinable on any milling machine. Very often a 5-axis milling machine is limited in its rotational axes. The following two 5-axis machines Auerbach IA 5 B made by Auerbach and DMC 75V made by DMG (Fig.4) are exemplary for this: The Auerbach machine has a tilt angle limit of [-95°, 95°] while the DMG machine has a tilt angle limit of [-110°, 9.5°]: Taking the 5-axis toolpath from Fig.3 we find out that the Auerbach machine doesn’t have any problem in running it. In contrast we detect that the DMC 75V will run into a problem when the negative tilt angle of -30° along the vertical wall crosses the vertical at the top and runs into a positive tilt. When the limit of 9,5° is reached the machine will immediately stop (Fig.5). All angles above 9,5° are marked with a red triangle and would cause the machine to stop.

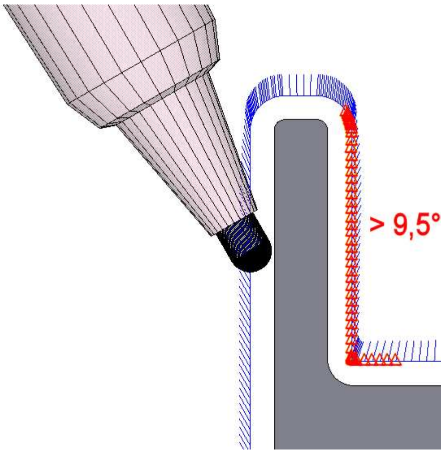

Fig.5 The angle limit of 9,5° will immediately stop DMC 75V.

The example shows that for an automatic solution the machine must be known and considered during the calculation process. It is by far not enough to consider the machine at post-processor level. Chapter 6 gives more details on strategies of how to avoid and solve angle limitations.

3. Strategies for 5-axis toolpaths

Today's CAM systems offer a variety of 5-axis toolpaths. The general problem with simultaneous 5-axis machining is that five axes simply offer too much freedom. The two degrees of freedom for the axis tilts result for any toolpath position in an infinite number of correct tilt values which are still collision free but completely different. Finding the optimum angles is important. As a consequence any CAM-system needs parameters by the user in putting constraints to the toolpath creation process. Fig.6 shows an example of a simple z-level finishing cutterpath around a hemisphere. Each of the three 5-axis toolpaths was generated with a different constraint. The first is generated normal to surface, the second is directing to an attraction point on a centre line above the hemisphere and the third uses a square as leading curve. The example shows that constraints are not only necessary but also need to be defined very well. The constraints two and three will probably never be milled because they don't make sense from a machining point of view.

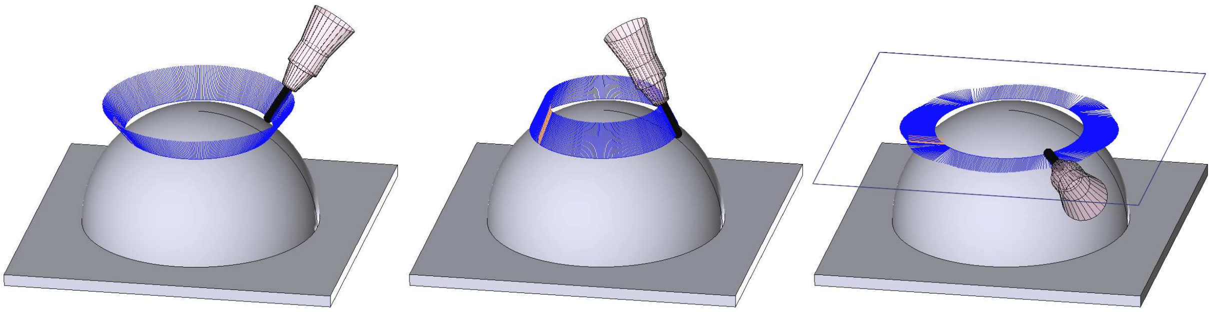

Fig.6 Degrees of freedom in 5-axis machining is both boon and bane.

