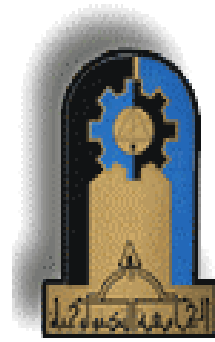


Republic of Iraq
Ministry of Higher Education
And Scientific Research
University of Technology
Department of Production and Metallurgy Engineering



STUDYING CURVE INTERPOLATOR FOR CNC SYSTEM

A Thesis

*Submitted to the Department of Production and Metallurgy
Engineering / University of Technology in partial fulfillment of the
requirements for the Degree of Master of Science in Production
Engineering*

By

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2008

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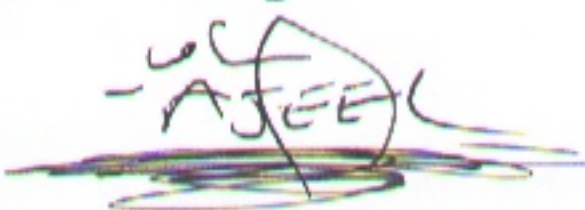
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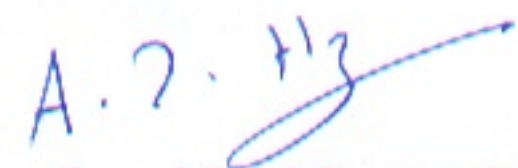

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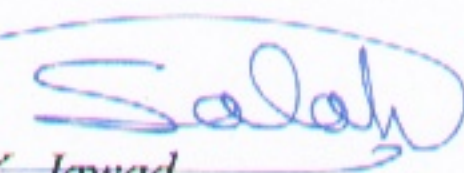
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*I would like to dedicate this thesis to all for
their support and encouragement*

To my mother and to all my dear friends

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Abstract

This thesis focuses on developing algorithm to calculate best length line segments in (u) and (w) directions for free form surface. This work includes generating of tool paths for free form surfaces based on the required accuracy of the manufactured part, which is represented by mathematical curves and surfaces, Bezier technique was used to apply the proposed algorithm because it is easily derived and simply applied. The proposed algorithms consist of two parts; the first part is to calculate the better length line segment in (u) direction between cutter contact points (CC), and best length line segment depends on the tolerance and minimum radius of curvature calculated on the surface, the second part is to calculate the better line segment in (w) direction depending on the type of surface (flat, concave or convex), cutter radius, tolerance and height scallop being given. The algorithms are applied in production field such as design of extrusion dies using three types of curve interpolation such as approximation cubic Bezier, interpolator Bezier and compound-CRHS profile die.

In this thesis, the manufactured part is by using a 3-axis CNC milling machine (FANUC 15MB), therefore to obtain on the language machine (G-code) from (SURFCAM) software. The results of this thesis show that the presented method is capable and robust to avoid gouging in 3-axis milling machines.

The machining operation is simulated using SURFCAM software depending on the different interpolation techniques mentioned. An evaluation test is applied to the three interpolation methods based on Finite Element Method (FEM) using ANSYS 9.0 software to define the strain and force required to extrude billet through the dies which are designed using the three mentioned interpolation methods.

The G-code programs have been implemented on 5-axis CNC machine (Okuma VH-40-HS dynamic machine), the sample material is (cibatool) and the machining process is achieved without a lubricant at the Protoshop Oy in Helsinki/Finland.

Finally, the thesis content a comparison between the mentioned methods with respect to the following criteria: Length line segment in (u) and (w), curvature, radius of curvature, number of segments, height scallop, size store in memory in (Bytes), number of G-code, number of tool path, length of tool path, strain and force required to extrude aluminum billet. Interpolator Bezier profile die gives better surface quality because its number of segment more than cubic Bezier profile die within (%74) and than compound-CRHS within (%66). The number of tool path for interpolator Bezier profile die is equal to (124); it is more than that of cubic Bezier and compound-CRHS within (%12.9). The required force to extrude metal (aluminum) is more than that of cubic Bezier profile die within (%8.5) but less than that of compound-CRHS within (%3.8).

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LIST OF SYMBOLS

- 1D One Dimensional Machining.
- 2Dm Two Dimensional Machining.
- 3D Three Dimensional Machining.
- AFA Automatic Feedrate Adjustment.
- CAM Computer Aided Manufacturing.
- CAD Computer Aided Design
- CAGD Computer Aided Graphics Design.
- CNC Computer Numerical Control.
- CL Cutter Location.
- CCP Cutter Contact Point.
- CP Control Points.
- CM^2 Curvature Matched Machining.
- g Side Step.
- h Height Scallop.
- HSM High Speed Machining.
- IGES Initial Graphics Exchange Specification.
- L Forward Step.
- MCU Machine Control Unit.
- NC Numerical Control.
- r Radius of Cutter.
- u, w Two Independent Surface Parameters.
- δ Tolerance.
- ρ Radius of Curvature.
- ρ_{\min} The Minimum Radius of Curvature of the Overall
 Surface.
- S Rate of Deformation.

-
- n Polynomial Degree.
 - $B_{i,n}$ Bezier Coefficient.
 - Δu Incremental Value in u-Direction.
 - Δw Incremental Value in w-Direction.
 - T The Number of knots.
 - K B-Spline Order.
 - $N_{i,k}$ B-Spline coefficient.
 - CRHS Constancy of the Ratio of the Successive Generalized Homogeneous Strain-Increment.
 - DCRHS Decelerated Constancy of the Ratio of the Successive Generalized Homogeneous Strain-Increment.
 - ACRHS Accelerated Constancy of the Ratio of the Successive Generalized Homogeneous Strain-Increment.
 - UCRHS Uniform Constancy of the Ratio of the Successive Generalized Homogeneous Strain-Increment.
 - ϵ_h Homogenous strain at any section (n) From Die.
 - R_o Initial Radius for Rod.
 - R_n Radius of Workpiece (Rod) at any Pass.
 - Z_n A function that reflects the dimension of workpiece of the Pass.
 - DXF Data Exchange Format.
 - NCC Numerical Control Code

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CHAPTER ONE

INTRODUCTION

Introduction

1.1 CNC Machining, NC Programming and Postprocessing:

Computer-Aided Manufacturing (CAM) is the utilization of computers to assist in the process of manufacturing. CAM includes the on-line and the off-line applications of the digital method. Computer Numerical Control (CNC) machining is the on-line application, which uses a computer with a machine control unit (MCU) to generate commands for controlling the machining process. The off-line application is the utilization of computers in production planning and non-real-time assistance in the manufacturing processes [1,2].

In CNC machining, the MCU plays a key role in the on-line control of machining. Its functions include (1) reading and decoding the information from the tool path data and distributing the data among the controlled axes; (2) controlling the tool centre, automatic tool selection, and the various compensation functions; (3) the feedrate calculations, the preparatory functions, the spindle motions and the miscellaneous functions control; (4) the interpolation to supply velocity commands between successive data points; (5) control of simultaneous multi-axis movements; (6) on-line diagnostics and troubleshooting; (7) display of machining information on the CRT screen and (8) the communication between the MCU itself and the external devices. The off-line application of CAM includes NC part programming and postprocessing. NC part programming involves the collection of all data required to produce the part. The calculation of a tool path along which the machine operations will be performed, the arrangement of the given and calculated data in a standard format which could be converted to an acceptable form for a particular CNC machine [1].

Most CAM systems generate one or more types of neutral language files containing instructions for CNC machining. The postprocessors are the interfacing tools between MATLAB program and CNC machines. A postprocessor is software which is used for translating neutral instructions from the MATLAB program into the specific instructions required by a CNC machine tool such as (DXF-file). The CLDATA defines the tool path with cutting conditions in the pan coordinate system.

Each command (part program) contains all required data: the preparatory functions codes (G-codes) functions for preparing the MCU to perform a specific mode of operation, the miscellaneous function codes (M-codes) which pertain to the auxiliary information, the geometry descriptions of the workpiece dimensions and cutting conditions, such as the feedrate, the spindle speed and the tool [1,2].

1.2 Sculptured Surfaces Machining Methods:

A sculptured surface can be represented by a set of curves that connect the design points of the surface. Two main approaches are commonly used for obtaining the curved surfaces: the first approach using parametric curves representation, while the second uses contouring planes (frequently. geometrically equally-spaced parallel planes) to intersect the surface for obtaining a curved surface. In the first approach, straight lines in a parametric domain are used to define the parametric curves $P(u, w)$ on the actual surface in cartesian space. By setting one parameter say w , a set of cutting curve functions $P(u, w)$ defines the entire surface. The parametric curves approach includes schemes of the isoparametric curves and the variable parametric curves. With isoparametric curves, tool paths are uniformly distributed across the parametric domain.

The step-over interval (which is the distance between tool passes referred to as cutting curves) is the same in the parametic domain. The

step-forward distance (which is the segment length along a cutting curve) is the same in the parametric domain and is independent of the surface geometric properties and of the machining tolerances. This approach is simple and generally efficient because the tool contact curves are easy to retrieve from the surface definitions [1]. Figure (1-1) shows cutter contact (CC) points for the tool that touches the design surface, cutter location point (CL) is tool center location, feed forward distance (L) is distance the tool travels in a single continuous tool motion, side step distance (g) is distance between two consecutive parallel tool paths, feed forward error (δu) and scallop height (h) are height of material left between two consecutive passes of the tool [3].

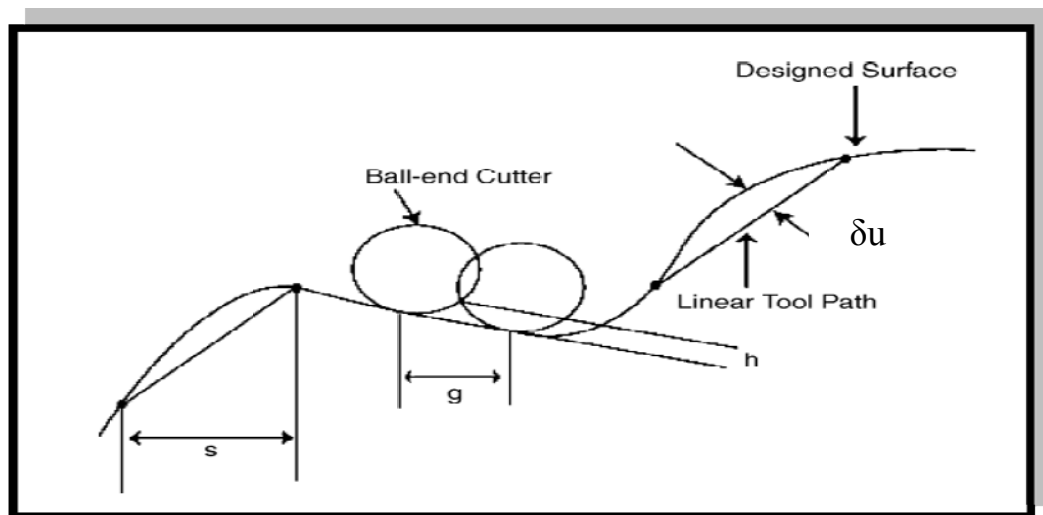


Figure (1-1): Forward and side step for cutter contact points [3].

1.3 Multi-Axis CNC Machining Characteristics and Machining Errors:

For machining sculptured surfaces, a tool path is required to contain the spatially varying cutter positions and its axis orientations (referred to as the cutter locations) in order to achieve better cutter accessibility for machining non-single-valued surfaces. Many factors contribute to CNC machining errors. One of the factors is the MCU interpolation method. Essentially, this method connects a straight line between each consecutive

machining data point and then linear interpolation is used to generate the required commands for positions along each straight line segment. As shown in Figure (1-2), a line segment is used to connect two consecutive machining data points either for the machining of a concave desired surface or for the machining of a convex desired surface. Linear interpolation generates intermediate position points along the line segment. The desired surface is the design cutting curve (either concave or convex). The linear segment approximates the design cutting curve resulting in the linearity error (δ). A part from the linearity error, there is an additional machining error in 3-axis machining [1]. The two strategies are described in the subsequent paragraphs:

- Approximation Method.
- Interpolation Method.

1.3.1 Approximation Methods:

A piecewise linear approximation of the cross section line of the patch with the tool driving plane is obtained, then a normal at each cross point is computed, thus the location of the center of a ball end tool is easily calculated by shifting the touching points coordinates along the surface normal with ball radius. This step is repeated at the adjacent point on the cross section until the boundary of the patch is reached [5].

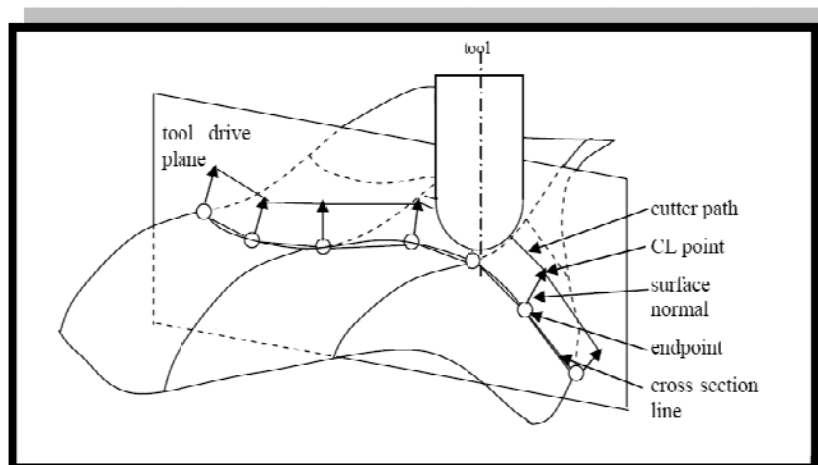


Figure (1-2): Cutter path generation using cross section lines [5].

