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Comparison of 5-Axis and 3-Axis Finish Machining of Hydroforming Die Inserts

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The recent growth in hydroforming technology has sparked interest in alternative methods to the current conventional die manufacturing techniques. Hydroforming dies typically have shallow forming channels and open, low curvature surfaces, making them ideally suited for 5-axis machining. To fully appreciate the benefits and to properly demonstrate the capabilities of 5-axis machining for hydroforming dies, a comparison of 5-axis and 3-axis finish machining was done. Two hydroforming die insert sets were machined on a 5-axis machine with a tilt/rotary table. The tool paths for 5-axis machining were generated using custom software based on a modified form of a tool positioning strategy called the principal axis method. The quality of generated 3-axis toolpaths was verified against the machining times of a third set of die inserts, similar to those machined in 5-axis, by an independent industrial mould and die manufacturer using a 3-axis high-speed machine. A comparison of the generated 3-axis paths versus the 5-axis paths for one of the die inserts was made using total finish machining tool path lengths to eliminate differences in machines. The results show that the generated 3-axis tool paths are longer than the 5-axis paths by at least 247%. The paper discusses the different tool-path generation methods along with the geometry of cusp formation and the effect of tool selection. Methods to improve the 3-axis results are also presented.

Keywords: 5-axis; Finish machining; High-speed machining; Hydroforming; Sculptured surfaces; 3-axis; Toolpath

1. Introduction

There are many published works claiming significant advantages of 5-axis machining of sculpted surfaces over 3-axis [1–6]. The faster machining times and better surface finish in 5-axis machining are achieved by using flat and radiused-corner endmills instead of the ball-nose endmills favoured in 3-axis finish machining. The extra two axes of a 5-axis machine are used to adjust the tilt and rotation (i.e. orientation) of the tool with respect to the surface normal at the machining points on the workpiece. When a flat or corner-radius endmill is tilted, the curvature cut by the edge geometry of the tool on the workpiece is altered. This means that the curvature of the designed surface at the point being machined, can be matched more closely, which reduces the number of passes required to machine the surface and lowers the cusp height and density. Two methods of tool positioning have been developed at the University of Waterloo: multi-point machining and the principal axis method. In multi-point machining (MPM) a flat or radiused-corner endmill is positioned on a surface such that it generates the designed surface at two separate points simultaneously [1]. The principal axis method (PAM) extracts curvature data from the design surface and calculates the required tilting of a flat or radiused-corner endmill to match the curvature at the point being machined [2,3]. Another method is the Sturz method, sometimes referred to as the inclined tool method [4,7]. In this method, the tool axis is inclined at a constant angle with respect to the surface normal for the entire surface.

Workers involved in the above methods have favoured the approach of comparing computer simulations of 3- and 5-axis methods because of the cost involved in actual machining, and, in most cases, the limited access to full simultaneous 5-axis milling machines. The samples that have been used for comparison are usually simple surfaces or a fraction of an actual industrial part. The issues involved with die and mould manufacturing such as interference, gouging, depth of the surfaces, depth of cut, and the machining of several connected surfaces found in real parts are not all simultaneously addressed by these simulations and laboratory surfaces. This paper documents the machining of hydroforming die inserts in 5-axis, for a comparison with 3-axis finish machining. The inserts have since been used to produce test parts by the company that originally issued the study. Figures 1 and 2 show samples of the female and male sides of the hydroforming die inserts. The basis for comparing the tool paths in 3-axis and 5-axis will be the total finish machining tool-path length. Tool paths for 3-axis were generated with one of the leading commercial computer-aided manufacturing (CAM) packages. An independent mould and die manufacturer was commissioned to

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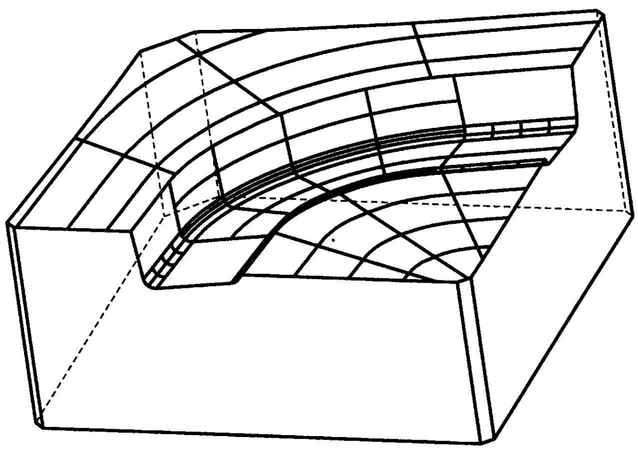

Fig. 1. Female hydroforming die insert.

