A CAD/CAM System for Die Design and Manufacture

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The manufacture of directionally solidified cast turbine blades relies on the precise casting of wax patterns of the actual turbine blade. This, in turn, requires the design and manufacture of a complex die. A CAD/CAM system is presented specifically for producing manufacturing information for dies based on basic data defining the shape of a turbine blade. The system is based around a UNIX graphics workstation which forms part of a CIM system being developed as part of an SERC Teaching Company based at Rolls-Royce plc, Derby.

1. INTRODUCTION

CAD/CAM is becoming increasingly important in manufacturing industry as leadtimes need to be reduced in product development as well as costs. The trend is to use production tooling in development and this tooling, wherever possible, is in the form of computer software. Thus, with the appropriate integrated CAD/CAM philosophy, this tooling can be speedily changed to meet modifications that might be required as a result of inspection or performance evaluation. The application of an integrated CAD/CAM approach to the design and manufacture of dies for use in the manufacture of wax patterns of turbine blades is a particularly good example. The reasons are that turbine blade shapes are difficult to specify, particularly for manufacture and furthermore, changes in die shapes are often required as a result of final product inspection.

A particularly important aspect in the design and manufacture of the dies is the generation of manufacturing information directly from design data. Furthermore, there is a need to simulate the manufacturing process in order to verify manufacturing data before a commitment is made to expensive machinery. The use of CAD/CAM in the form of an interactive graphics workstation can play an important role in this process.

In the SERC-Rolls-Royce teaching company programme in turbine blade manufacture, a die design and manufacturing CAD/CAM system was developed based around the UNIX workstation CIM philosophy described by Brookes.[1] The objective was to produce a system that would allow manufacturing data to be easily and speedily specified for the manufacture of dies, starting from a turbine blade definition resulting principally from aerodynamic calculations.

2. TOOL PATHS FOR 3D SURFACE MACHINING

In the application of the manufacture of die blocks for casting wax patterns of turbine blades, the critical problem is one of defining tool paths for surface machining where the surfaces are often curved in three dimensions. In this case the dies are machined from solid billets and so it is necessary to provide a considerable amount of machining

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information for a CNC milling machine to be able to machine the billet using a ball nose cutter. This information will include: the cutter starting point, the depth of cut and the cutter location paths for roughing and finishing.

The turbine blade model is based on aerodynamic and stress analysis. The model is built up around section information which is presented as B splines. These sectional B splines are joined together to form a mesh defining the blade.

In order to define cutter paths for machining an image of the blade surface, i.e. the die, more detail must be added to the geometric model. Of particular importance is the derivation of the cutter offset curves which define the tool centre locus.

2.1 Surface Definition

In order to generate tool offsets, component surfaces must first be defined. The object is therefore broken down into its principal surfaces.

Mathematically defined surfaces such as cylinders, planes, circles, quadrics and ellipses are described implicitly by the equation:

$$f(x,y,z) = \phi \tag{1}$$

However, complex 3-D surfaces such as blade aerofoils are described in a parametric form:

$$r = r(u,v) \tag{2}$$

where the function is a single-value in u and v. By fixing one of these variables a set of curves can be generated in one direction. Then by fixing the other variable, another set of curves can be generated in the other direction. Such curves are called parametric curves and are on the surface. Their precise nature will depend upon the particular way in which the parameters are chosen.

2.2 Differential Geometry of Surfaces

In order to calculate cutter offsets, the normals to the part surface being machined need to be determined.

For implicitly defined surfaces, the normals can be defined by partial differentiating the function in (x,y and z). So for any curve $r = r(s)$ lying on the surface, the normal is:-

$$\frac{df}{ds} = \frac{\partial f}{\partial x}\frac{dx}{ds} + \frac{\partial f}{\partial y}\frac{dy}{ds} + \frac{\partial f}{\partial z}\frac{dz}{ds} = \phi \tag{3}$$

or

$$\text{Gradient Vector} = \frac{\partial f}{\partial x}i + \frac{\partial f}{\partial y}j + \frac{\partial f}{\partial z} \tag{4}$$

For a 3-D parametric surface, the tangents for the constant u and constant v curves are calculated. The cross product of the tangents at any point on the surface, where the two curves meet, is the normal to the surface at this point. For example, the tangent at the intersection of these curves at $r(u_0,v_0)$ contains the two tangent vectors, so that the normal to the surface 'n' is given by the equation:-

$$n = \pm \quad \left[\frac{dr}{du} \times \frac{dr}{dv}\right] \quad \left[\frac{dr}{du} \times \frac{dr}{dv}\right] \tag{5}$$

The curvature of the surface is obtained by differentiating the surface function a second time. Continuity of the function is necessary if the surface is to have a well defined normal.