There are three important piecewise linear approximation for cubic curves:

- Bezier technique.
- B-spline technique.

1.3.1.1 Bezier Technique:

Bezier curves as free-form curves are a powerful designing tool. They need only a few points to define a large number of shapes, hence their wide use in computer aided design (CAD) systems. In mathematical terms, a Bezier curve of degree (n) is a polynomial interpolation curve defined by $(n+1)$ points defining the Bezier control polygon [6].

1.3.1.2 B-spline Technique:

B-spline curve is a generalization of Bezier curve and a more proper and powerful curve representation. It has following features [7]:

- Local control of curve shape .
- Adding control points without increasing the degree of the curve.

Cubic B-spline is sufficient for most applications ($k=4$).

- Interpolate or approximate a set of given points (open or closed).
- Degree of resulting curve is independent of the number of control point.

1.3.2 Interpolation Method:

The tool moves along determined line segment. The surface curve is approximation by this number of calculated line segment and normal vector is calculated in the end points. The end point for each line segment is computed from variable radius of curvature for each point on the surface. If the distance between adjacent tool paths becomes unacceptably big it will affect the surface machined (finishing). And if line segment is small it will affect the machining time. Therefore it must be calculated for better line

segment. There are two important interpolation methods for represent curves and surfaces:

- Linear interpolation.
- Circular interpolation.

1.3.2.1 Linear Interpolation:-

The ability of the control system to guide the workpiece along straight-line path at an angle to the slide movements is called linear interpolation [7]. Curves can be produced with linear interpolation by breaking them into short straight-line segments. This method has limitations because a very large number of points would have to be programmed to describe the curve in order to produce a contour shape [9]. Figure (1-3) shows tool paths of cutter determined by line segments of the linear interpolated cutter path.

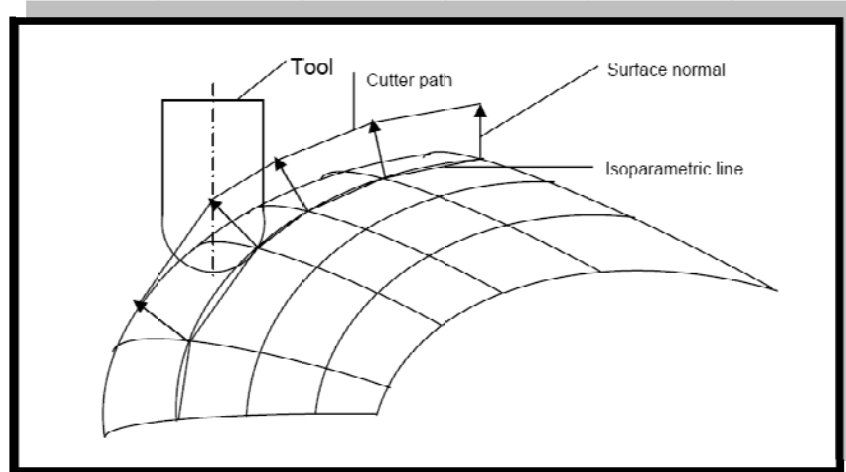


Figure (1-3): Machining along isoparametric lines [5].

1.3.2.2 Circular Interpolation:-

Circular interpolation is shown in Figure (1-4) that requires coordinate positions of the (X,Y) axes of the circular center, the radius of the circle, the start point, end point of the arc being cut and the direction in which the arc is to be cut (clockwise or counter clockwise) [9]. This procedure

eliminates the need to break the arc into straight –line segments [8]. Figure (1-4) shows tool paths of cutter determined by start point, end point and center radius of the circular interpolated cutter path.

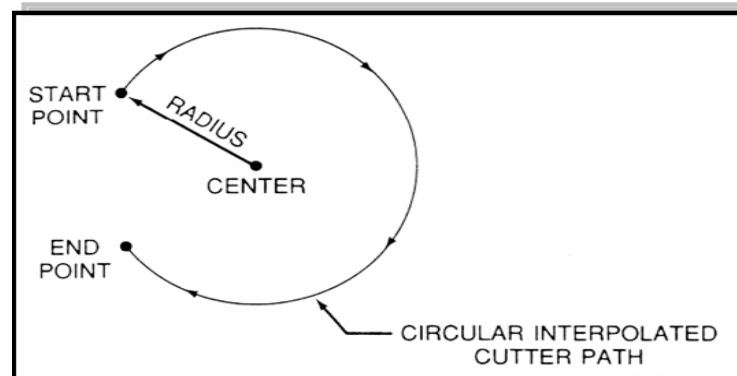


Figure (1-4): Circular interpolation [5].

1.4 Application of CAD/CAM and FEM in Production Engineering Field:

With the ongoing rapid improvements in the areas of Computer Aided Design, Computer Aided Manufacturing and Finite Element modeling, some attempts for developing an integrated manufactured part such as (extrusion die design) system have been made. In a Computer Aided Manufacturing environment this allows for direct data transfer to the CNC-machines. The Finite Element Calculations can be used to check the assumptions made for a specific design, improve existing design rules, develop new design rules or just improve the general understanding of the extrusion die design. Furthermore, the CNC-machines may be programmed with the help of the 3D model and the design application must incorporate the limitations and possibilities of the available machines and tools. A computer based design application will help the experienced die designer to progress from the design of the profile to the design of the die by supplying him with the maximum support without limiting its possibilities [54].

1.5 Goal of the Thesis:

For curve design, we use cubic Bezier polynomials. An attempt has been made to investigate the applicability of free form surfaces after determining better length line segment in direction (u) and (w) for free form surface using MATLAB software.

1.6 The Scope of the Thesis:

We structure the thesis as follows:

- In Chapter Two, we give a literature survey with emphasis on three topics:
 - 1- Curve and surface presentation.
 - 2- Tool path generation approaches.
 - 3- Surface machining approaches.
- Chapter Three covers different methods to represent curve and surface (Bezier, B-Spline and NURBS) in a mathematical way, also different types of (Lagrange, linear) interpolation methods.
- In Chapter Four, we focus on the manufacturing conditions and automatic generation of part programming.
- Chapter Five includes the applied proposed algorithms in production engineering field, visualization and discussion compared with proposed algorithms (interpolator Bezier profile die), cubic Bezier and compound CRHS profile die.
- Chapter Six represents the discussion of results, conclusion, and suggestions for future work.

CHAPTER TWO

LITERATURE SURVEY

Literature Survey

2.1 Introduction:

Theories and algorithms which relate shapes and geometries of CAD models to the path and motion controls of CNC machine tools constitute a subject area called motion intelligence. This area of concern consists mainly of three categories [1]:

- Curve and surface presentation.
- Tool path generation approaches.
- Surface machining approaches.

This chapter reviews the articles of published literature that are mostly related to the scope of this thesis.

2.2 Curve and Surface Presentation:

Currently, CAD tools have been widely used in the production and manufacture field. The body shapes of automobiles are presented by free-form surface. The most common free form shape description is parametric surfaces. Polynomial parametric surfaces are called sculptured surfaces. The terms “sculptured surface”, “curved surfaces”, “free-form surfaces” and sometimes simply “surfaces” are used interchangeably [10].

Sculptured surfaces are used in geometric modeling to describe variable shaped surfaces, such as dies, car bodies, airplane wings, turbine blades and so on that cannot be described by simple curved surfaces such as cylinders and cones. Sculptured surfaces are difficult to be machined. The popular surface representations include Bezier surfaces, B-spline surfaces and NURBS. The theory of these representation methods has been widely applied to current existing sculptured surface CAD systems [10].

The following paragraphs are better in present tense:

Thilo Kielmann (2007) [11] investigated computer graphics curves and surfaces. In this research, he studied mathematical representation of curves (explicit, implicit, and parametric), the representation of parametric surfaces for quadratic and cubic polynomial. He studied cubic interpolation and joining interpolating segments. This study is applied to Hermit, Bezier and B-spline curves and surfaces.

Akeel S. Bedan (2006) [12] investigated automation surface generation from wireframe data in CAD application. He created an efficient and accurate 3D surface interior data depending on primary initial data based on approximation and interpolation techniques. The research presents a mathematical algorithm to generate 3D surface design using three different approximation methods (Hermit, Bezier and B-Spline technique). A comparison has been made between the two adopted techniques of surface generation (approximation and interpolation) depending on several standard functions (sine-cosine functions, exponential functions, parabola functions, fractional functions and polygons).

Hayder K. Al-Abedi (2002) [13] showed the development of the free form surface construction approach by using computer. He constructed free form surface, which consists of two stages for construction curves, surfaces and test stage. The first stage is for the uniform B-Spline curves, the second concerns surfaces, the third grade thereby is for the direct method application in a generating the B-Spline surface and curves through inserting the control points between the parts of the curve. Concerning the second stage, non-uniform B-Spline functions, were used (Rational & non-Rotational) for the second and third grade to generate the free form

surface. The author has concentrated on the mathematical foundation of the uniform and non-uniform B-Spline surfaces and curves.

Kaspar Fischer (2001) [14] discusses a piecewise linear approximation of Bezier curves. He explained Bezier curves. Also, he presented Bezier curve by sequence of connected line segments.

Andres Iglesias (2001) [15] describes Bezier curves and surfaces. He showed Bezier curves (control polygon and control points), different functions for Bezier curves degree, and properties of the Bezier curves, comparison between Bezier and B-Spline curve (local, global control), rotational Bezier curves and Bezier surfaces.

Andes Iglesias et al (2001) [16] studied a high level computation program (mathematical and MATLAB) in computer-aided geometric design (CAGD) and computer graphics. They introduced algorithms to represent mathematical package for learning and teaching computer-aided geometric design (CAGD). The package showed commands for the treatment of the most usual curves and surfaces in (CAGD) (Bezier, B-Spline, rational, etc). The powerful symbolic and graphical mathematical capabilities, the functional, pattern recognition programming and the mathematical visualization environment have been extensively applied to get a user-friendly, didactic and powerful tool for education, with application in areas as (CAGD) and computer graphics.

Kenneth I. Joy (2000) [17] presents a quadratic Bezier curves. The curve can be obtained by repeatedly inserting midpoints into the curve. However, he developed the curve by calculation of points other than midpoints, to obtain a more useful parameterization of the curve.

2.3 Tool Path Generation Approaches:

The goal for tool path generation is to create a machined surface which closely approximates the CAD designed surface within a certain prescribed tolerance. The concept of tolerance is central to manufacturing, and its importance cannot be over-emphasized. Therefore, the errors introduced by tool path generation algorithms, namely, the errors caused by using the linear segment to approximate the desired machining curve must be bounded. Machined surfaces must be gouge free, and the scallop height between tool paths is to be controlled [1].

Young-Keun Ehoi et al (2007) [18] investigated tool path generation and tolerance analysis for free-form surfaces. They focus on developing algorithms that generate tool paths for free-form surfaces based on the accuracy of a desired manufactured part. A manufacturing part is represented by mathematical curves and surfaces. This algorithm reduces manufacturing and computing time as well as the (CC) points while keeping the given tolerance and scallop height in the tool paths.

Sug-Gun Lee et al (2007) [19] studied Mesh-based tool path generation for constant scallop-height machining. This paper presents a new approach to mesh based tool path generation for obtaining constant scallop heights. Also the paper proposes and compares four methods to estimate curvatures from the mesh surface; the curvature is essential for calculating unevenly spaced tool path intervals. The paper proposes an improved drive surface method to propagate CL-paths unevenly and to generate tool paths with various topologies.

L. P .Zhang et al (2003) [20] investigated tool path regeneration for mold design modification. They present a novel mold modifications tool path regeneration algorithm for three-axis (CNC) machining based on ball end mills. It is proven that if the boundary of the mold modification is interference free only the tool path points inside this boundary are affected by the mold modification. The tool path points that are outside the boundary can be reused to machine the modified mold .where the affected tool path points are detected, they are removed and replaced by the new tool path points. The scallop height values for the modified region are then checked. The algorithm has been tested on several industrial parts and it is proven to be efficient and robust. Figure (2-1) shows workpiece after removing some materials from it.

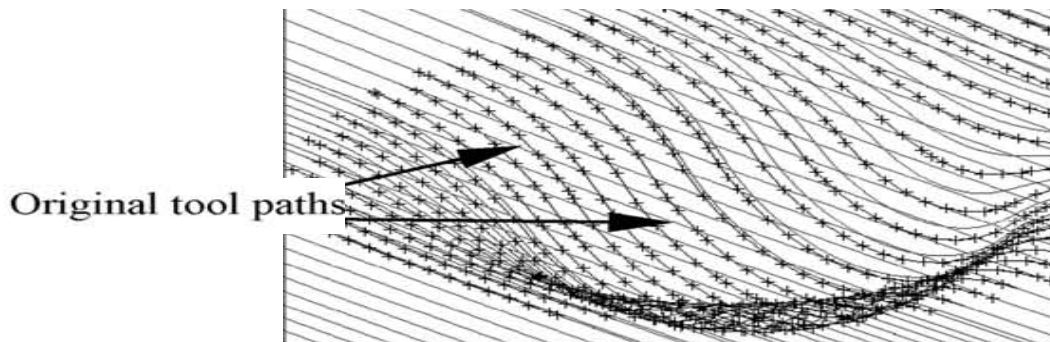


Figure (2-1): Tool path before and after modification with replaced points and added lines [20].