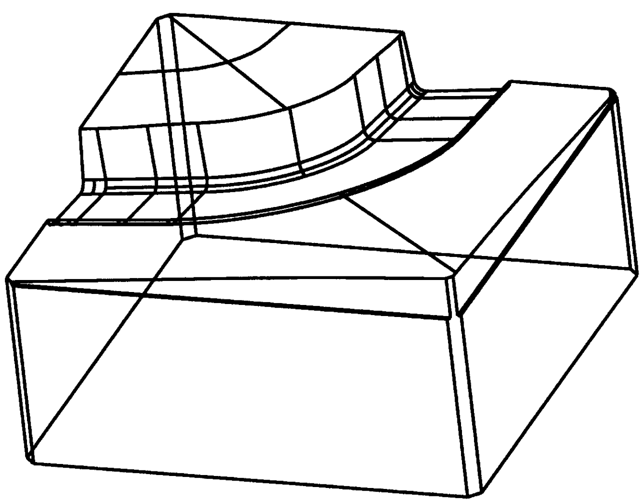

Fig. 2. Male hydroforming die insert.

machine a similar set of die inserts using a 3-axis high-speed machine. The machining times recorded by the manufacturer were used to verify the machining time of the 3-axis paths generated for the comparison.

2. 5-Axis Machining of Hydroforming Dies

The purpose of hydroforming is to change the cross-section of a tube from round to rectangular. Though other cross-sections are possible, they are rare. Water pressure is used to expand the tube walls to conform to that of the forming channel of the hydroforming die. Thus, the deepest depth in the die is approximately the diameter of the formed tube, the largest being typically no more than 150 mm in diameter. These shallow depths can be machined easily with 5-axis machines without the problems of interference of the tool shank (crashing) when orienting the tool. Since the cross-section is typically rectangular in shape, the forming channel wall and floor will be perpendicular. This means that with a 5-axis machine, the forming wall can be machined in one pass by flank milling and in one set-up. Also, the bottom of the forming channel can be machined quickly and accurately with no cusps, using the bottom of the milling cutter. The constant radius along each of the four edges of the tube can be machined easily with a corner radius endmill in one pass while flank milling the forming channel walls.

The mating surfaces of the dies are curved surfaces because they follow the material flow along the formed part (Fig. 1). The surfaces are open and have low curvatures, making them ideal candidates for 5-axis machining. The open surfaces ensure that there will be no interference with the tool when orienting the tool axis. Low curvature surfaces can be cut with large diameter endmills which means that large cross-feeds can be used, resulting in very short machining times for very small cusps. The low curvature also reduces the risk of gouging. The simple geometry of the forming channels combined with very shallow and low curvatures of the mating surfaces makes the machining of hydroforming dies an ideal application for 5-axis machining.

3. Cusp Formation

Whenever a curved surface is machined with a ball-nose or corner radius endmill, cusps are left on the surface owing to the cross-feed, the radius of the tool, and the curvature of the surface (Fig. 3). With 5-axis machining, the two rotational axes can be used to tilt the tool such that the effective radius of the tool matches or approximates to that of the local radius