2.3 Cutter Offset

For $2\frac{1}{2}$-D components, an offset boundary may be formed around each surface by calculating the relative position of the cutter centre at the corners of the surface. The relative cutter positions at the corners of the boundary will depend on whether the boundary is external or internal and the accessability of the edges. The boundary that is formed by the cutter offset for each surface will define a surface parallel to the surface to be machined and at a distance from it equal to the cutter radius. By finding the intersections of the offset boundaries with each other, the limits of machining may be defined.

For 3-D surfaces, when a surface is machined using a ball nose cutter, the tool centre moves on a parallel surface, offset from the original by an amount equal to the cutter radius R. If the radius R exceeds one of the principal radii of curvature, the normals to the original and offset surfaces will be in opposite directions. So in machining a surface, the cutter radius must not exceed the minimum radius of curvature of the surface, otherwise gouging of the surface will occur.

Consider machining a 3-D surface shown in Figure 1. When cutting along the curve $u = u_0$ on the surface $r = r(u, v)$, using a ball nose cutter of radius R, the cutter centre will follow the path:-

$$r = r_c(u_0, v) = r(u_0, v) + R.n \qquad (6)$$

and the cutter tip will follow the path:-

$$r_t(u_0, v) = r(u_0, v) + R\,(n - a_x) \qquad (7)$$

where n is the unit normal to the surface at the point of contact on the curve $u = u_0$ and a_x is the unit vector along the cutter axis.

For bounded surfaces, the cutter must be moved in such a way so as to maintain a correct machining tolerance with respect to the machined surface (part surface) and the bound surface (drive surface if it is along the cutter movement or check surface if it terminates the cutter movement). When the tool is in the vicinity of the boundary, its

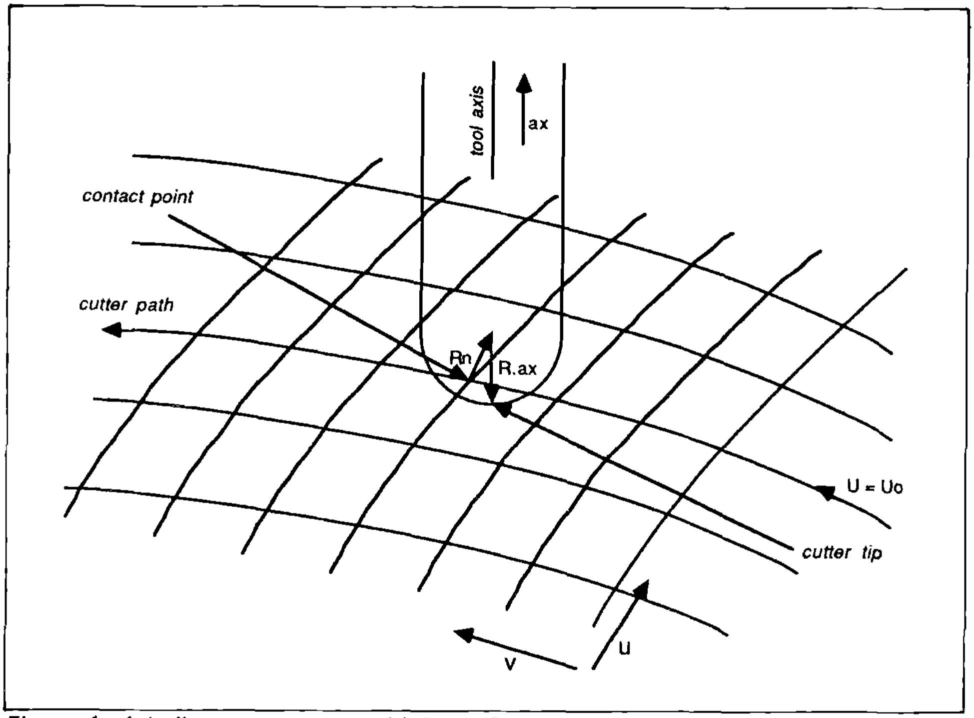

Figure 1. A ball nose cutter machining a 3-D surface

position must be checked relative to the bounding surface. If the tool tip is inside the part surface and within the bound surface tolerance, the tool position is correct. If the tool position is outside the tolerance, an iterative procedure must be used to bring it back within the tolerance. Tool positions that cannot be brought back to within tolerance must be rejected from the cutter path.