The question remains:	Which is the correct constraint?
The simple answer is:	It depends!

The dependencies are the milling machine itself with its angle limitations and its physical ability to run simultaneous 5-axis toolpaths. Also the used material, the surface quality, the 5-axis strategy and available cutter are influencing the user's constraints.

In general we can distinguish the following main types of 5-axis strategies:

Normal to surface: The cutter follows the surface normal.

Constant angle: Any axis is part of a cone having a constant angle. The other degree of freedom is taken from the surface normal or a leading entity (e.g. point or curve).

Guiding: The shortest distance to a guiding entity (e.g. point or curve) defines the tilt axis.

Surface specific: Constraints are given by the surface itself. Examples are rolling toolpaths where the cutter rolls along a ruled surface or strategies for tubes and impellers.

From the user's point of view he just has to choose a strategy (depending on whatever he thinks is suitable) and run the calculation. During the calculation process the problem may arise that a constraint cannot be held along the whole surface. An example for this is the strategy normal to surface (Fig.7). Here the toolpath climbs from a bottom plane onto a box. The real normals are shown in the left picture.

It is clear, that it would never be machined directly because the angle difference is too big at two positions and some points would lead to collisions with the holder. To be able to smoothly machine this toolpath we must temporarily remove the normal constraint by allowing anticipation and post-compensation of angle changes.

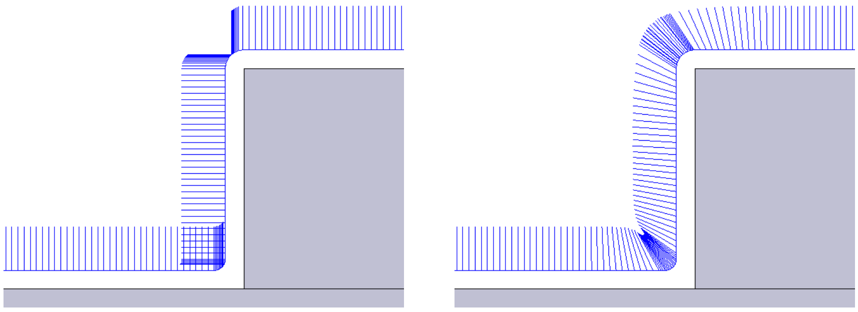

Fig.7 A normal to surface toolpath can usually not directly be machined.

The smoothness of a 5-axis toolpath is very important for the efficiency on the machine. Smoothing a toolpath usually means locally removing its constraints. In addition the process of collision avoidance has the same effect. The constraints cannot be held if the tool holder must avoid a collision. Since ball cutters are usually used for machining 5-axis toolpaths a slight change of the tilt angle is not a problem.

4. Collision control and collision avoidance

For a CAM-system the movements of the cutter itself are not the biggest challenge but the creation of a collision free 5-axis toolpath which is smooth and runs fast on any machine [1, 4, 6-9, 11, 12]. A smooth variation of the axes while anticipating the next cavity or corner is very important for the milling machine and the resulting surface quality. The task for every colliding position can be sketched easily:

- Find a collision free position (When possible respect all constraints).
- Only small and smooth variations are allowed.

The example in Fig.8 shows a simple toolpath and four collision free positions. When the cutter at position 1 approaches the vertical wall it must be tilted more and more until it reaches 2. Position 3 is critical because if the tool moves up from 2 there is a big tilt when the holder reaches the top of the wall. Here, the collision free position can immediately be vertical again which is by far not smooth. As a consequence the big tilt change must be distributed smoothly around position 2. While distributing the tilts to a toolpath region it must be guaranteed that we don’t get new collisions where we didn’t have ones before. This process of continuously finding collision free positions, distributing the tilt smoothly and guaranteeing that we are still not colliding somewhere else is a complex and time consuming task, ideally suited for computers.