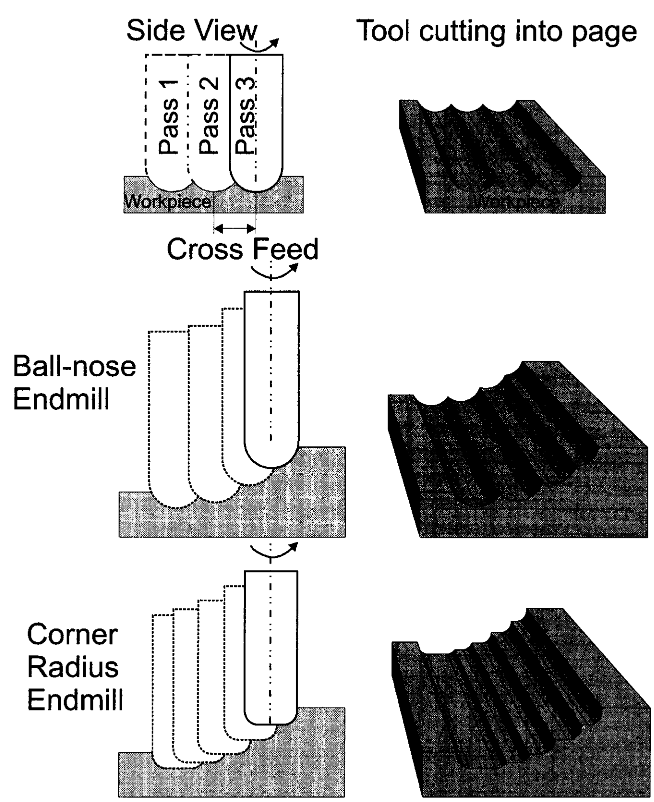

Fig. 3. Cusp formation.

of curvature at the point being machined on the surface (Fig. 4) [2,3]. With this method, smaller cusps are generated, but, more importantly, the intended surface can be machined more closely, resulting in a more accurate surface.

4. Tool Path Generation Methods

4.1 5-Axis Methods

There are not many commercial CAM packages available today that are capable of producing 5-axis tool paths. The ones that are capable of doing so do not currently perform curvature matching of the tool with respect to the design surface. Some tool positioning strategies available are summarised in the following subsections.

4.1.1 Sturz or Inclined Tool

CAM package developers favour this method because it is relatively simple computationally. In this method, an arbitrary inclination angle of the tool axis with respect to the surface normal is selected and applied to a flat or radiused-corner endmill at all points on the workpiece. If the angle is too small, gouging may occur, and if the angle is too large, excessively large cusps remain [1,3]. Research is currently underway to optimise and change the inclination angle dynamically [8]. Even with the arbitrary process, significant reductions in machining times have been realised, compared to 3-axis machining with the same size ball-nose endmill [4,7].

4.1.2 Multipoint

In this method the cutter is oriented such that it contacts the design surface at two points simultaneously. The distance between the two contact points is arbitrarily selected. The method can work only with flat or radiused-corner endmills because tilting a ball-nose endmill will not affect the geometry seen by the surface; it will always be spherical. The problem with this method is that it is difficult and complex to implement, also, many of the parameters involved remain to be studied. One advantage is that gouge avoidance is built into the algorithm.

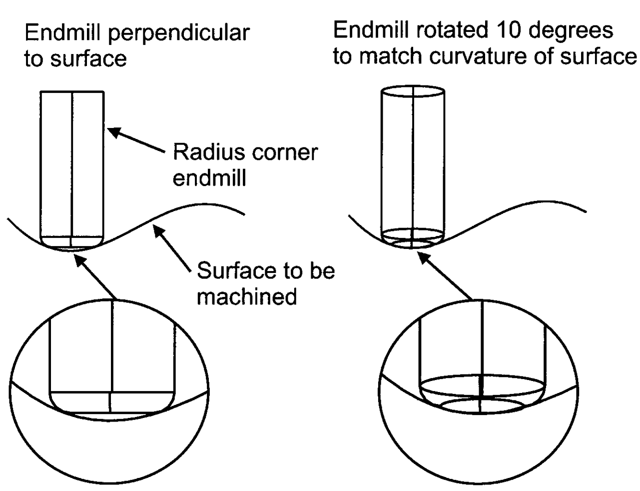

Fig. 4. Curvature matching with 5-axis.

4.1.3 Principal Axis

Given a fully defined surface, the local curvature at any point may be calculated. At any point on a curved surface there will be a local maximum and minimum curvature. The vectors that are tangential in the direction of the maximum and minimum curvature at the defined point are the principal axes. It has been shown that these three vectors (the normal and the two principal axes vectors) are all perpendicular [2]. In the principal axis method, the tool is tilted such that the effective tool radius seen by the surface is matched to its maximum curvature at the point being machined. The feed direction is along the minimum curvature. Like the multi-point method, the principal axis method is not effective with ball-nose endmills. The main problems with this method include potential gouging, and the tool paths generated may not be practical or efficient because the feed direction must always follow the direction of minimum curvature.