Sang C. Park (2003) [21] investigated tool path generation for z-constant counter machining. He presents a tool path generation procedure consisting of two parts:

- 1- Calculating the counter TPE (tool path element) by slicing the CL-surface with horizontal planes.
- 2- Generating a tool path by linking the counter.

It is desirable, to simplify the linking problem of the developed data structure, called a TPE-net information is provided on the machining constraint among the tool path element by making use of the TPE-net. The tool path linking problem becomes a touring problem in which every node is to be traversed. Figure (2-2a) shows an example of a simple part surface and its contour curves are shown in Figure (2-2b). There are eight closed tool-path-elements (C_1, C_2, \dots, C_8) on five horizontal planes (Z_1, Z_2, \dots, Z_5).

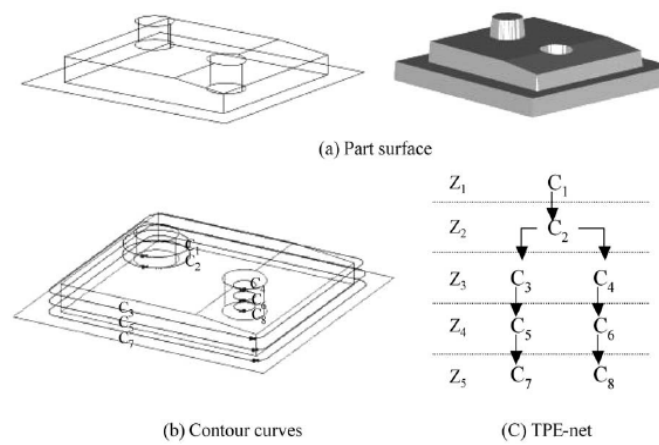


Figure (2-2): Example of contour curves [21].

Eungki Lee (2003) [22] showed a contour offset approach to spiral tool path generation with constant scallop height. He presents an algorithm for a new tool path generation for high-speed finish cutting process. In order to minimize the fluctuation of cutting load and the possibility of chipping on the cutting edging high speed machining (HSM), a spiral topology tool path that is to cut continuously with the minimum number of cutter retraction during the cutting operation is developed. This algorithm begins with the contour offset procedure along the boundary curve of the sculptured surface being machined. The spiral path is generated as a kind of the diagonal curve between the offset curves. This paths strategy is able to

connect to neighbor path without cutter retraction. Therefore the minimum retraction tool path can be generated.

His-Yung Feng et al (2002) [23] studied constant scallop-height tool path generation for three-axis sculptured surface machining. They present a new approach for the determination of efficient tool paths in the machining of sculptured surface using 3-axis ball end milling. The objective is to keep the scallop height constant across the machined surface such that redundant tool paths are minimized. Their work determines the tool paths without resorting to the approximated 2D representation of the 3D cutting geometry. Two offset surfaces are employed to successively establish scallop curves on the scallop surface and cutter location tool paths for the design surface. The results indicate the constant scallop-height machining achieves the specified machining accuracy with fewer and shorter tool paths than previous path generation approaches.

C. Lartigue et al (2001) [24] investigated CNC tool paths in terms of B-Spline curves. They propose an accurate and efficient method to generate a CNC tool path for a smooth free-form surface in terms of planar cubic B-Spline curves which will be fed into a free form curve interpolator. They assumed the use of a three-axis CNC machine tool with a ball end-mil cutter, they first interpolated break points which are generated by computing with a planar cubic B-spline curve. Then they evaluated the maximum scallop height along a scallop curve by computing the stationary points of the distance function between the scallop curve and the design surface. Furthermore they computed the maximum pick feed so that the maximum scallop height along a scallop curve coincides with the prescribed tolerance.

2.4 Sculptured Surface Machining Approach:

In general, parts designed with sculptured surfaces are machined by roughing and 3-axis finishing. A smaller ball-end mill is commonly used in finish machining to obtain a finer finish part. The general method of 3D finishing of a free-form surface is to use a ball mill to trace along the part surface by maintaining an acceptable tolerance. The leading commercial CAD/CAM systems have well developed ball-end machining capacities. Ball-end machining is widely used in sculptured surface machining [9].

G. kiswanto et al (2007) [25] showed gouging elimination through tool lifting in tool path generation for five-axis milling based on faceted models. This paper presents a method to eliminate gouging during tool path generation in five-axis milling based on faceted model. In order to speed up the process, gouging with vertices is eliminated first, then, continued by eliminating gouging with faces and edges of triangles. The tests showed that the presented method is capable and robust to avoid gouging in five-axis milling using either varying optimal tool orientation (inclination angle) or constant tool orientation.

D.K. Pratihari et al (2005) [26] studied optimization of CNC isoscallop free form surface machining using a generate algorithm. They presents isoscallop machining with edge-based master cutter path (MCP), which essentially ensures uniformity of surface, roughness over entire surface of part but may not necessarily ensure minimization of machining time. In their work it has been shown that there is a provision for minimizing machining time while implementing isoscallop machining by optimizing the orientation of the primary or master (MCP) through

application. The results indicate substantial reduction in total machining time for the proposed approach compared to those obtained through previously reported cutter path generation strategies.

Jianguo Wang (2005) [10] investigated global finish curvature matched machining. The thesis focuses on how to determine the uncut or rework areas of the previous CM^2 and how to define the boundary of these regions. Strategies for generating more efficiency CM^2 tool paths are also discussed. The goal was to improve surface finish and achieve design surface dimensions more accurately.

Diaa F.Elkott (2005) [29] worked on isoparametric line sampling for the inspection of planning of sculptured surfaces. He presents a new approach for the sampling of sculptured surfaces using continuous scanning coordinate measuring machine probe heads. This approach is based on scanning isoparametric lines on the sculptured surface. These lines are fitted to construct substitute geometry of the surface. The accuracy of the sampling plan is characterized by the maximum deviation between the substitute geometry and the CAD model. Two new algorithms for sampling isoperimetric lines are proposed. Automatic sampling uses the deviations between the substitute geometry and the surface CAD model to determine the sample locations. Curvature changes – based sampling uses the change in surface curvature to determine the sampling line locations.

Jenq-Shyong Chen et al (2004) [27] address the surface scallop generation mechanism in the ball-end milling process, in a new model that describes the path interval and feed internal scallop generating mechanism in the ball-end milling processes. Parameters such as the tool radius, feed/pick ratio, initial cutting edge entrance angle and tool-axis inclination angles have been studied and experimentally verified. It was found that the

feed interval scallop height was (3-4) times larger than the path interval scallop height at the high-speed machining cases.

Eing-Jerwei et al (2004) [28] concluded a study on general analytical method for (CNC) machining of the free form surfaces. They establish a systematic analytical method for (CNC) machining of the free form surfaces and developed the postprocessor to obtain the (NC) code. The method comprises of five steps to find the equation of surface, curvature analysis, the selection of tool, the error calculation of the linear incremental kinematics and the calculation of the tool path interval.

Marchenko Tikhon et al (2004) [30] established NURBS interpolator for constant material removal rate in an open NC machines tools. They present a NURBS interpolator based on the adaptive feedrate control for the constant material removal rate. This is accomplished by varying feedrate using the curvature compensated feedrate system to be an important potential application in ensuring part accuracy and protecting the cutting tool.

Debananda Misra et al (2004) [3] investigated zigzag tool path generation for sculptured finishing. They present a CL-based approach to generate tool paths for finishing operation of sculptured surfaces. An inverse tool offset algorithm was used to generate the discredited offset surface. Tolerance requirement and maximum allowable scallop height were used as the limiting conditions for CL-data generation in the feed-forward and side step direction respectively.

Zezhong C. Chena et al (2003) [31] introduced the automated surface subdivision and tool path generation for 3 ½ ½ axis CNC machining of sculptured parts. They investigated a new tool path

generation method to automatically subdivide a complex sculptured surface into a number of easy to machine surface patches; identify the favorable machining set-up/orientation for each path; and generate effective 3-axis CNC tool path for each path introduced.

Tao Chen et al (2002) [32] studied a tool path generation strategy for sculptured surfaces machining. They presents a strategy to generate interface free tool paths for machining sculptured surfaces on a three axis milling machine. The strategy proposed here is to first determine the tool path topology. The values of the step length and path interval are then calculated based on the machining tolerance requirements. After detecting and eliminating the tool interference, the interference-free tool path generated.

S. Mansour (2002) [33] worked on automatic generation of part programs of milling sculptured surfaces. He presents an attempt to establish simple but effective software to link CAD package and (CNC) machine tools. To achieve this, software package was developed capable of exploring initial graphics and exchanging specifications (IGES) files of simple or free form surfaces created on any CAD package. Depending on the size of created surfaces, various dimensions of cutting tools are selected by the user. Other features included in this package are the ability to automatically detect the correct machining direction and correct machining of surfaces. Obviously its main feature is its stability to automatically generate part programs for machining sculptured surfaces.

Cha-Soo Iun (2002) [34] showed a new curve-based approach to polyhedral machining. He presents a new approach to three-axis NC tool path generation for sculptured surfaces. In the proposed curve-base approach the gouge-free tool paths are generated from a polyhedral model

of the STL (stereo lithography) format. The polyhedral model is offset by local-offsetting schemes. Then the offset elements such as triangular facets, trimmed spheres are sliced by series of drive plans. The curve segments on a drive plane are stored, trimmed and linked, while the concave gouge is removed during the trimming process. The main advantage of the proposed method is that the tool path can be generated from a polyhedral model without any concave and convex gouge, especially on an NC machine that supports NURBS interpolation.

B O H Kim (2002) [35] studied machining efficiency comparison direction parallel tool path with contour-parallel tool path. He presents a machining time model that considers the acceleration and deceleration of the CNC machine, using the proposed model to compare the machining efficiency of the tool paths currently employed in molds and dies manufacturing of three types of direction-parallel tool paths (one-way path, pure zig zag path and smooth-zig zag path) and contour parallel tool path, the results and the effects of acceleration and deceleration are notably revealed at higher feed rates.

Yuam-Shin Lee et al (2000) [36] worked on rolling-ball method and contour marching approach to identifying critical regions for complex surface machining. They present a surface analysis method that includes a rolling-ball-algorithm and a contour machining algorithm for identifying the critical regions that are unfeasible for machining. For a given cutter size, the algorithms automatically identify the regions that are unfeasible for machining and dichotomize the surface into the critical region and the machinable region. A rolling ball method is used to find the starting points of the critical region boundary. A contour machining method is then used

to construct the actual boundary of the critical regions by using the starting points found in the rolling-ball method.

Chih-Ching Lo (2000) [37] has studied CNC machine tool surface interpolator for ball-end milling of free-form surface. He presents a new type of (CNC) machine tool interpolator that is capable of generating the cutter path for ball-end milling of free form surface. The surface interpolator comprises on-line algorithms for cutter contact (CC) path, scheduling (CC) path interpolator and tool offsetting. The interpolator algorithms for isoperimetric, isoscallop and isoplanar machining methods are developed, respectively. The proposed surface interpolator method gained the advantages for minimizing the data loaded to the (CNC) machining tool and maintaining the desired feedrate and position accuracy along the (CC) path.

2.5 Remarks on the Conducted Literature Surveyed:

The following remarks could be summarized from previous literature survey:

- 1- The use of computer based on mathematical methods in representing curves and surfaces for sculptured surface geometric modeling has been covered. For our purpose, MATLAB (7.4) is the most suitable choice.
- 2- Most of the relevant researchers and papers focus on interpolation methods to represent geometric surfaces. In our research, we have developed algorithms to obtain improved line segments in (u) and (w) directions based on the given values of tolerance and height scallop.
- 3- 3-axis CNC machine for machining sculptured surface is being suggested in our experimental investigation.
- 4- In the CNC machining field, most of the papers study the efficiently surface process. Our research leads to an improvement surface machining, reduce machining time and cost through the application of the proposed tool path strategies.

CAPTER THREE

APPROXIMATION AND INTERPOLATION TECHNIQUES

3.1 Introduction:-

Curves are often defined as the locus of a point moving with one degree of freedom. History records many variations in the idea of a curve as a path of one dimension having length only. Ways to mathematically describe curves for geometric modeling include intrinsic equations, explicit, implicit equations and parametric equations [38]. This chapter introduces the mathematical representation and geometric modeling of different curves and surfaces. Complex curves and surfaces are required for other applications, such as the design of airplanes ships, and automobiles etc.....

In CAD a form is needed for representing curved surface that:

1. looks nice (smooth contours).
2. are easy to manipulate and manufacture.
3. follows prescribed shape (airfoil design) [7].

3.2 Parametric and Implicit Equations:-

Curves are represented in two forms, parametric and implicit. The parametric is represented as follows:

$$X=X(u), \quad Y=Y(u), \quad Z=Z(u) \dots \dots \dots (3-1)$$

Where u : parameter $0 \leq u \leq 1$

The representation permits a quick computation of the X , Y and Z coordinates of all points on the curve with each point coordinate defined separately. Because curves are usually bounded in computer graphics, this characteristic is of considerable importance [10].