2.4 Surface Machining
In order to machine a surface completely, a number of cutter paths must be defined. For rough cutting the cutter spacing is based on maximum metal removal without exceeding the power of the machine or its stability. However, for finishing cuts, the spacing represents a compromise between excessive cusp height and long machining times.

3. THE CAD SOFTWARE

The CAD/CAM system is made up from a basic graphics or CAD system which is directly coupled to CAM software. A brief description will be given of the hardware and CAD software since it is described elsewhere.[1] The UNIX-based workstation, on which all the software runs, consists of a CODATA multibus computer, with a Motorola 68000 processor, containing 3Mb of RAM, 80Mb Disk and a nine-track magnetic tape unit. The graphics display is powered by a Matrox graphics driver giving bit mapped graphics with 4 bit planes and 16 colours. The system drives a colour monitor to a resolution of 1025 x 1025 pixels. The system is driven via a tablet and an alphanumeric terminal.

The basic CAD graphics philosophy is described by Glover.[2] The graphics system is three-dimensional with a comprehensive menu facility to control it. The graphics display can be divided into four working areas which correspond to the planes *x-y*, *y-z* and *z-x*. The fourth area is reserved for isometrics. Any one of the four areas can be worked on in detail either by windowing that area or using the viewpoint facilities.

An extensive range of menu facilities can be displayed along the lower point of the screen which makes the user's task easy when selecting functions to aid the graphics modelling process. The menu is displayed in groups of functions depending on the desired tasks. For example, a call for EDIT will result in the EDIT menu consisting of such functions as EDIT LINE, EDIT MACRO, EDIT ALPHANUMERICS, EDIT POINT, etc.

Some of the more difficult work in manufacture is concerned with the machining of curved surfaces such as is found with the dies corresponding to turbine blade surfaces. Such surfaces, particularly the gas washed surfaces, are described by a series of sections together with contours joining the sections. A set of menu modules was developed for such problems and allow sections and surfaces to be defined from a set of input data. In the case of a turbine blade the input data consisted of a set of points defining blade sections which were obtained from the Rolls-Royce blade file based on design calculations. Details of the spline blending of points to give sections and the surface modelling are described by Brookes[1] and Cardew-Hall.[3] These splines are particularly important since they are used in the determination of cutter paths for the machining operations.

4. THE CAM SOFTWARE

The CAM program modules are entered after the turbine blade surfaces have been defined. The mould for casting a wax pattern of the turbine blade is made from a number of die blocks, usually six, two dies for the shroud, two for the gas washed surfaces (the aerofoil) and two for the root. The boundaries of each die block are defined at the appropriate stage during the CAM process. The CAM system is interactive although much of the manufacturing information is derived based on a knowledge of the component geometry and its material. The system can generate APT-type output ready for an APT post processor or output in G-code format ready for a CNC controller.

Once the CAM system has been entered, any changes to the design data are inhibited. It is then necessary to make a number of decisions such as the selection of a machine tool type, cutter definitions, cutting data, surface definition, etc. The system contains sufficient information that will enable the inexperienced user to make such decisions. These decisions and related information are now discussed.

- **Machine Tool Selection**

The user may select a machine tool from the existing library on which manufacture is to take place. If a suitable machine is not available in the database then an option can be selected for defining a new or suitable machine tool. Once a machine has been selected then only functions and menu instructions pertinent to that machine are available to the user. Information on the characteristics of the machine tool such as machine power, spindle speeds and feeds are taken from the database and stored in the manufacturing file ready for use.

- **Material of Workpiece**

The system contains a library of materials together with their relevant properties. Common materials are specified in British, German, French or American Standards. When a specified material is selected, recommendations on cutting data tool geometries are displayed to assist the user.

- **Cutter Definitions**

A tool library is available for selecting tools and this library contains all the relevant properties and geometry of each tool.

- **Cutting Data**

Three methods are available for defining cutting data and these are as follows:-

- ○ The first method is by the selection of the cutting operation such as heavy roughing, light roughing or finishing. The recommended feeds and depth of cuts are selected according to the tooling data.
- ○ The second method is dependent on the surface finish required. In this case the required surface finish is combined with the tool geometry and the cutting data is then selected
- ○ The third method relies on the user selecting the depth of cut and the feed rate. In this case a check is made to ensure that the machine has sufficient power.