4.1.4 Modified Principal Axis

A study of the effect of feed direction with the principal axis method was conducted by Rao et al. [2]. It has been shown that the direction of minimum curvature is not necessarily the best or most practical direction of feed as it can vary wildly over complicated surfaces because the curvature typically changes over the surface. Two problems may arise from following the direction of minimum curvature: excessive jerk of the machine's axes, and unintuitive, inefficient tool paths may be generated. In the modified principal axis method, described in detail in [2], the principal curvatures and directions are no longer used. A feed direction is selected based on the part geometry; typical choices for machining passes include iso-parametric and offset Cartesian planes. Curvature is now calculated in a plane perpendicular to the feed direction. It is this curvature that is used to determine the tilt angle of the tool. If the calculated tool position produces gouging, it is modified by increasing the tilt angle to avoid gouging. This modified method thus addresses the problems of gouging and the restrictions on the feed direction of the principal axis method.

4.2 3-Axis Methods

There are several conventional methods for surface machining in 3-axis, common to most CAM packages. A quick survey of the top CAM packages on the market will show that each provides similar tool-path generation methods for finish machining in 3-axis. The characteristics of three of the most common methods are discussed in the following subsections.

4.2.1 Contour

This method intersects the surface with planes parallel to the machine worktable in increasing Z-depths until the bottom of the surface is reached. The contour line formed at the intersection of the plane and the surface outlines the path for the tool for each specified depth, and Z-level machining is used to cut the part. This is a very good technique for rough machining because the *Z*-depth for each pass is constant, which means the machine is cutting in its most rigid state. For finish machining it is less desirable because the geometry of the remaining cusps between the passes can vary considerably, making hand polishing very difficult.

4.2.2 Surface Flow

A constant uniform cusp over the machined surface is the objective of this method. To achieve this the cross-feed for the area of largest curvature of the surface is calculated for a specified maximum cusp height. This value becomes the arc length between each pass on the surface. This only approximates a constant cusp over the surface. The feed direction follows either the constant *u* or *v* lines of the NURB surfaces which are indicative of the flow of the surface. Patches of connected surfaces with similar surface flows are selected and programmed. Thus, areas of the workpiece of similar surface flow are programmed together. Patches that are not connected smoothly (having the same curvature along their intersection line) or do not have similar surface flows must be programmed separately. A poorer surface finish results and the risk of gouging increases. It also reduces the efficiency of cutting and increases the programming time. Extra care must be used with this method because of the increased complexity involved in calculating the tool position. Gouging and crashing of the tool is common.

4.2.3 Parallel

This method generates parallel passes over the selected surfaces. The surfaces are scanned for the minimum cross-feed required to produce the maximum cusp height specified. The value for the cross-feed is applied to each parallel pass. It is quick and easy to program and is a very reliable method, especially if using ball-nose endmills. The drawback of this method is that constant, uniform cusps will not necessarily be generated on curved surfaces.

5. Comparison of 5-Axis and 3-Axis Tool Paths

To eliminate differences between machines (i.e. horsepower, rapid travel speeds, rigidity, etc.) the basis for comparison used in the present work is the total tool-path length required to finish machine the die inserts. Three-axis tool paths were generated using a commercial CAM software package. Only a visual check using a wireframe tool-path simulation was used to check for gouging and for crashing of the tool. The tool paths were not used for actual machining of the die inserts. However, machining times for a similar die insert set from an independent die manufacturer were used to verify the quality of the 3-axis simulated tool paths. The 5-axis tool paths were generated at the University of Waterloo with custom software using a modified form of the principal axis method. These tool paths were used to finish machine two die insert sets on a retrofitted Rambaudi 5-axis rotary/tilt table milling machine.

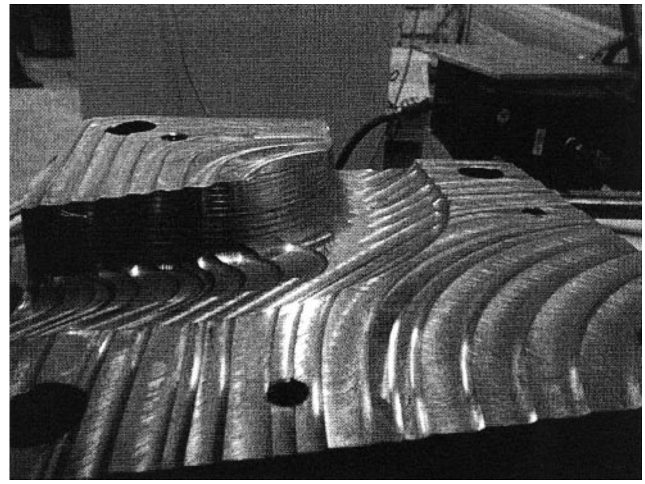

Fig. 5. 3-Axis contour rough machined die insert.