The implicit representation of plane curves in two and three dimensions goes via equations [39].

$$F(X,Y)=0 ; f(X,Y,Z)=0$$

The implicit equations of the straight line and conic curve are:

$$AX+BY+C=0 \dots\dots\dots (3-2)$$

And

$$AX^2+2BXY+CY^2+DX+EY+F=0 \dots\dots\dots (3-3)$$

where X, Y and Z are coordinates of all points on the curve or surface, A, B, C, D, E and F are constants. In geometric modeling, the most common form of curve representation has been the parametric form because of its ease of programming and computability.

3.3 Parametric Representation:

Curves used in geometric modeling can be as simple as a line or a circle. However, more complex curves and surfaces are required for many applications in industry and manufacturing, where various shape constraints must be met [3]. Figure (3-1) shows a parametric curve and a parametric surface when (u,w) are between [0 to 1].

Where u: surface parameter $0 \leq u \leq 1$

w: surface parameter $0 \leq w \leq 1$

- Curve

-Surface

$$P(u)=[X(u),Y(u),Z(u)]^T$$

$$P(u,v)=[X(u,v),Y(u,v),Z(u,v)]^T$$

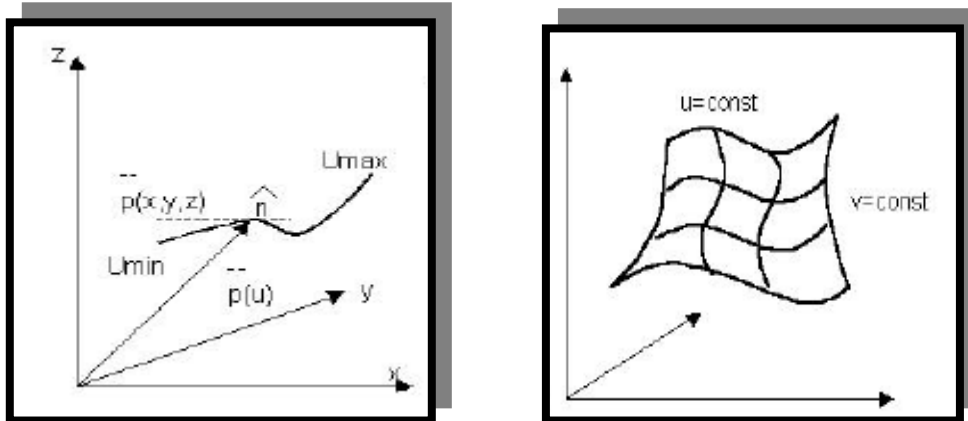


Figure (3-1): Parametric representation of curves and surfaces [7].

where $P(u,w)$ is coordinates of all points on the surface. We represent any curves as well as curved surface using parametric equations. In practice, curves are formed by a series of straight line segments.

3.4 Bezier Representation:

P. Bezier of the French automobile company of Renault first introduced the Bezier curve. A system for designing sculptured surfaces of automobile bodies (based on the Bezier curve) was introduced in (1962) [7]. Bezier has chosen a family of functions called 'Bernstein polynomials' to satisfy these properties. Bezier started with the principle that any point on a curve segment must be given by parametric function of the following form where $(u$ and $w)$ are surface parameters, $B_{i,n}$ is Bezier coefficient [38]:

$$P(u) = \sum_{i=0}^n P_i B_{i,n}(u) \quad u \in [0,1] \dots \dots \dots (3-4)$$

where the basic functions are:

$$\left. \begin{aligned} B_{i,n}(u) &= \binom{n}{i} u^i (1-u)^{n-i} \\ B_{i,n}(u) &= \frac{n!}{i!(n-i)!} u^i (1-u)^{n-i} \end{aligned} \right\} \dots\dots\dots (3-5)$$

This produces the following polynomials form:

When n=2 and or for three control points.

$$\left. \begin{aligned} B_{0/2} &= (1-u)^2 \\ B_{1/2} &= 2u(1-u) \\ B_{2/2} &= u^2 \end{aligned} \right\} \dots\dots\dots (3-6)$$

so that:

$$P(u) = (1-u)^2 P_o + 2u(1-u)P_1 + u^2 P_2 \dots\dots\dots (3-7)$$

When n=3 for four control points:

$$\left. \begin{aligned} B_{0/3} &= (1-u)^3 \\ B_{1/3} &= 3u(1-u)^2 \\ B_{2/3} &= 3u^2(1-u) \\ B_{3/3} &= u^3 \end{aligned} \right\} \dots\dots\dots (3-8)$$

so that:

$$P(u) = (1-u)^3 P_o + 3u(1-u)^2 P_1 + 3u^2(1-u)P_2 + u^3 P_3 \dots\dots\dots (3-9)$$

3.4.1 Matrix Form:-

For the cubic Bezier curve, n=3 equation (3-9) is written in matrix form as follows:

$$P(u) = [(1-3u+3u^2-u^3)(3u-6u^2+3u^3)(3u^2-3u^3)u^3] \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{bmatrix} \dots\dots\dots (3-10)$$

$$P(u) = [u^3 u^2 u^1] \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{bmatrix} \dots\dots\dots (3-11)$$

Letting

$$V = [u^3 \ u^2 \ u^1]$$

$$P = [p \ p^1 \ p^2 \ p^3]^T$$

$$M_B = \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

This equation can be written even more compact as:

$$P(u) = UM_B P \dots\dots\dots (3-12)$$

where (U) is the vector of surface parameters, M_B is the Bezier matrix that represents cubic Bezier curve and (P) is the vertex information matrix (control point).

Figure (3-2) shows the flowchart of construction and visualization of Bezier curve. To construct a Bezier curve from a number of control point as input (CP) and increment value (Su), we will compute each point on the curve by equation (3-12) and parameters curve (u) don't exceed (1) because parameters curve (u) is from (0 to 1).

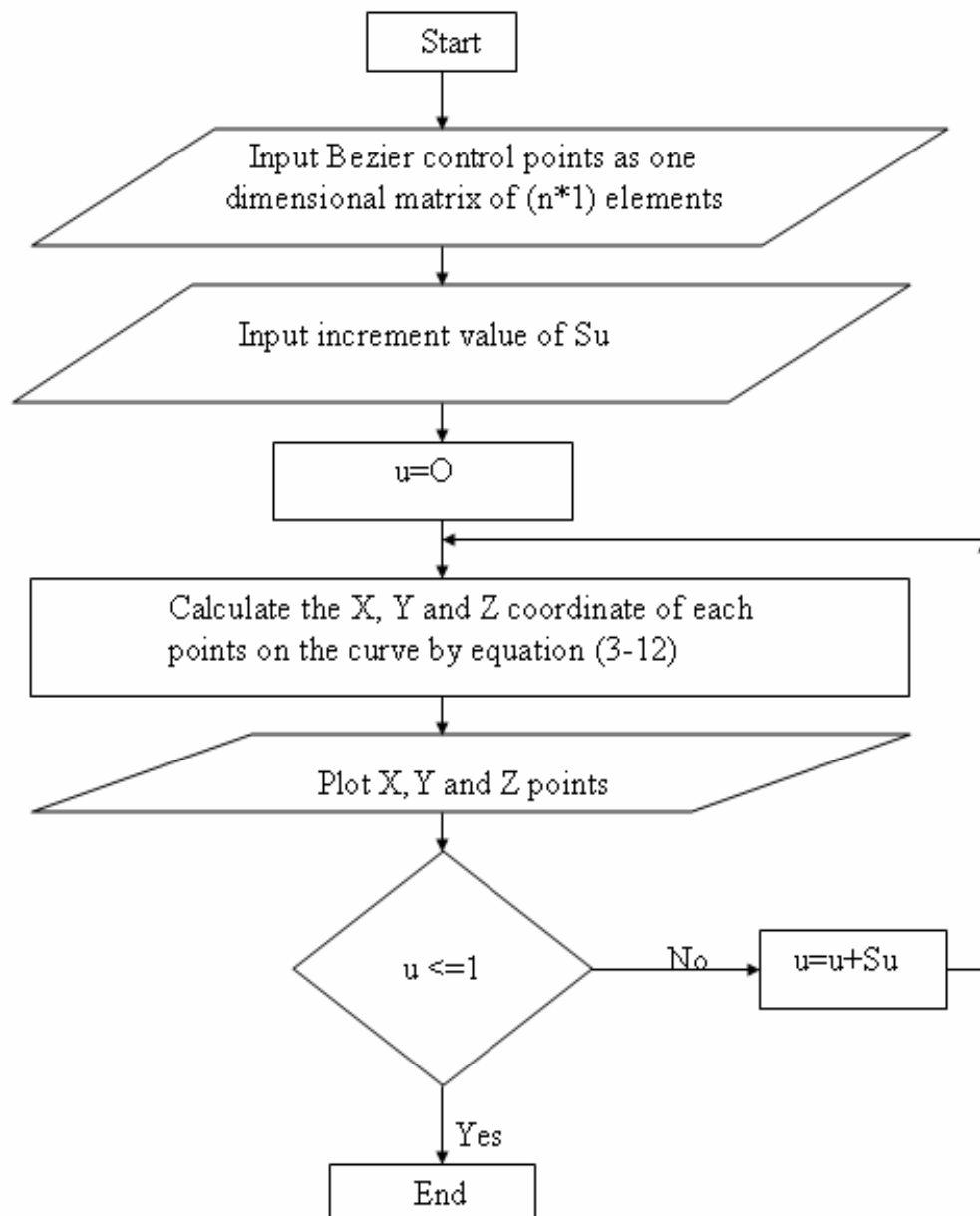


Figure (3-2): The flowchart to represent a Bezier curve.

In addition to the initial data that generates the desired curve the proposed program represents the curve in a graphical mode with the aid of MATLAB (V 7.4) software. Which figure a final result of practical application of the proposed program.

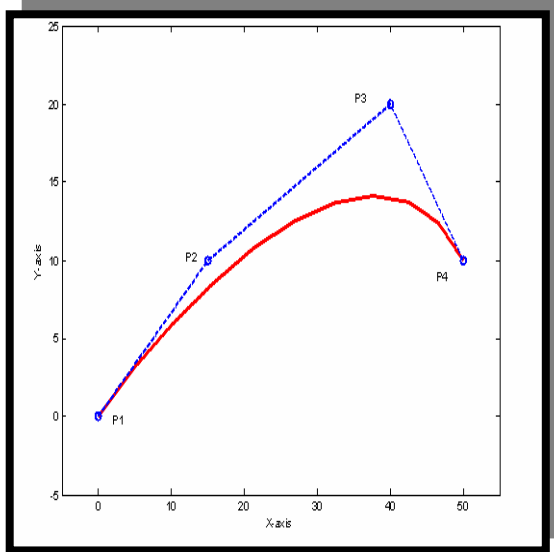
Figure (3-3A) shows the construction of a Bezier curve from third degree (3rd degree) and Fig. (3-3B) shows construction figure from two cubic Bezier curves (3rd degree). The matrix form of a Bezier curve when n=4:-

$$P(u) = [u^4 \ u^3 \ u^2 \ u \ 1] \begin{bmatrix} 1 & -4 & 6 & 4 & 1 \\ -4 & 12 & -12 & 4 & 0 \\ 6 & -12 & 6 & 0 & 0 \\ -4 & 4 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix} \dots\dots\dots (3-13)$$

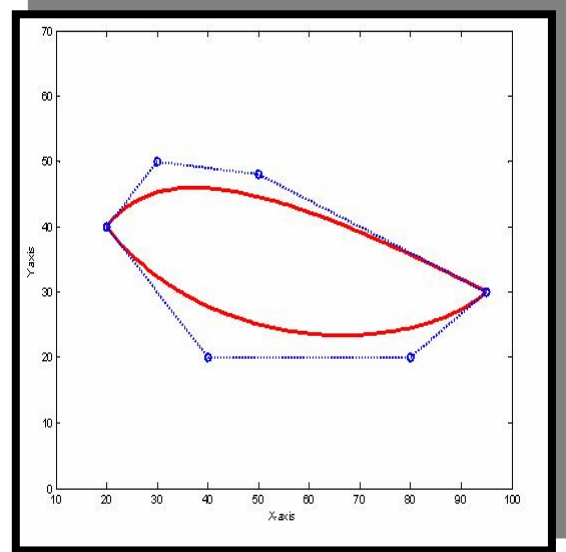
Figure (3-3C) shows the construction of a Bezier curve of 4th degree, which is a more complex curve that is used in applications such as complex die and free form surface. The matrix form of the Bezier curve when n=5:-

$$P(u) = [u^5 \ u^4 \ u^3 \ u^2 \ u \ 1] \begin{bmatrix} -1 & 5 & -10 & 10 & -5 & 1 \\ 5 & -20 & 30 & 10 & 0 & 0 \\ -10 & 30 & -30 & 10 & 0 & 0 \\ 10 & -20 & 10 & 0 & 0 & 0 \\ -5 & 5 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{bmatrix} \dots\dots\dots (3-14)$$

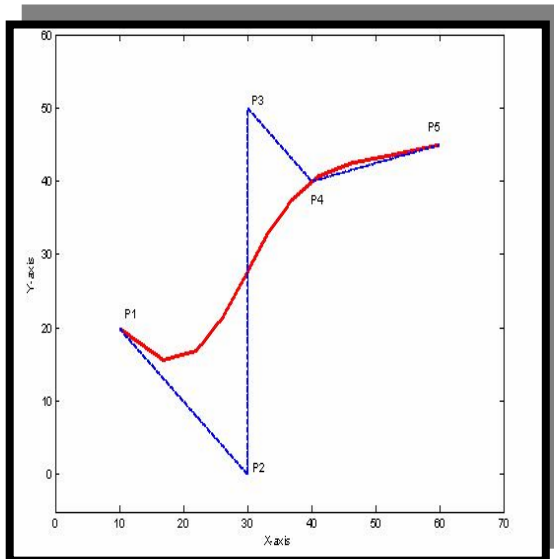
Figure (3-3D) shows construction of Bezier curve from fourth degree (5th degree) to represent different complex shapes.