- **Power Determination**

When a machining operation is specified, the power required for the machining process is calculated. This is determined from the combined information derived from the material selected, the cutter geometry, the cutting data and the machine tool specification. The material properties combined with the cutting data gives the cutting speed. The spindle speed is then determined from a knowledge of the cutting speed and machine tool specification. Knowledge of the tool geometry and the cutting data leads to an average cutting chip thickness and with information of the material the specific cutting force can be determined.

The cutting power can be determined from cutting forces and speed and compared with the available power. If the cutting power exceeds the available power then the user is asked to re-specify the cutting data.

- **Boundary Definition**

The boundary of the surface to be machined is defined so that machining limits can be calculated. The boundary can be defined in two ways. The first is to select lines and curves from the surface file to define the boundary. The system then determines how these lines and curves are joined relative to each other to form the boundary. The second method depends on the selection of points on the surface to define the boundary. The boundary information is then stored in the boundary file and the boundary displayed together with a message on whether it is open or closed.

- **Machining Limits**

Once the boundary and cutter geometry have been defined, the machining limits of the surface can be calculated. If the cutter and boundary have been properly defined then a window is set around the *x*-*y* projection of the boundary data and displayed for checking. At each point on the boundary the user is asked to select a cutter position relative to the vector on the boundary at that point. A cutter position file is created and then checked for cutter interference. This file may have to be modified to avoid interference. The machining limits are finally filed together with information about the cutter. The surface together with the machining limits are displayed for checking. The machining limits will form a boundary to act as a constraint on cutter movements when the surface is machined.

- **Cutter Path Definition**

When machining complex surfaces and having selected the surface together with its external boundary and determined the machining limits, the procedure is then to establish the required cutter spacing and machining dominance (cutting direction). The cross section data of the surface, in the form of a spline is then selected and divided into a number of points depending on the cutter spacing. The sections are then joined together in the direction of dominance, by either straight lines, cubic splines or B splines. Where two surfaces join together, then each surface can be separately specified and the relationship between them defined.

- **Cutter Offsets**

The surfaces may be milled using a ball nose cutter, on a three- or five-axis milling machine. In the present work a three-axis machine was used. In order to determine the cutter offsets and assuming a ball nose cutter, three splines are considered together. At a point selected on the middle spline, four planes are determined using the outer two splines, with each plane being defined by three points. The direction cosines of the perpendicular to these planes are calculated and the cutter offset determined from the selected point. This procedure is repeated across the surface until it is covered by the correct cutter location paths. When all the cutter positions have been calculated, the system then tests for cutter interference with the surface; that is it checks to see if there is any undercutting. Once this has been completed, the cutter path is stored in a cutter location file. This file contains the cutter location for the finishing cut. If a component is to be machined from a solid billet, such as with the dies, then roughing cuts are also required.

- **Roughing Cuts**

When roughing cuts are required, the user must first specify the height of the billet. The depth of cut is then specified and the final cutter location extracted from the file. The cutter location is then determined for each cutter pass. The height of each pass is reduced by the depth of cut until a minimum value of metal removal is reached. The finishing cut is then specified. The cutter paths may then be displayed and stored in the manufacturing file when checked.

- **Control Information**

Some control functions are added to the process during the production of the machining data. These functions include coolant ON/OFF, spindle ON/OFF and dwell. Any of these functions may be selected during the generation of the cutter location file. The appropriate miscellaneous code will be generated when the machine command information is generated.

● **Detection of Erroneous Data**
The following checks are made to detect erroneous information:-

○ Prior to generating the cutter path the component is checked for overlapping data. If any is detected, the data are modified to avoid undercutting.

○ The second inspection is to test that the cutter can reach all parts of the surface without undercutting. If any undercutting results from this source, the user is advised to use a smaller cutter.

○ The third inspection checks for interference between the cutter assembly or tool holder and the billet.

5. RESULTS FROM SYSTEM USE

The system has been tested on the manufacture of die blocks for the aerofoil section of turbine blades. The geometric definition of one half of a die block for the gas washed surface is shown in Figure 2. An example of the die block with cutter offsets is shown in Figure 3. Figures 4 and 5 show the finishing cutter location path for the **u** and **v** directions respectively. The time taken to produce and check the cutter paths for machining the die blocks for the aerofoil section was about 30 minutes. With a DNC link to a CNC Bridgeport milling machine, G-codes were passed directly to the machine tool controller and machining commenced immediately after the CL data was produced. □