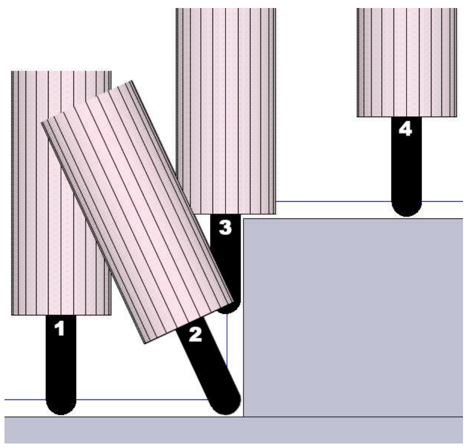

Fig.8 Collision free toolpath positions.

5. Automatic conversion from 3+2-axis to simultaneous 5-axis toolpaths (Auto5)

Since 3+2-axis toolpaths are very well understood and have existed for years with a huge variety of strategies, the question arises if we can modify them for 5-axis machining. The necessary task is simply verbalized:

> Is it possible to convert a 3+2-axis toolpath to a collision free 5-axis toolpath automatically?

The answer is: Yes it is possible! Sescoi has developed over the last years a module called WorkNC Auto5 which does exactly that job. With WorkNC Auto5 Sescoi presents a fully automatic 5-axis toolpath strategy which takes as input an arbitrary 3+2-axis finishing toolpath and calculates a collision free 5-axis toolpath by considering the machine's angle limits and kinematics. In addition the user can influence the resulting toolpath in many ways by setting various parameters. The final toolpath is smooth, holder collision free and respects the machine angle limits and kinematics. Fig.9 shows that the WorkNC Auto5 machining process works in two steps:

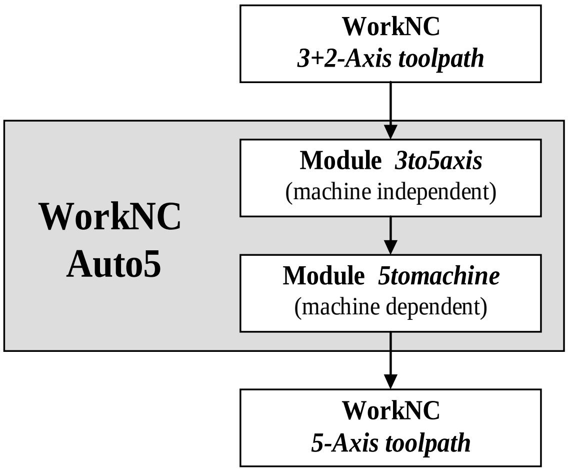

Fig.9 The Auto5 conversion process.

1. The first step uses the module *3to5axis* which takes a 3+2-axis toolpath and calculates a 5-axis toolpath by avoiding collisions. If a collision can not be avoided the position is marked. This process does *not depend* on the machine.

2. The second step uses the module 5tomachine which takes the output of 3to5axis and considers the machine angle limits. This process *depends* on the machine. All positions of the toolpath which have a collision are cut out from the resulting toolpath. The remaining toolpath is smoothly linked.