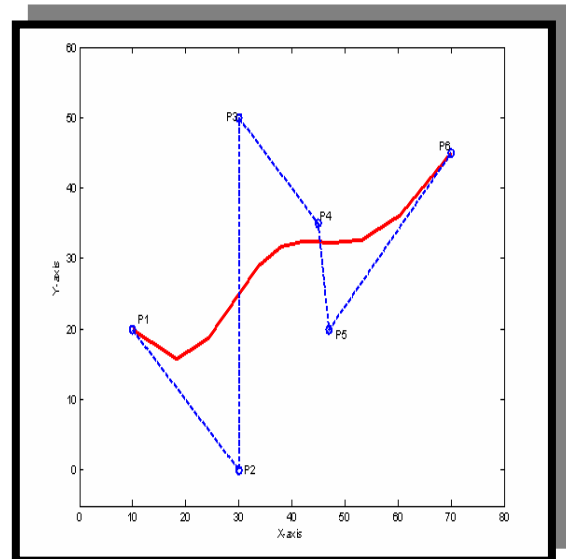
(A)



(B)



(C)



(D)

Figure (3-3): Represent Bezier curves. (A) Bezier curve (3^{rd} degree). (B) Complex Bezier curve (3^{rd} degree). (C) Bezier curve (4^{th} degree). (D) Bezier curve (5^{th} degree).

3.4.2 Bezier Surfaces:

Points on a Bezier patch are given by the following tensor product, which is a simple extension of the general equation for points on Bezier curve:

$$P(u, w) = \sum_{i=0}^n \sum_{j=0}^m P_{ij} B_{i,n}(u) B_{j,m}(w) \dots\dots\dots(3-15)$$

The P_{ij} comprises of a $(n+1)*(m+1)$ rectangular array of control points defining the vortices of the characteristic polyhedron of the Bezier patch which lies entirely within its convex hull. $B_{i,n}(u)$ and $B_{j,m}(w)$ are the basis functions, defined in the same way as for Bezier curves. The general matrix equation for a Bezier patch is:

$$P(u, w) = U_{1 \times m} M_{Bm \times m} P_{m \times n} M_{Bn \times n}^T W_{n \times 1}^T \dots\dots\dots(3-16)$$

where (U) holds the surface parameters (in u direction), ($M_{Bm \times m}$) is the Bezier matrix to represent the surface, ($P_{m \times n}$) is vertex information matrix (control point), ($M_{Bn \times n}^T$) is the inverse Bezier matrix for representing Bezier surface and ($W_{n \times 1}^T$) holds the surface parameters (in w direction). The material dimensions depend on the dimensions of the control point array. The Bezier patch need be described by a square array of control points although the bicubic Bezier patch is defined by a (4×4) array of control points [12]. Bicubic Bezier patches are expressed in a form similar to the Bicubic Hermit patch-using the binomial representation of the cubic Bezier curve. The matrix equation for a patch defined by a (4×4) array of control points is:

$$P(u, w) = V_{1 \times 4} M_{B, 4 \times 4} P_{4 \times 4} M_{B, 4 \times 4}^T W_{4 \times 1}^T \dots\dots\dots(3-17)$$

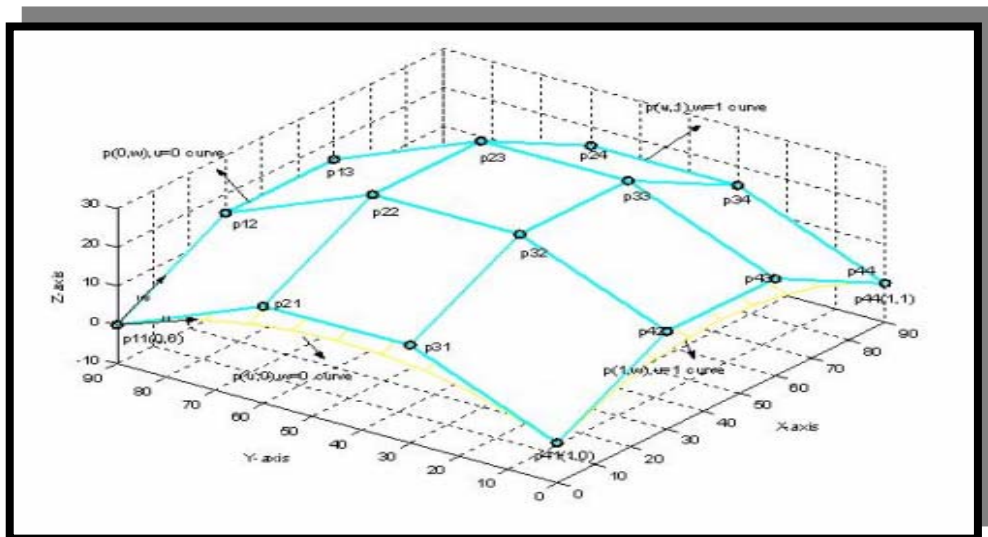
Again where the subscripts on the matrices indicate their dimensions expanded this equation becomes:-

$$P(u, w) = [(1-u)^3 \quad 3u(1-u)^2 \quad 3u^2(1-u) \quad u^3] P \begin{bmatrix} (1-w)^3 \\ 3w(1-w)^2 \\ 3w^2(1-w) \\ w^3 \end{bmatrix} \dots\dots\dots(3-18)$$

Where

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{bmatrix} \dots\dots\dots(3-19)$$

The matrix P contains the points that define the characteristic polyhedron and thereby the Bezier patch [38]. Figure (3-4) illustrates the control points of the polyhedron and the resulting patch. In the Bicubic Bezier formulation only the four corner points p_{11} , p_{41} , p_{14} and p_{44} actually lie on the patch.



Figure(3-4): Cubic Bezier patch.

Figure (3-5) shows the flowchart of the construction and visualization of a Bezier surface. To construction Bezier surface from input number of control point, increment value (S_u) and (S_w). After inputting control point (CP), (S_u) and (S_w), we will compute each point on the surface by equation (3-16) and parameters surface (u) and (w) don't exceed (1) because parameters surface (u) and (w) are from the interval [0 to 1].

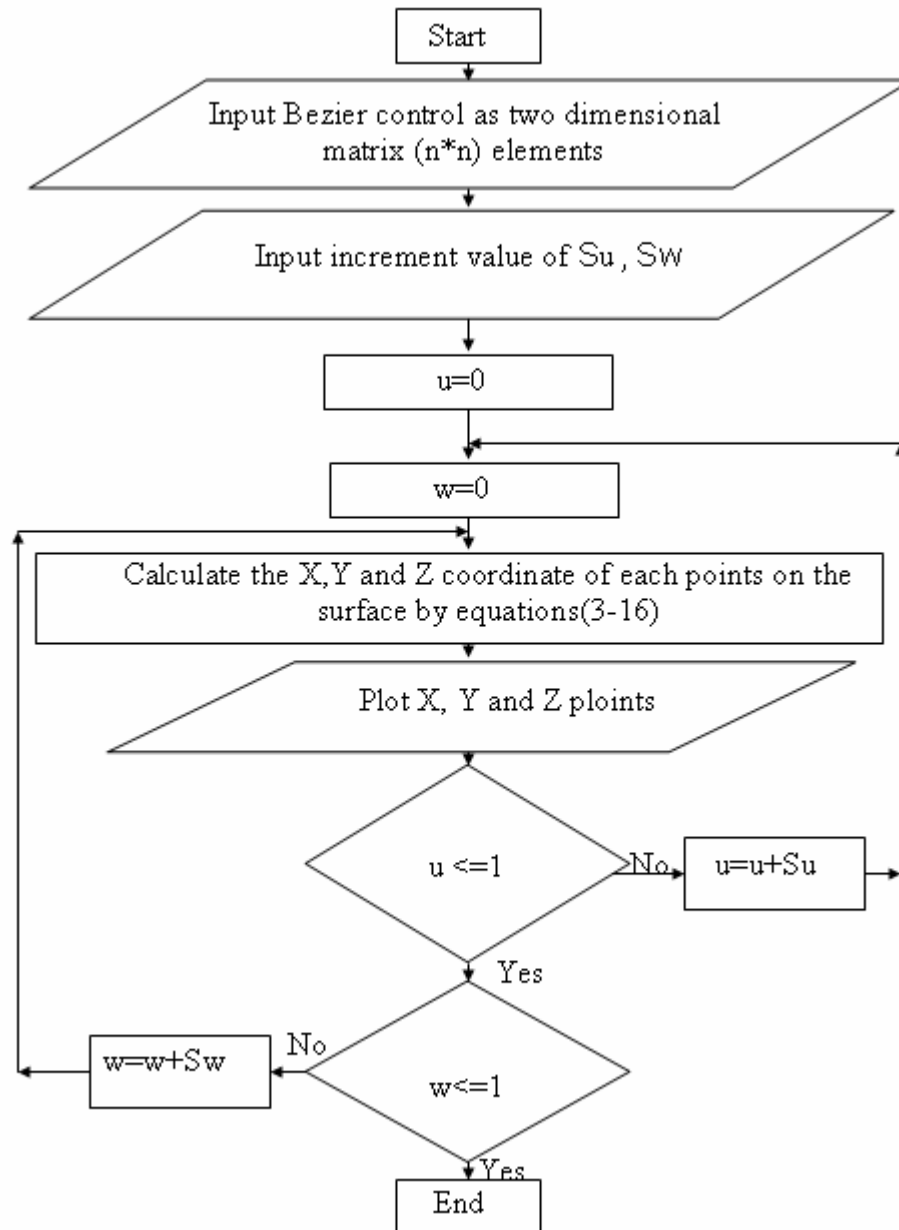


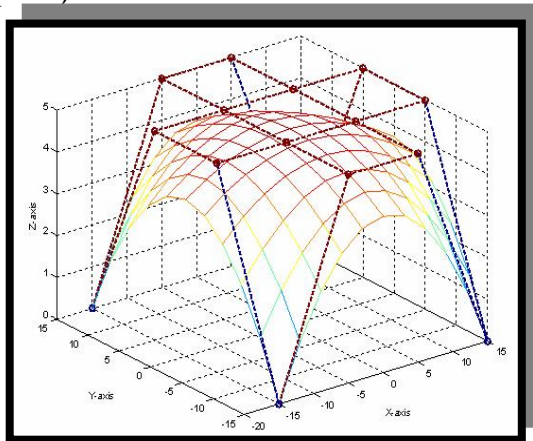
Figure (3-5): The flowchart to represent a Bezier surface.

In addition to the initial data that have been generates the desired surface the proposed program represents the surface in a graphical mode with the aid of MATLAB (V 7.4) software. The figure below shows the final result of a practical application of the proposed program.

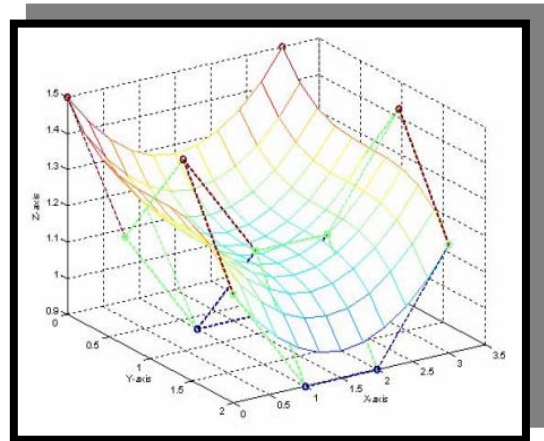
Figure (3-6A) shows the construction of a convex Bezier surface from a (4*4) control point and figure (3-6B) shows the construction of concave Bezier surface from (4*4) control points.

Figure (3-6C) shows the construction of a convex Bezier surface from a (4*5) control point and figure (3-6D) shows construction of triangular mesh concave Bezier surface from third degree (4*4) control point.

Figure (3-6E) shows the construction of a complex Bezier surface from a (4*5) control point and figure (3-6F) shows construction of regular body by using Bezier surface from using two parts from control point (4*4).