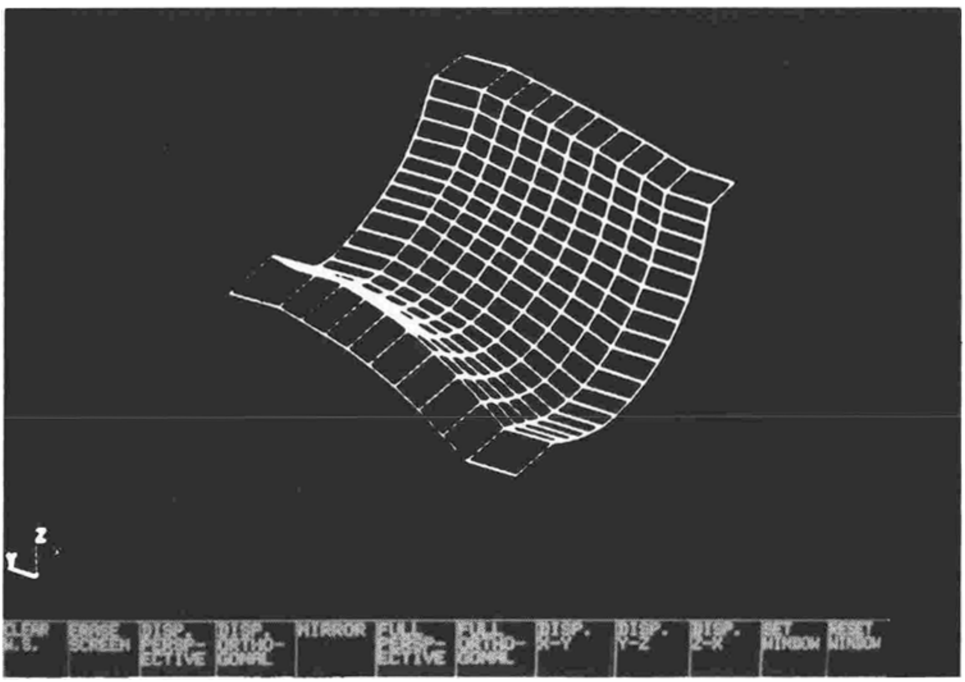

Figure 2. The geometric definition of one half of a die block for the gas washed surface