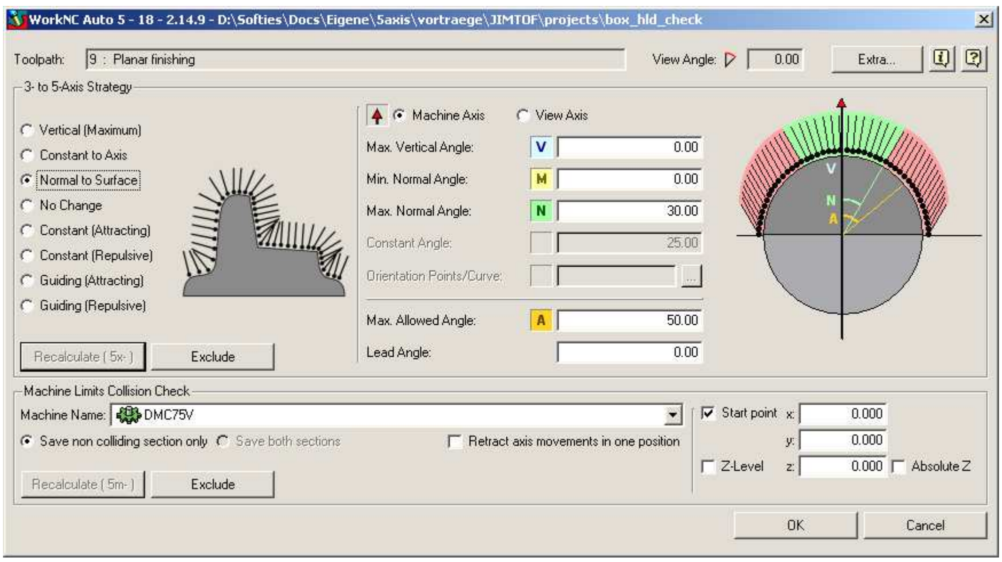

Fig.10 WorkNC Auto5 user interface.

Fig.10 shows the graphical user interface of Auto5. The upper options group is related to the module *3to5axis* where the user can choose from one of the available strategies. Depending on the strategy, there are several constraint parameters possible. The lower group is dedicated to *5tomachine*. Here the milling machine and start condition can be set.

6. Consideration of the milling machine

The module *5tomachine* takes as input a 5-axis toolpath from either *3to5axis* or is a WorkNC standard 5-axis strategy (e.g. *5-Axis Rolling)*. After choosing a milling machine the module calculates a collision free 5-axis toolpath. All collisions which could not be avoided are cut out and linked again by respecting the toolpath's retract and approach settings. In the left picture of Fig.11 some collisions have been marked. Those are cut out and either linked vertically (centre picture) or linked smoothly (right picture).

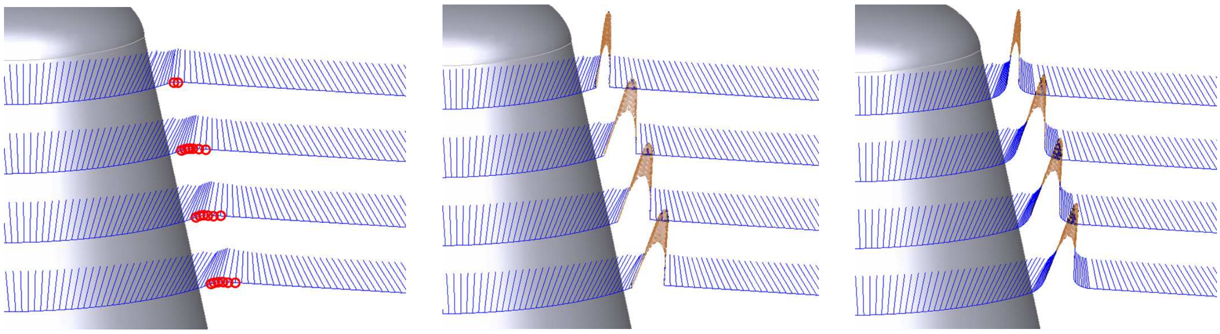

Fig.11 Marked collisions are replaced by vertical or radial movements.

In addition to colliding points there a several cases which let the toolpath immediately stop the machine. Since many machines are limited in its angle positions (see chapter 2) the question is:

Can we avoid a machine's angle limitation?

The answer is: Yes it is possible! The milling machine DMC 75V (Fig.12) has an angle limit of [-110°, 9.5°] (see Fig.5). Such an angle limit can be solved by flipping the corresponding angles. E.g. an axis defined by the angle pair (9.5, C) is identical to the angle pair (-9.5, C±180°). Fig.13 illustrates how *5tomachine* solves the problem by anticipation. Problems 1 and 2 are both caused by the 9.5° angle limitation:

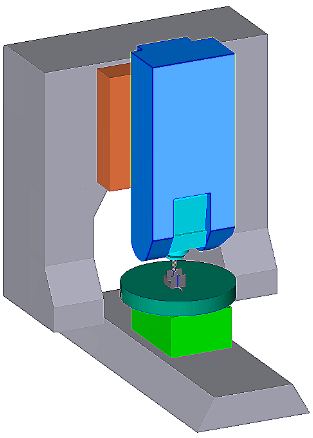

Fig.12 DMC 75V

Problem 1: When the cutter approaches position 1 it is looking far ahead and realizing that it will hit the 9.5° limit. Since it is currently vertical it can easily turn the C angle by ±180° without moving up from the surface.