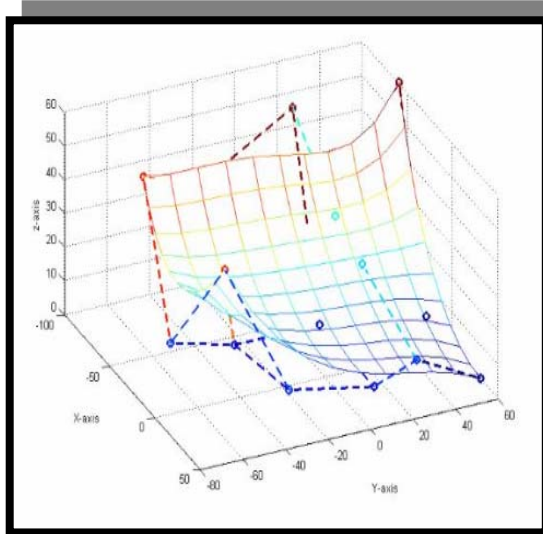


(A)

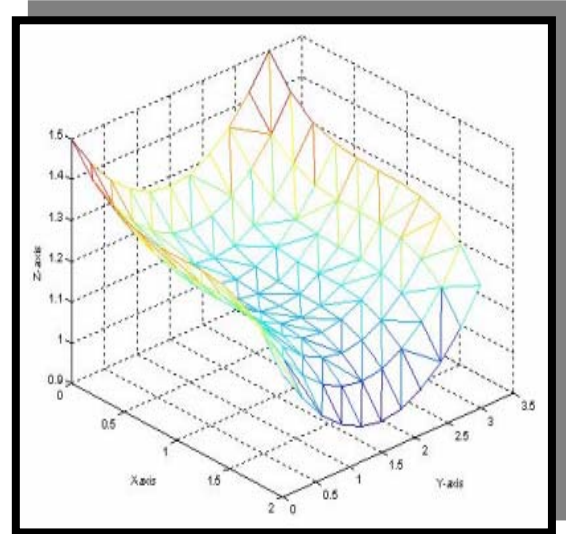


(B)

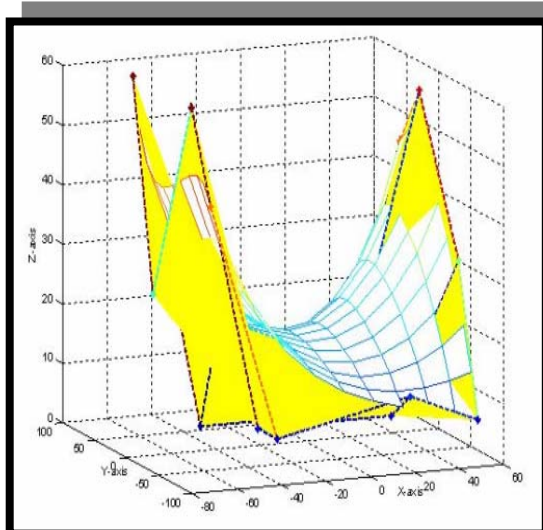
Figure (3-6): Represents Bezier surfaces. (A) Convex Bezier surface (3rd degree). (B) Concave Bezier surface (3rd degree). (C) Concave Bezier surface (4th degree). (D) Triangle mesh for Bezier surface (3rd degree). (E) Bezier surface with control point. (F) Complex Bezier surface.



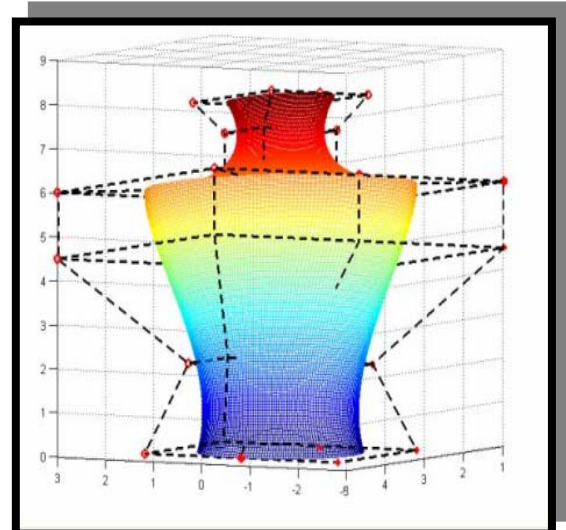
(C)



(D)



(E)



(F)

3.5 B-Spline Representation:

As seen from the previous section, Bezier blending functions make use of Bernstein polynomials, which depend on the number of control points available. These curves possess what is called global control, meaning that the movement of a single control vertex affects the entire curve. To avoid high degree polynomials and reduce the global effect Bezier curves are frequently built by connecting several segments of lower

degree. The degree of the polynomial for B-Spline curves is selected by the designer independent of the number of control points. It is the degree of the blending or basis function that controls the degree of the resulting B-Spline curve. B-Spline curves exhibit local control that is if one vertex is moved only some curve segments are affected and rest of the curve remains invariant [40].

3.5.1 Uniform Cubic B-Splines:

Uniform cubic B-Splines functions are determined equation by [8]:-

$$N_{i,k}(u) = \begin{cases} 1 & \text{if } t_i \leq u \leq t_{i+1} \dots\dots\dots (3-20) \\ 0 & \text{otherwise} \end{cases}$$

And:

$$N_{i,k} = \frac{(u - t_i)N_{i,k-1}(u)}{t_{i+k-1} - t_i} + \frac{(t_{i+k} - u)N_{i+1,k-1}(u)}{t_{i+k} - t_{i+1}} \dots\dots\dots (3-21)$$

where

$N_{i,k}$ = B – spline coefficient

k = equation order

$K - 1$ = equation degree

t_i = knot values

T = knot vector [38].

Figure (3-7) shows the flowchart for construction and visualization of a B-Spline curve. To construction B-Spline curve from input number of control points, increment value (S_u) after input (CP) we will compute each point on the curve by equation (3-21) and parameters curve (u) don't exceed (1).

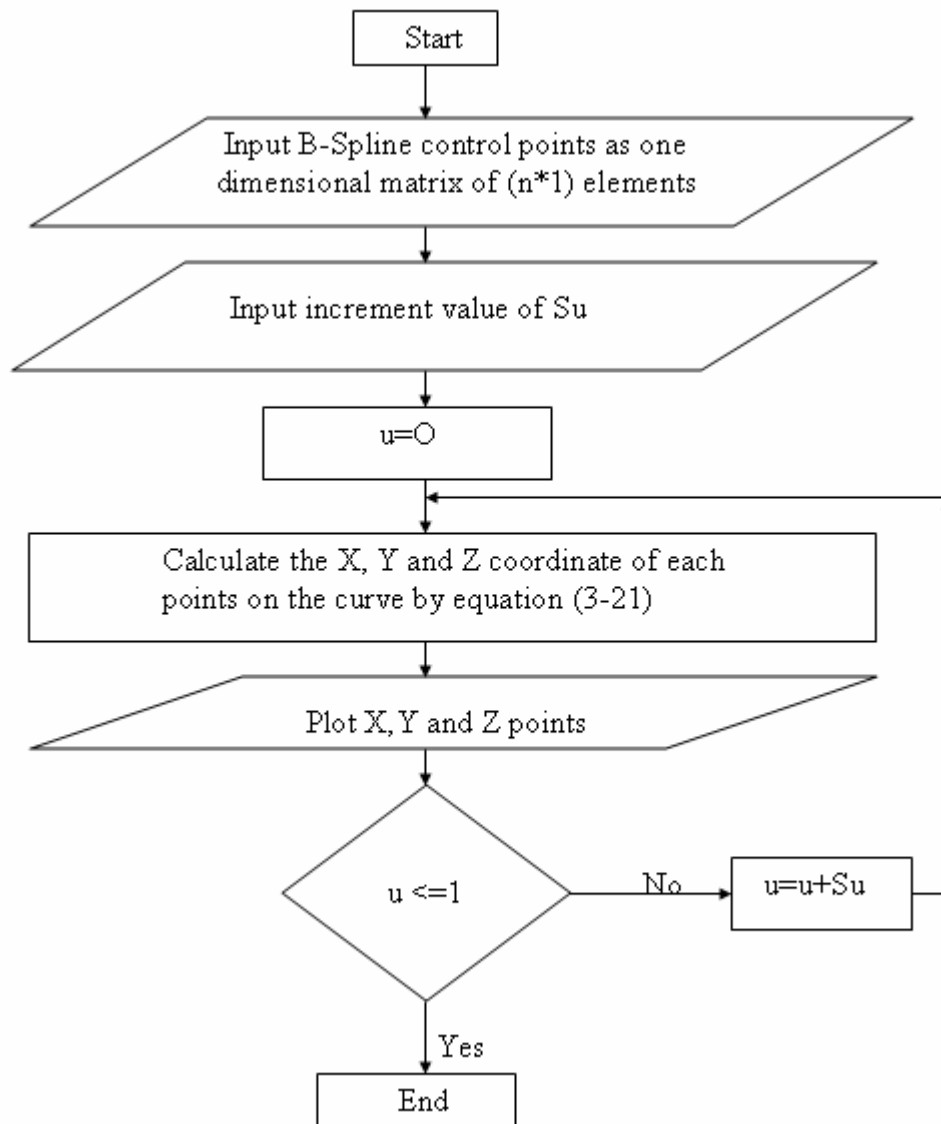


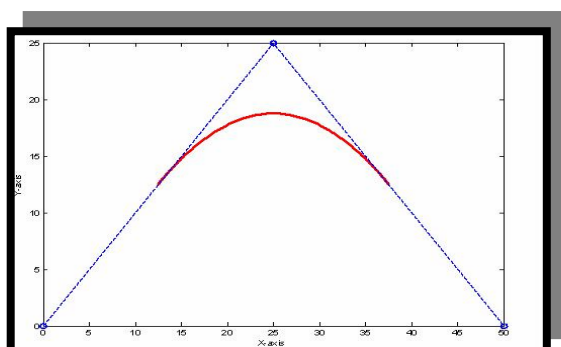
Figure (3-7): The flowchart for to represent a B-Spline curve.

In addition to the initial data generates the desired curve the proposed program can represents the curve in a graphical mode with the aid of MATLAB (V7.4) software.

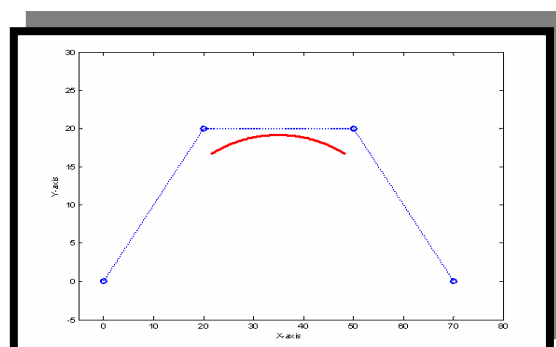
Figure (3-8A) shows the construction of a B-Spline curve from a second degree (2^{nd} degree). Figure (3-8B) shows construction of a B-Spline curve from third degree (3^{rd} degree).

Figure (3-8C) shows construction of a B-Spline curve from of third degree (3^{rd} degree). Figure (3-8D) shows construction figure from of the number complex control point (2^{nd} degree).

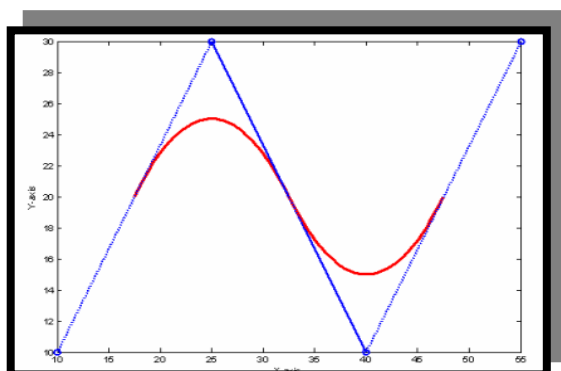
Figure (3-8E) shows construction of a regular body by use B-Spline curve from third degree (3^{rd} degree). Figure (3-8F) shows construction of the figure when different (k) and (n) are used.



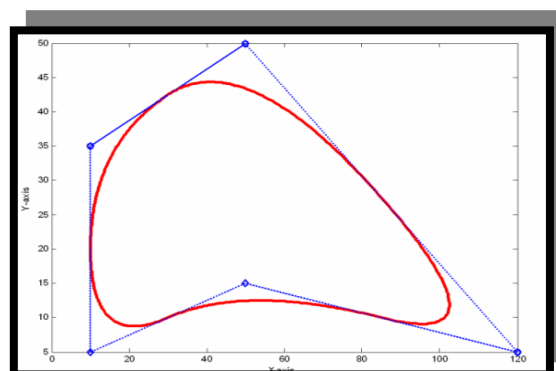
(A)



(B)



(C)



(D)

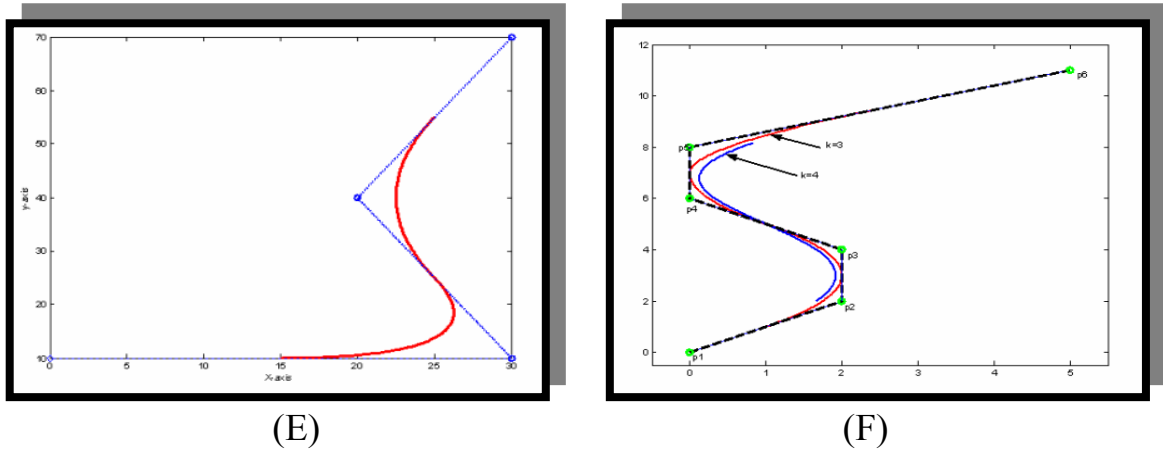


Figure (3-8): Represent B-Spline curves. (A) B-Spline curve (2nd degree). (B) B-Spline curve (3rd degree). (C) Complex B-Spline curve (3rd degree). (D) Airplane B-Spline curves. (E) Design the cup by B-Spline curves. (E) B-Spline curves (n=5 k=3, n=5 k=4).