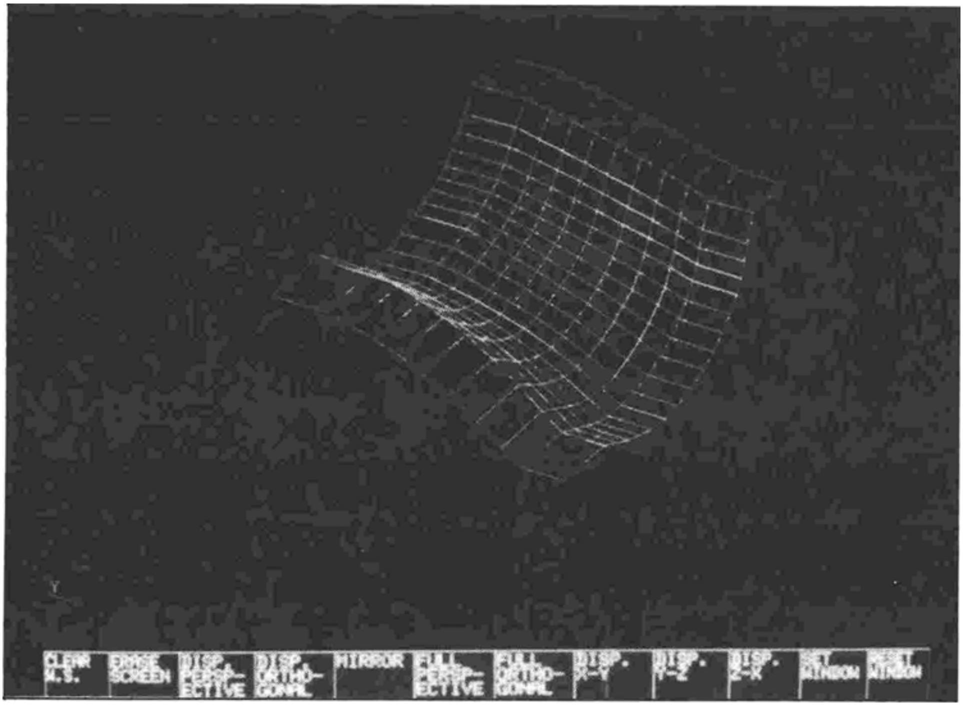

Figure 3. An example of the die block with cutter offsets

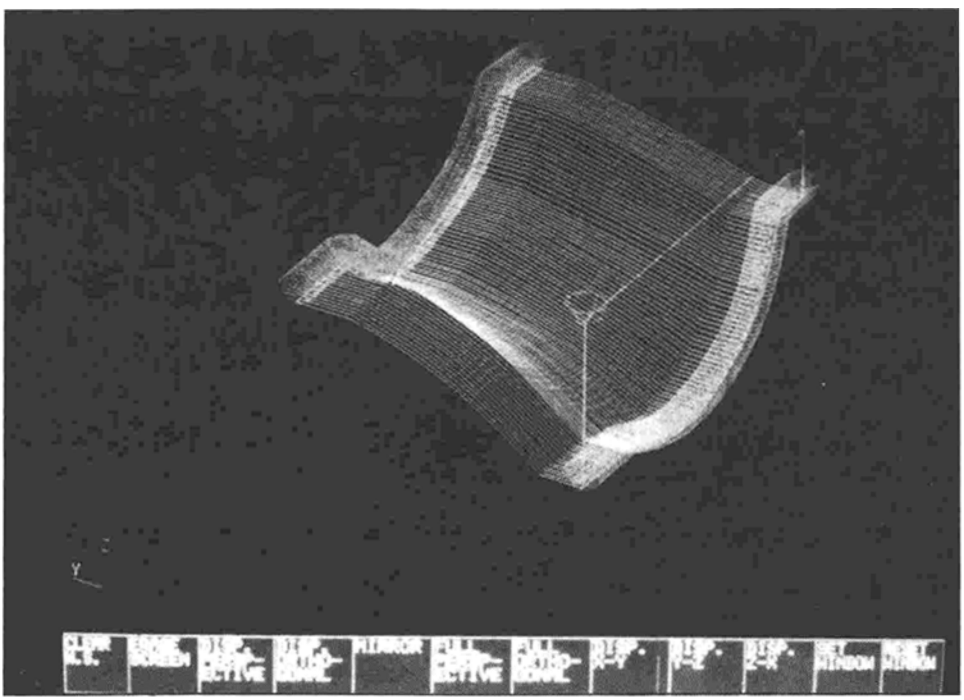

*Figure 4. The finishing cutter location path in the **u** direction*

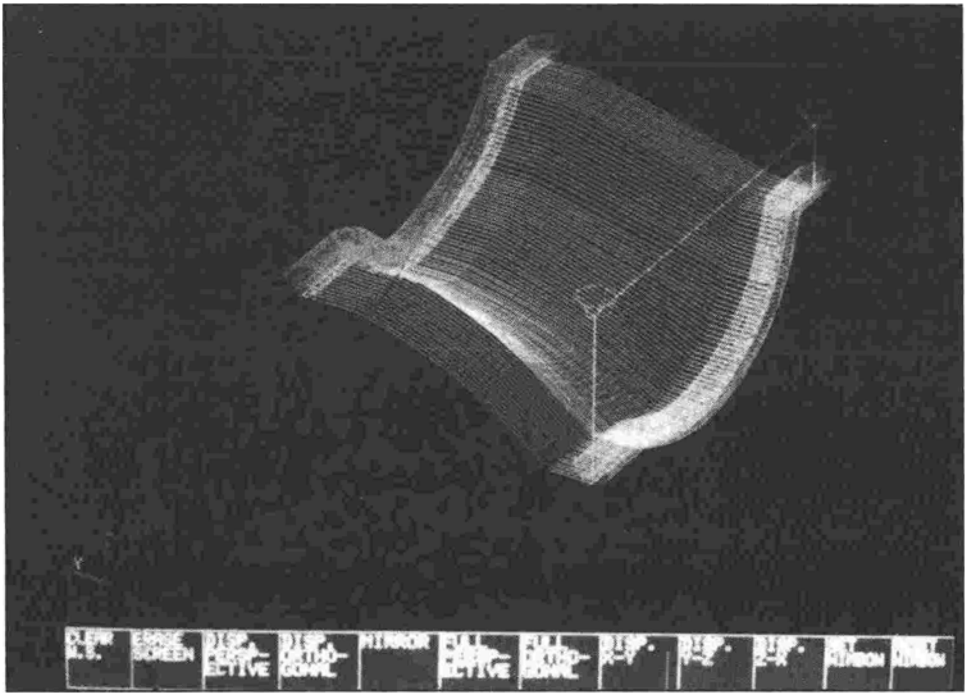

Figure 5. The finishing cutter location path in the ***v*** *direction*

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