Problem 2: Here the axis is not vertical so it must move up, turn to a vertical position, turn the C angle by ±180° and approaches again.

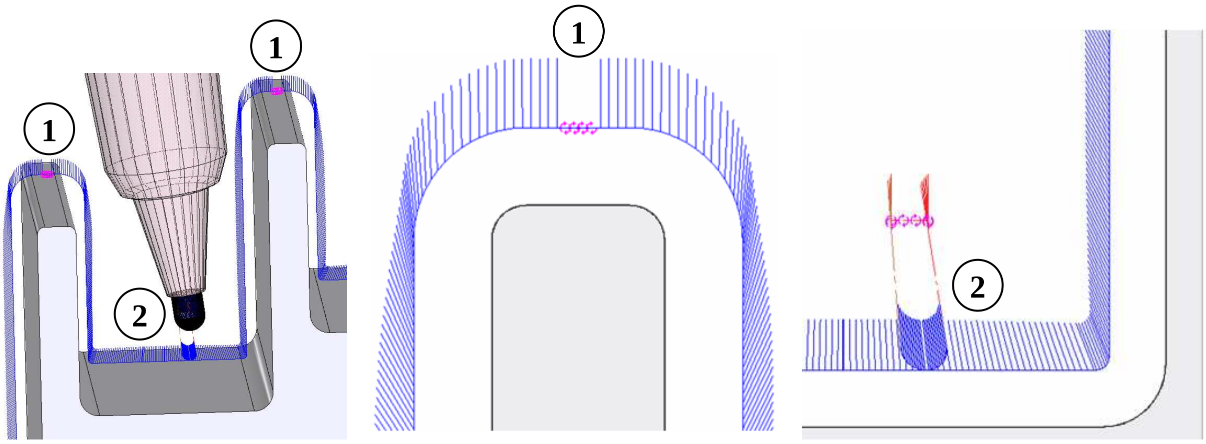

Fig.13 Anticipating and solving angle limitations of DMC 75V.

Other problems related to the machine can be caused by the machine's kinematics and the limitation in X, Y and Z. In addition there are several other collisions between machine, part, cutter, holder and spindle possible. The knowledge of all these limitations and problems of a milling machine is needed in advance and it has to be taken into consideration while the toolpath is being calculated.

7. Challenges of CAM users

It is necessary for CAM operators to not only be well versed in the options of the CAM software used, but also in the specific kinematics of the 5-axis milling machine being used. This way the programmer can tailor his CAM programming for the idiosyncrasies of the particular milling machine.

Additionally, the programmer must make logical determinations of where to use a 3+2 axis strategy or instead use a 5-axis strategy. Some machines may be more accurate in 3+2 strategies, and this method may be used when precision is critical. Some milling machines do not blend multiple 3+2 machining views as well as the part requirements dictate, yet when one 5-axis cutterpath is run instead of several machining views, the blending may look much better. Just because someone has a simultaneous 5-axis milling machine does not mean every cutterpath should be done in 5-axis. Choose the combination of strategies which will yield the best finishes with the minimum amount of time. Users may choose to break up a cutterpath, and leave one portion as a 3+2 axis path and convert the remaining portion to 5-axis.