3.5.2 B-Spline Surface:-

The equation of a B-Spline surface follows directly from the equation of a B-Spline curve [10]. B-Spline like Bezier surfaces are represented by the tensor product [12]:

$$P(u, w) = \sum_{i=0}^m \sum_{j=0}^n P_{i,j} N_{i,k}(u) N_{j,l}(w) \dots\dots\dots (3-22)$$

where $P_{i,j}$ is the control points and $N_{i,k}(u), N_{j,l}(w)$ are the B-Spline blending functions as defined in section (3.5.1). The knot vectors in the two directions of parameterization are classified as periodic/uniform. Non-periodic and non-uniform are like the B-Spline curves. The surfaces lie within the convex hull formed by the control points. The figures below give examples of B-Spline surfaces.

The matrix form of a B-Spline surface is similar to the form that was developed from the B-Spline curve [12].

$$P(u, w) = VM^T W^T \dots\dots\dots(3-23)$$

when $u, w \in [0,1]$

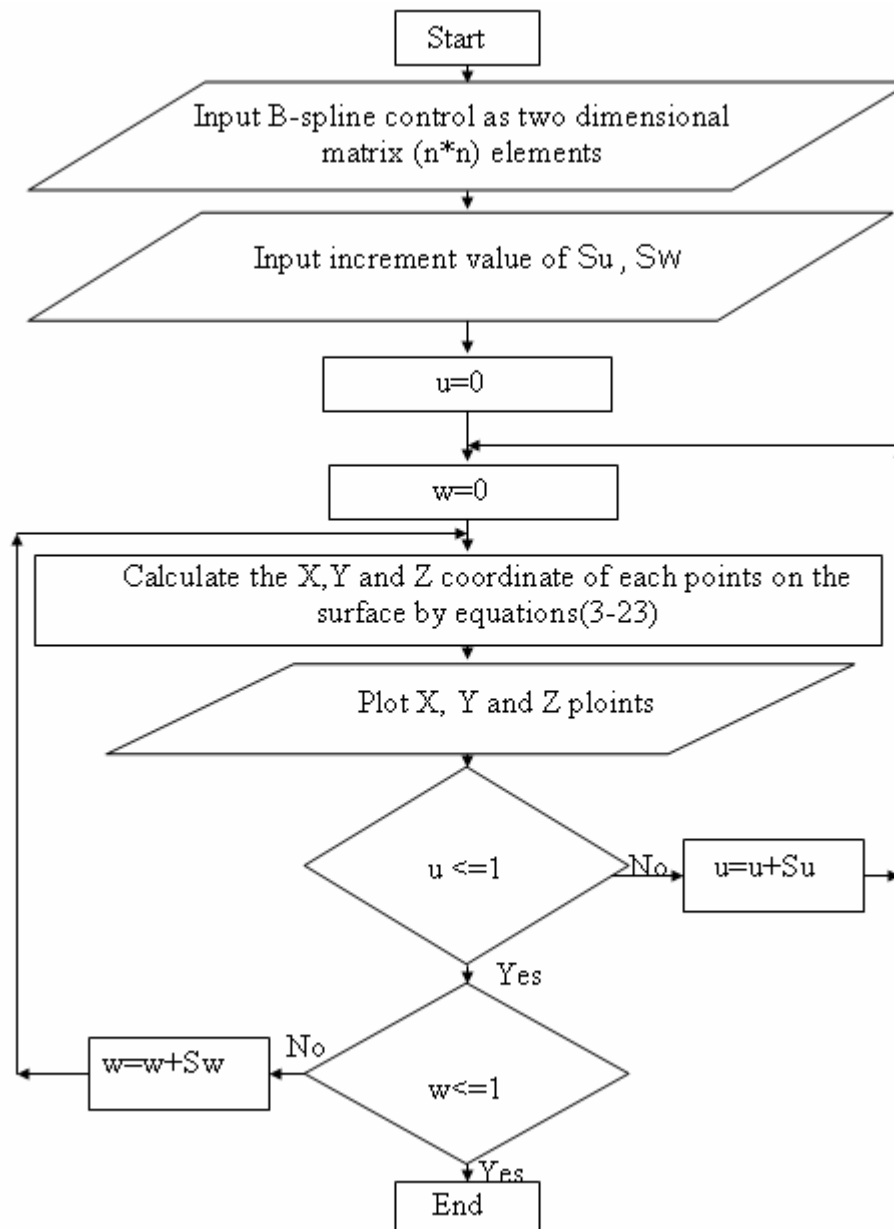


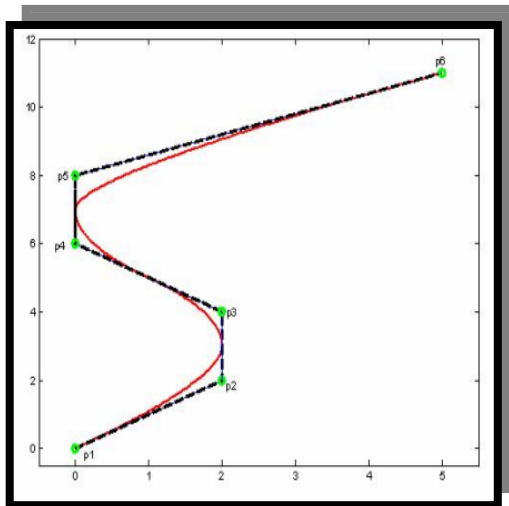
Figure (3-9): The flowchart to represent a B-Spline surface.

In addition to the initial data that is generated to obtain the desired surface, the program can represent the surface in a graphical mode with the aid of MATLAB (V7.4) software.

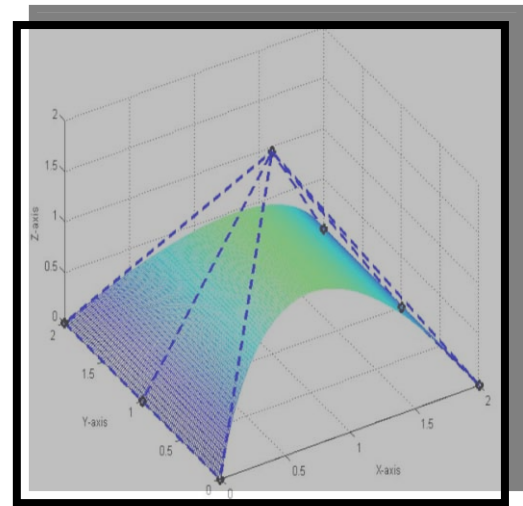
Figure (3-10A) shows the construction of a convex Non-uniform B-Spline curve by using ($n=5$ and $k=3$). Figure (3-10B) shows the construction convex non-uniform B-Spline surface by using ($n=2$ and $k=3$) control point.

Figure (3-11A) shows the construction of a convex B-Spline surface from a (4×4) control point. Figure (3-11B) shows the construction of a concave B-Spline surface by using (4×4) control point.

Figure (3-11C) shows construction of a complex B-Spline surface by using (4×4) control point. Figure (3-11D) shows the construction of a convex-concave B-Spline surface by using (4×4) control point.

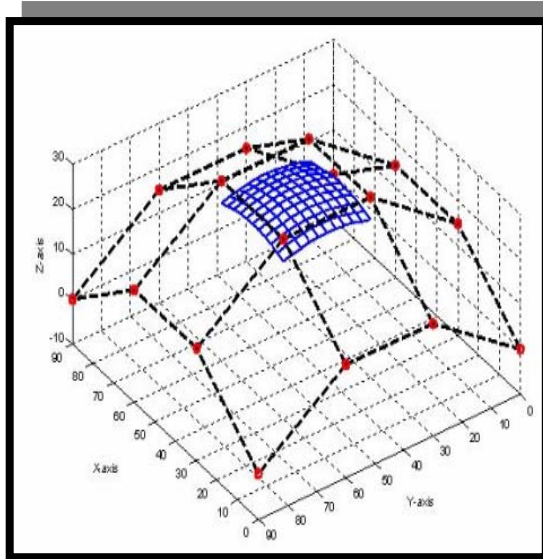


(A)

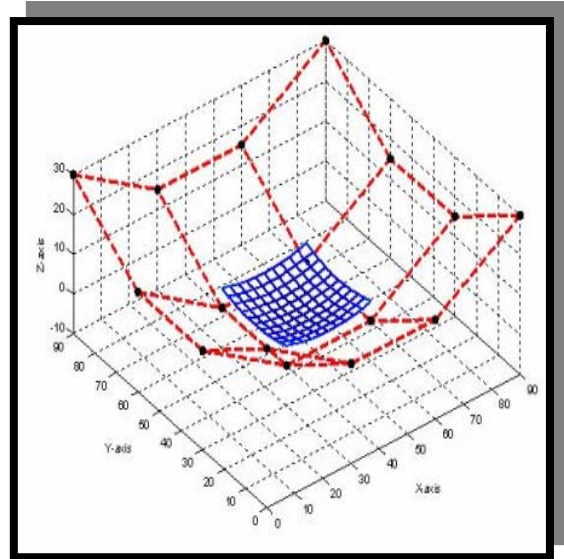


(B)

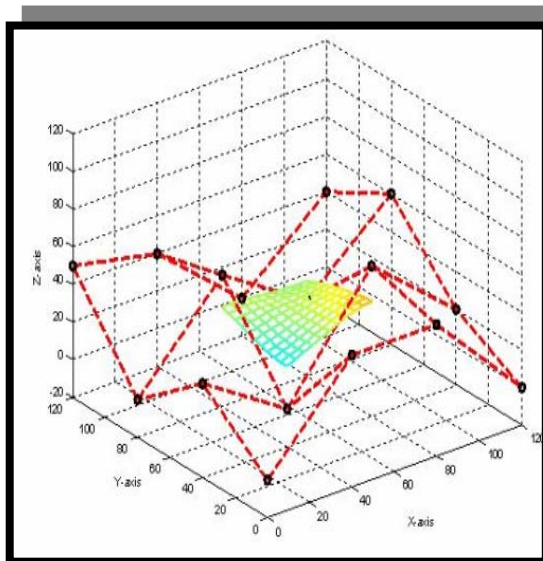
Figure (3-10): Represent non-uniform B-Spline curve and surface. (A) Non-Uniform B-Spline curve ($n=5$, $k=3$). (B) Non-Uniform B-Spline surface ($n=2$, $k=3$).



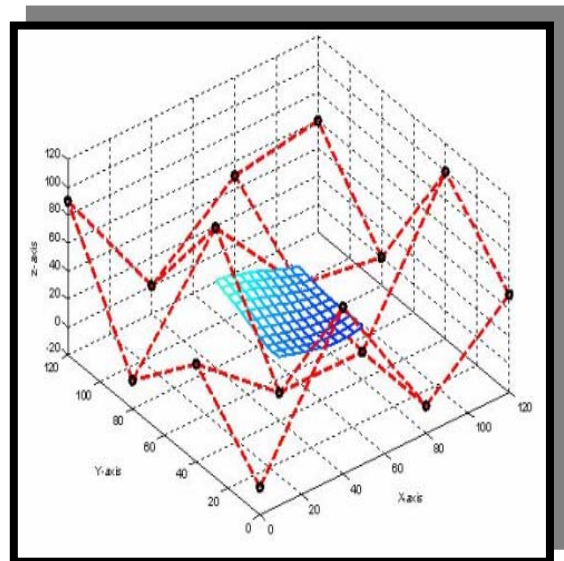
(A)



(B)



(C)



(D)

Figure (3-11): Represent B-spline surfaces. (A)Convex B-spline surface (3^{rd} degree). (B) Concave B-spline surface (3^{rd} degree). (C) Complex B-spline surface (3^{rd} degree). (D) Concave-convex B-spline curve (3^{rd} degree).