5.1 Rough Machining

Four blocks of 44W hot rolled steel were rough machined on a 3-axis OKK machining centre to the approximate shape of the inserts in vertical contoured steps of 1.5875 mm (Figs 5 and 6).

5.2 5-Axis Machining

For the mating surfaces, an indexible 38.1 mm diameter shoulder/facemill with 6.35 mm radius round inserts was used. For the forming channel, a 25.4 mm diameter endmill was used, with a corner radius ground to 6.5 mm.

The modified principal axis method was used to create the tool paths. The modifications allow the programmer to control the direction of cutting. The paths used are shown in Fig. 7. Machining in a zigzag pattern would have reduced the machining times. However, with the zigzag pattern, the surface finish

Fig. 6. 3-Axis contour rough machined die insert.

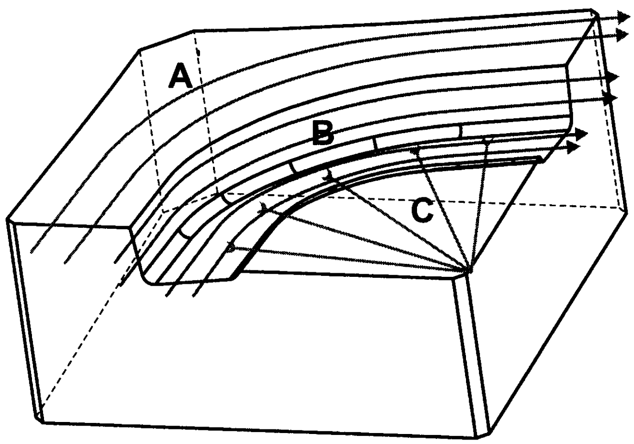

Fig. 7. 5-Axis finish tool paths used. A, mating surface; B, forming channel; C, mating surface.

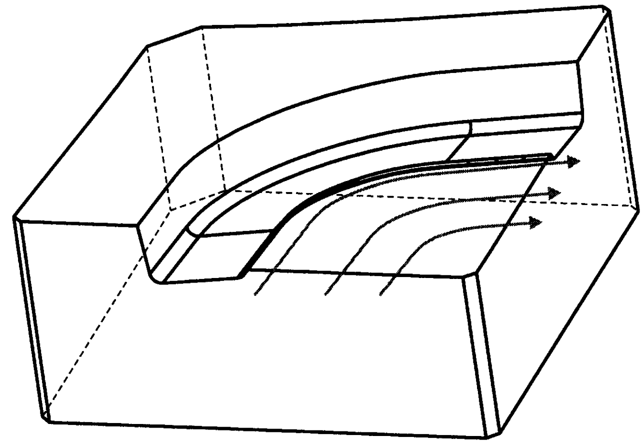

Fig. 9. Alternative 5-axis tool path for mating surface C.

would be less uniform because the cutting conditions would be alternating between up and down milling with each pass.

The small mating surface identified in Fig. 7 as surface C was a problem for the principal axis method. It is actually a patch of three surfaces trimmed at their intersections (Fig. 8). The problem lies in the fact that the slopes of the surfaces are discontinuous at the trim lines where they intersect (i.e. their tangents did not match at the lines of intersection). Continuity is required for the calculations performed for the curvature matching of the tool to the surface being machined and for tool positioning. Figure 9 shows an alternative path. Although this path gives the minimum number of passes, the tool must undergo large rotations at the surface intersection line, which would gouge the surface at that point. To avoid the problem of gouging, the path shown in Fig. 7 was used.

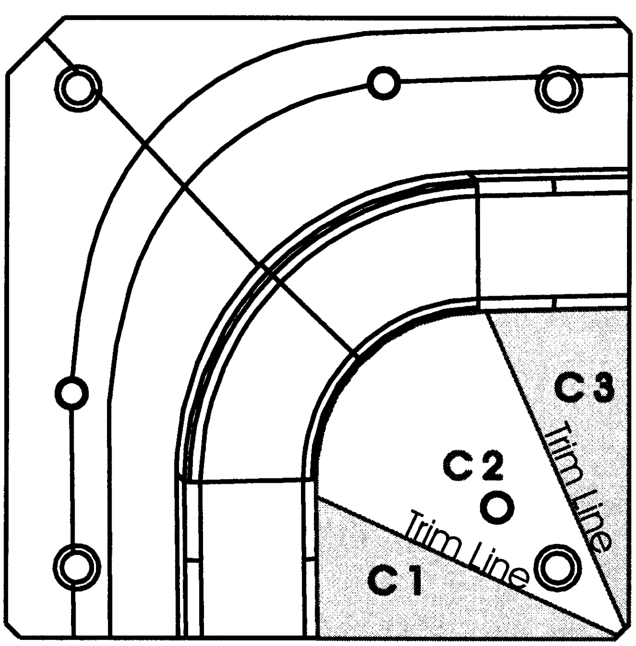

Fig. 8. Mating surface trim lines.