The performance and limitations of the different rotation axes on a milling machine should also be considered when creating 5-axis cutterpaths. Some machines have unlimited C-axis movements, while many have limits on their C-axis. Programming a cutterpath that must "unwind" the C-axis on every cutting pass may lead to inefficiencies due to air time, it may be better to mill the part as two separate halves when 5-axis is required. Some 5-axis milling machines have a relatively slow C-axis rotational capability. In these instances it may be prudent to create cutterpaths that limit the amount of C-axis rotation in favour of the A or B axis.

8. Examples and case studies

Fig 14 shows a part where corners are being re-machined with a small diameter cutter. The wall is not only steep, but also quite tall, over 200mm, and it was being machined with a 6mm diameter cutter. It was necessary to keep the cutter as short as possible, and to have not only the tool holder, but also the spindle avoid the part data. Large portions of the floor area, labelled as "A", could be machined in a vertical configuration. If the tool was constantly tipped, then that would mean the "C" axis on this particular mill would be used more, and on this particular mill, this could have affected overall performance. Here we used a "vertical" strategy which kept the tool vertical, reducing C movements, and the software automatically rotated the tool out of the way when the vertical setting would have resulted in a collision. Once the collision was successfully avoided, the tool was placed back into a vertical position.

However, the wall area, which is labelled "B" was cut with the A-axis of the machine placed in a constant angle. Additionally, a guiding curve was utilized which helped to limit the amount of rotation done in the C-axis. The result is that twenty separate 3+2 machining angles were replaced by one 5-axis cutterpath .Blending of all of the 3+2 cutterpaths would have been problematic to the customer, but was not a problem in this instance.