Another way to avoid this problem is to design the surface differently. The edges of the surface were trimmed to a point. If the surfaces were designed by translating the parting line of the forming channel to outside the die and then trimming the surfaces at the edge of the die (Fig. 10), a shorter tool path could be generated than that shown in Fig. 7.

5.2.1 5-Axis Finish Machining Results

The cusps produced during the finish operation did not exceed 0.1016 mm for the mating surfaces of both the die insert sets. The forming channels were machined exactly to size without any cusps. Figures 11 and 12 are photographs of the finish machined die inserts.

5.3 3-Axis Machining

The typical industrial practice for finish machining of curved surfaces is to use ball-nose endmills because they are easier to program than radius corner endmills and they leave a uniform cusp on the surface [1]. Programs generated for these tools are robust and reliable and gouging of the surfaces is highly unlikely.

Many CAM packages can generate tool paths for radiused corner endmills but they may not necessarily be useful or efficient. Often, the positioning strategy employed is to cut the surface using the radiused corner of the tool. This will

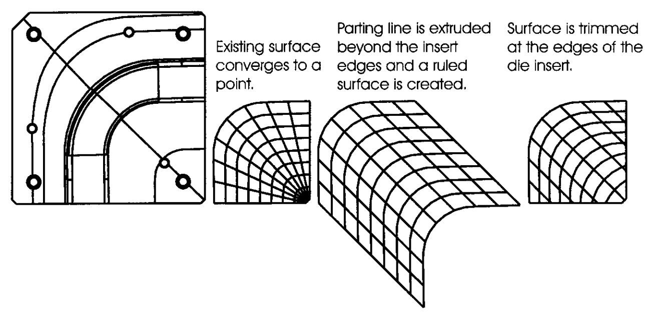

Fig. 10. Alternative surface construction method.

Fig. 11. Finish machined female die insert.

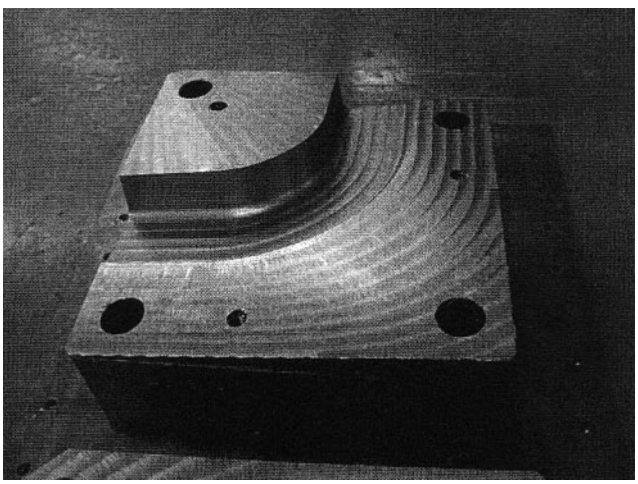

Fig. 12. Finished machined male die insert.

inherently nullify the effect of the overall diameter of the tool if the path chosen is not in the steepest direction. It may also be impossible to cut the bottom of a concave surface because of the diameter of the tool. Tilting the workpiece or the tool can rectify this.

5.3.1 3-Axis Tool Path Generation

One of the leading CAM packages was selected for generating the 3-axis tool path because of its availability and its large variety of finish machining capabilities. The package shares similar path-generation methods with those at the top of the market and may represent, to a large extent, the current capabilities available in 3-axis finish machining. For 3-axis finish machining, the code-generation methods have been under continuous improvement for a long time and most of the packages are capable of producing robust codes for ball-nose surface machining.

The two types of path generated were parallel passes and surface flow. Various sizes of ball-nose and corner radius endmills were also tried. For each tool and surface, several combinations and variations in the cutting path directions were generated. The lengths of these paths were computed by the software and the parameters that gave the shortest total finish machining paths were used in the comparison. These paths are shown in Figs 13 and 14.

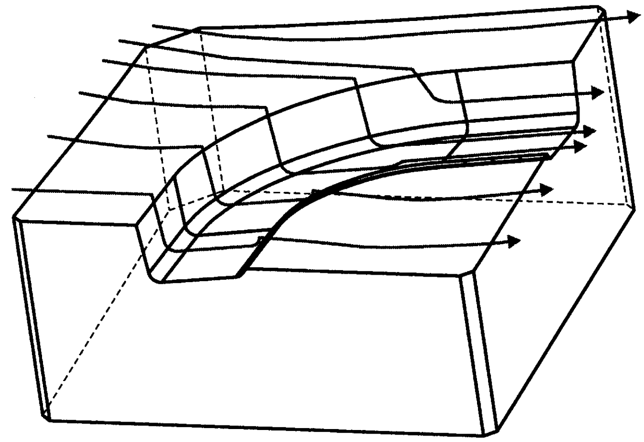

Fig. 13. 3-Axis parallel tool paths.

The first path generated is a parallel path over all the surfaces using ball-nose endmills. The second path was generated using the surface flow method with ball-nose endmills. The third path was also generated with surface flow but a radius corner endmill was used instead. Each path was generated to produce a maximum cusp height of 0.1016 mm.

The finish operation requires the use of a 12.7 mm ball-nose cutter or smaller to be able to cut the radius in the forming channel (Fig. 15). Paths were generated for both the surface flow and parallel methods with a 38.1 mm ball-nose endmill. Additional paths were created using surface flow with a 38.1 mm endmill with 6.35 mm radius corners. For each case, a $\frac{1}{2}$-inch ball-nose endmill was programmed to finish machine the forming channel to a cusp height of 0.1016 in.

A similar set of die inserts was machined by an independent mould and die manufacturer using a high-speed 3-axis machine.

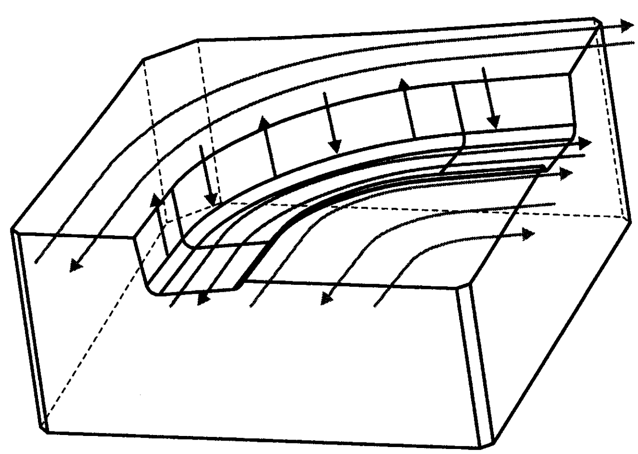

Fig. 14. 3-Axis surface flow tool paths.

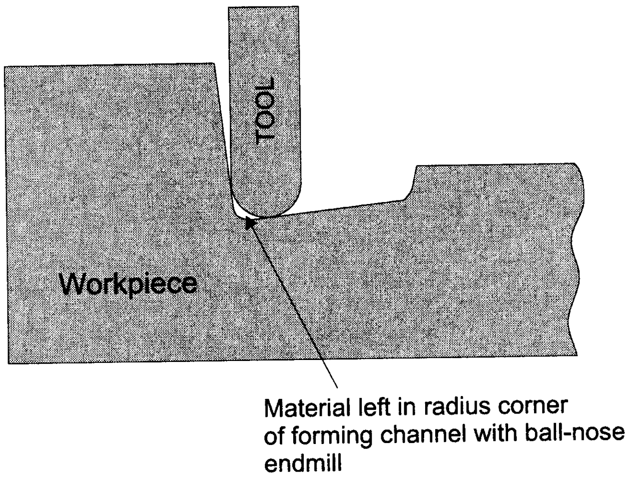

Fig. 15. Ball-nose endmill in forming channel.