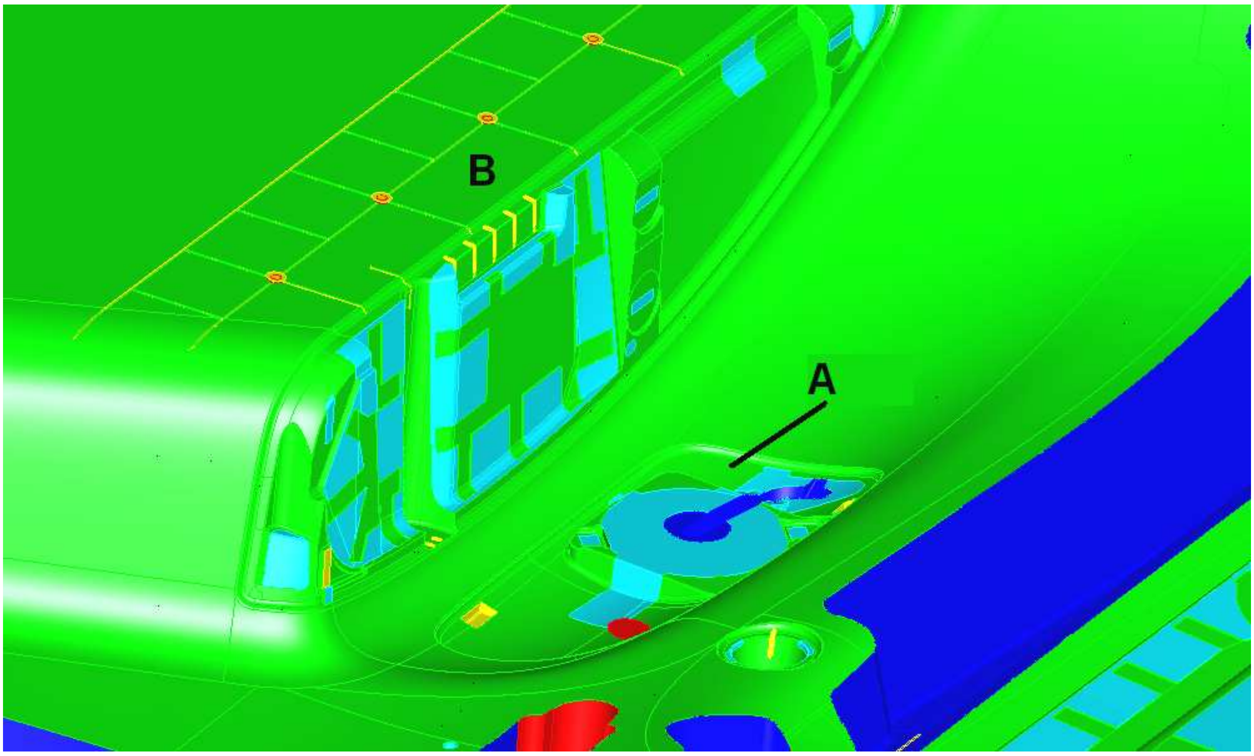

Fig.14 Different shapes require different strategies. Staying vertical for the floor "A" whenever possible and having the tool tipped at a constant angle for "B".

9. Conclusion

It has been shown that 5-axis machining is powerful and can solve many of the problems of 3-axis and 3+2-axis machining. It is even possible to have a "push-button" solution. Sescoi's WorkNC Auto5 provides a module which takes as input a 3+2-axis toolpath and outputs automatically a collision free and machine dependent 5-axis toolpath. However it is important to note that a 5-axis toolpath may not run optimal on any machine by default. Although the CAM system has taken lots of the responsibilities the user had to the take care about in former days, he is still urgently needed. The choice of the optimal 5-axis strategy in dependency on the material, the 5-axis machine, the available tools and holders is necessary and a mandatory task of the user. The correct settings influence everything, the cutterpath calculation time, the machine run-time and the surface finish quality.

References

1. M. Balasubramaniama, S. E. Sarma, K. Marciniak, Collision-free finishing toolpaths from visibility data, Computer-Aided Design, 35(4): 359-374, April 2003.
2. G. Elber, Free Form Surface Analysis using a Hybrid of Symbolic and Numeric Computation, Ph.D. thesis, University of Utah, Computer Science Department, 1992.
3. G. Elber, E. Cohen, Toolpath generation for freeform surface models, Computer-Aided Design, 26(6): 490-496, June 1994.
4. B.K. Fussell, J.G. Hemmett and R.B. Jerard, Modeling of Five-Axis End Mill Cutting Using Axially Discretized Tool Moves, Proceedings of the 1999 NAMRC Conference, Berkeley, CA, May 1999.
5. A. Hansen, F. Arbab, Fixed-axis tool positioning with built-in global interference checking for NC path generation, IEEE Journal of Robotics and Automation, Vol 4, No 6 (December 1988), 610–21.
6. O. Ilushina, G. Elber, D. Halperin, R. Wein, M.-S. Kim, Precise global collision detection in multi-axis NC-machining, Computer-Aided Design, 37(9): 909-920, August 2005.
7. B. Lauwers, P. Dejonghe, and J. P. Kruth. Optimal and collision free tool posture in 5-axis machining through the tight integration of tool path generation and machine simulation. Computer-Aided Design, 35(5):421–432, April 2003.
8. Y.-S. Lee, T.-C. Chang. 2-Phase approach to global tool interference avoidance in 5-axis machining. Computer-Aided Design, 27(10):715–729, October 1995.
9. D. Roth, S. Bedi, F. Ismail, S. Mann, Surface swept by a toroidal cutter during 5-axis machining, Computer-Aided Design, 33(1):57-63, January 2001.
10. G.B. Vickers, K.W. Guan, Ball-Mills Versus End-Mills for Curved Surface Machining, ASME Journal of Engineering for Industry, 1989, Vol. 111, 22-26.
11. R. Wein, O. Ilushin, G. Elber, D. Halperin, Continuous Path Verification in Multi-Axis NC-Machining, Proceedings of the twentieth annual symposium on Computational geometry, ACM Press, New York, NY (2004), 86 - 95.
12. K. Weinert, A. Zabel, H. Müller, P. Kersting, Optimizing of NC Tool Paths for Five-Axis Milling using Evolutionary Algorithms on Wavelets, Proceedings of the 8th annual conference on Genetic and evolutionary computation, Seattle, ACM Press, New York, NY (2006), 1809 – 1816.