The machining times, cusp height, approximate feedrates, and tool diameters and types were recorded. The data were analysed and an approximation of the total tool-path length was generated. The CAM software used, slows the axes down for corners. According to the manufacturer, up to 70% of the cutting time can be due to the acceleration and deceleration of the axes; there is an acceleration and deceleration period at the beginning and end of each pass, respectively, and for any curves or changes in direction. Thus, relatively small parts are not ideal for high-speed machining. The hydroforming die inserts are only $279.4 \times 279.4 \times 152.4$ mm^3 in size. An estimate of the tool-path length used by the independent manufacturer was also obtained with the same CAM software used at Waterloo for the same tooling and cusp height parameters. The data and results are given in Table 1.

The estimate is in good accordance with the actual time recorded for machining the die inserts. This shows that the CAM software used at Waterloo to represent 3-axis finish machining is comparable in performance to other CAM packages. It also illustrates the lower than expected productivity of high-speed machining with small workpieces because of the short passes of the tool.

Having demonstrated that the simulated 3-axis tool path produced similar machining times and path lengths to those used in actual machining, the former will be used in the comparison, presented next, between 5-axis and 3-axis.

Table 1. 3-Axis high-speed machining data.

Tools: 19.05 mm ball-nose for mating surfaces 9.525 mm ball-nose for forming channel	
Cusp height	0.0127 mm
Feedrate	2.54 m min^{-1}
Path length generated	103 m
Cutting time at feedrate	40.55 min
Time increase due to acceleration and deceleration of axes (70% of total cutting time)	94.61 min
Total cutting time estimate	**135.16 min**
Cutting time recorded by independent manufacturer	**120 min**

Listed in Table 2 are the total lengths for the different 3-axis tool paths and the 5-axis tool path. Paths generated with the corner radiused endmill in 3-axis were the longest because the curved surfaces are shallow and the CAM package used only the radius corners to cut the surface and predict the cusp height. Since the corner radius of the tool formed the surface, small side steps were used which made the total path length extremely long. The 5-axis tool paths were shorter than all the 3-axis paths generated. Five-axis machining allows for the optimisation of the cutting geometry of radius corner endmills by continuously adjusting the tilt of the tool with respect to the intended surface. This means that larger cross-feeds are generated for specified cusp heights and a lower density of cusps is formed than in 3-axis machining.

The die inserts are too small to take full advantage of high-speed machining. With such short passes in the tool path the machine spends most of the cutting time accelerating and decelerating and not cutting at the full programmed feedrate.

It must be mentioned here that there are ways to improve and speed up 3-axis machining. Often, in industry, non-critical surfaces such as the mating surfaces of dies are machined to have larger cusps to reduce machining times because the dimensional accuracy required of these surfaces is low. Finishing of these surfaces can be done very quickly with a pneumatic grinder.

Certain advantages are realised by tilting the tool or the workpiece by a fixed angle on a 3-axis machine [9]. With ball-nose endmills, the surface finish can be improved, because cutting with the zero rotation point at the bottom of a ball-nose endmill can be avoided. That point on the cutter only rubs material away and leaves a very poor surface finish. Other advantages are that it allows for the use of larger diameter radius corner endmills and the steepest direction of cut can be forced to be the same throughout the workpiece. Thus, parallel passes in the direction of the steepest slope can be used throughout the whole part. However, this solution can complicate the set-up and it inherently increases the risk of set-up and programming errors. This introduces many parameters that are mostly workpiece dependent. For this reason, and because

Table 2. Tool path length comparison.

Path type	Tool and diameter (mm)	Total path length (m)	% Longer than 5-axis path
3-Axis parallel*	38.1 Ball-nose	32.02	249
3-Axis surface flow*	38.1 Ball-nose	31.80	247
3-Axis surface flow*	38.1 Rad1	46.45	406
5-Axis principal axis	Mating surfaces 38.1 Rad1 Forming channel 25.4 Rad2	9.16	—

Rad1 = 38 mm endmill with 6.35 mm radius corners
Rad2 = 25.4 mm endmill with 6.5 mm radius corners
*Forming channel finished with a 12.7 mm ball-nose endmill using surface flow path generation.

it is not common practice in industry, it was not investigated in the current study.

6. Conclusion

This work has shown the advantages of using 5-axis machining in the production of hydroforming dies; the mating surfaces are shallow and of low curvature, and the forming channels are typically of very simple geometry. To the best of our knowledge, this paper presents the first investigation to highlight the application of the new 5-axis machining method to the expanding new technology of hydroforming. Only total tool-path length was used in the present investigation to compare 5-axis with 3-axis machining. Other parameters such as tool wear and machining dynamics should also be included in further studies.

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