3.6 Non-Uniform Rotational B-Spline Curves (NURBS):

One of the most versatile tools for curve modeling is the non-uniform rotational B-Spline curves or NURBS curve as it is popularly called. It has become so widely used that it is almost an industry standard. Its basis is the ratio of two non-uniform rotational B-Spline functions making it a vector-valued piecewise rational polynomial. As a rational form it exhibits the same invariance properties as the rational Bezier basis making use of homogeneous coordinates and characteristics of projective geometry. This means that the NURBS curves are invariant under translation, rotation, scaling, shear, and parallel and perspective projection. Like the rational Bezier curve we can use a non-uniform rotational B-Spline curve to represent exactly the conic curves with the added advantages of local control. Non-rational B-Spline curves and rational and non-rational Bezier curves are special instances of the rational B-Splines. Points on a NURBS curve are given by:

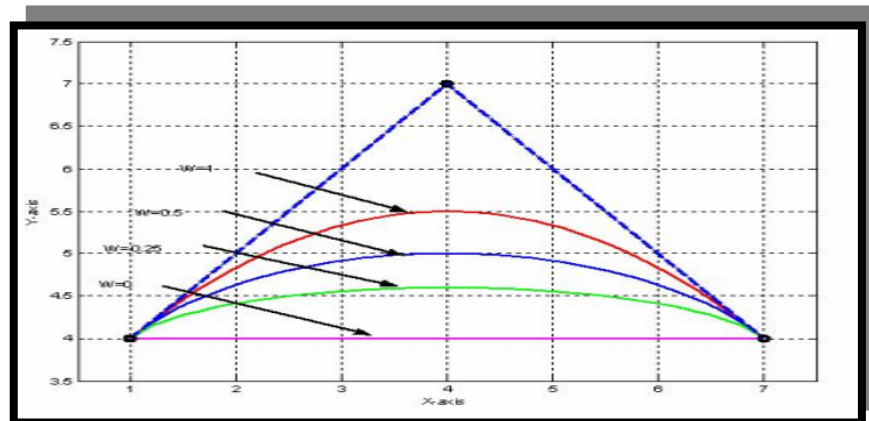
$$p(u) = \frac{\sum_{i=0}^n h_i p_i N_{i,k}(u)}{\sum_{i=0}^n h_i N_{i,k}(u)} \dots\dots\dots (3-24)$$

where the (h_i) is the weights. If weight $h_i=1$ for all i then the basis function of equation (3-24) reduces to the non-rational B-splines form $N_{i,k}$. However if the weights $(h_i=1)$ for all (i) and if the knot vector has the form $T=[0,0,\dots,0,1,1,\dots,1]$ where 0 and 1 each have multiplicity K then the basis function of this equation reduces to the non-rational Bernstein polynomial basis of degree $K-1$ for the Bezier curve $B_{i,k-1}(u)$. If a weight $(h_i=0)$ then control point (P_i) does not contribute to the curve shape [38].

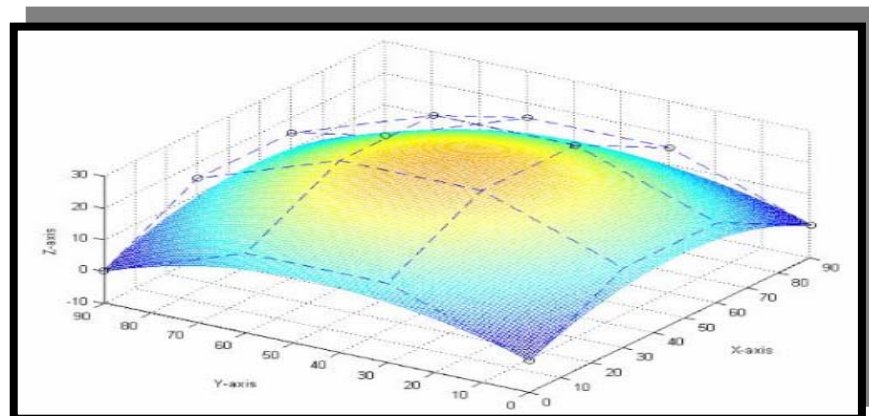
There are three ways to modify the shape of a NURBS curve:

- Change the knot vector.
- Move control points.
- Change the weights.

Figure (3-12A) shows construction of convex NURBS curve by using different weights, Figure (3-12B) shows construction of a convex NURBS surface by using ($n=3$ and $k=4$) control point.



(A)



(B)

Figure (3-12): NURBS curve and surface representation. (A) NURBS curve with different weight. (B) NURBS surface with different weight when ($k=4$, $n=3$).

Table (3-1) Comparison between the different methods of techniques curve and surface representation.

NO.	Curve Type			
	Bezier Curve	Uniform B-Spline Curve	Non-uniform B-Spline Curve	NURBS Curve
1	The curve follows the shape of the control point. The curve contact in the first and end control point only.	The curve follows the shape of the control point. The curve location is in the mid polygon and cannot contact or touch the polygon.	The curve follows the shape of the control point. The curve contacts in the first, end and the mid control point.	The curve follows the shape of the control point. The curve contact in the first and end control point only.
2	Global control of curve shape.	Local control of curve shape.	Local control of curve shape.	Local control of curve shape.
3	Adding control points increasing the degree of the curve.	Adding control points without increasing the degree of the curve.	Adding control points without increasing the degree of the curve.	Adding control points without increasing the degree of the curve.
4	Interpolate or approximate a set of given points	Interpolate or approximate a set of given points.	Interpolate or approximate a set of given points.	Interpolate or approximate a set of given points.
5	Degree of resulting curve is effective to the number of control point.	Degree of resulting curve is independent to the number of control point.	Degree of resulting curve is independent to the number of control point.	Degree of resulting curve is independent to the number of control point.
6	A cubic Bezier is sufficient for most applications.	Limited in the applications	A cubic non-uniform B-spline is sufficient for most applications (k=4).	A cubic NURBS is sufficient for most applications

3.7 Interpolation:-

Increasing demands on precise machining have necessitated that the tool move not only with position error as small as possible but also with smoothly varying feedrate. The motion commands such as the NC part program are realized by a sequence of very small step movements along the machine axes, in general this step movement is of the order of micrometer (μm) and it is the machine resolution. Computerized numerical control (CNC) interpolators generate the reference signals for the driving of the CNC machine tools [40]. Interpolation is the process of defining a function that takes on specified values at specified points. Interpolation is a process for estimating values that lie between known data points. When given $(X_0, Y_0), (X_1, Y_1), \dots, (X_n, Y_n)$, find the value of (Y) at a value of (X) that is not given [41].

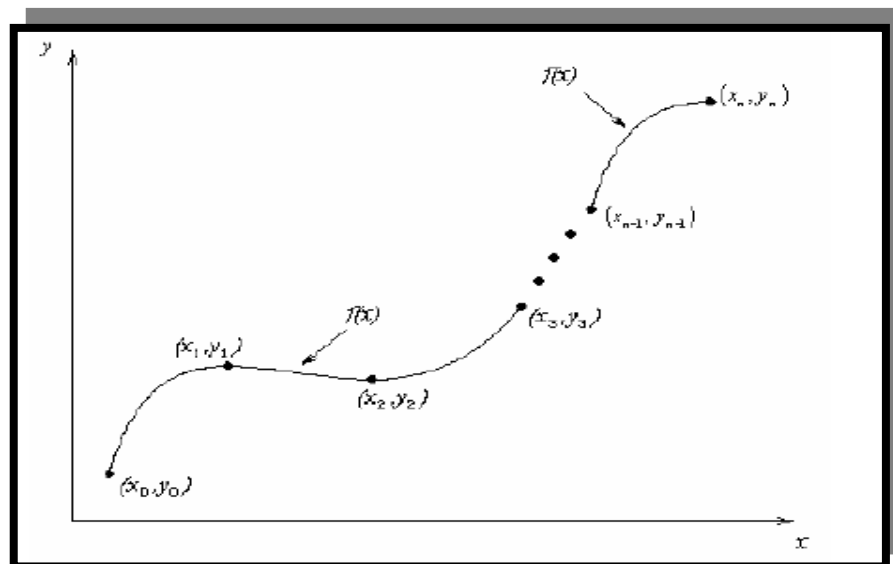


Figure (3-13): Interpolation curve [41].

3.7.1 Linear Interpolation:-

In linear interpolation (straight-line interpolation) as illustrated in figure (3-14), the interpolator within the control unit calculates a chain of points along a straight (linear) connection line between two tool positions. With this method of programming any straight line path can be traced which will include all tape cuts. During the tool movement from point to point, the axes movements are corrected continuously so that the tool does not deviate from these points by more than the permitted tolerance [55].

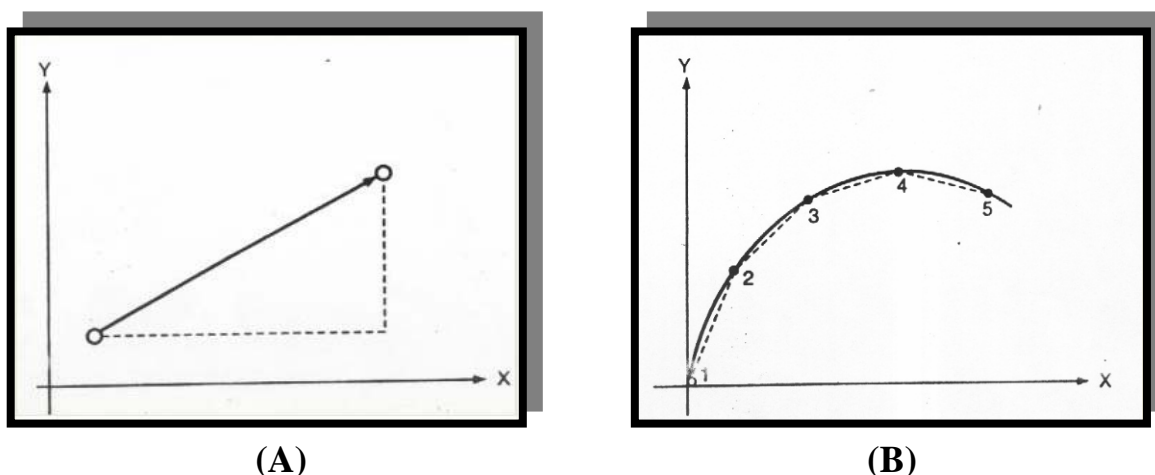
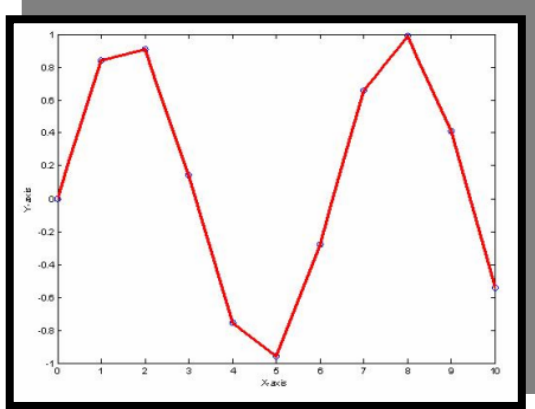
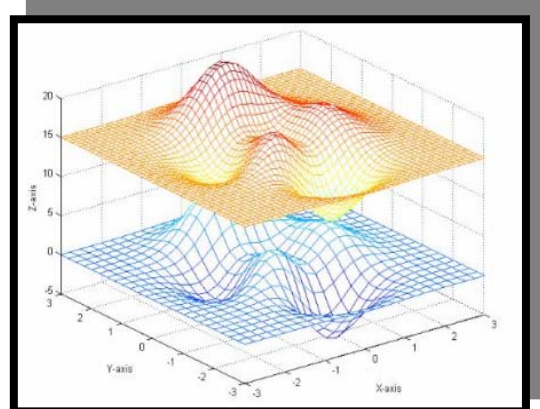


Figure (3-14): Linear interpolation representation. (A) Linear interpolation. (B) Continuous path approximation [55].

In addition to the initial data (X_0, Y_0) that have been generated of the desired linear interpolation curve and surface, the proposed program can represents the linear interpolation curve and surface and finds the value of (X, Y) that is not given in a graphical mode with the aid of MATLAB (V 7.4) software. The figure below shows a final result of practical application of the proposed program. Figure (3-15A) shows construction of sine waves by using linear interpolation. Figure (3-15B) shows difference between approximation surface and interpolation surface.



(A)



(B)

Figure (3-15): Representation of linear interpolation curve and surface. (A) Curve with linear interpolation. (B) Surface with linear interpolation.

3.7.2 Lagrange Interpolation:

Determine a polynomial which passes through a given set of points which concern the exact fitting of reliable data in two ways:-

3.7.2.1 Lagrange Interpolation ($y=F(x)$):

Consider a sequence of planar points defined by $(x_0, y_0), (x_1, y_1), \dots, (x_n, y_n)$ calculated as [39] :

$$f_n(x) = \sum_{i=0}^n y_i L_{i,n}(x) \dots \dots \dots (3-25) \text{ Where:}$$

$$L_{i,n}(x) = \frac{(x-x_0) \dots \dots (x-x_{i-1})(x-x_{i+1}) \dots \dots (x-x_n)}{(x_i-x_0) \dots \dots (x_i-x_{i-1})(x_i-x_{i+1}) \dots \dots (x_i-x_n)}$$

Short notation for this formula is:-

$$f_n(x) = \sum_{i=0}^n y_i \prod_{\substack{j=0 \\ j \neq i}}^n \left(\frac{x-x_j}{x_i-x_j} \right) \dots \dots \dots (3-26)$$

where Π denotes multiplication of the n factors obtained by varying (j) from $(0$ to $n)$ excluding $(j=i)$. We observe that the fraction multiplying (y_i) is equal to unity when $x=x_i$ but becomes zero when (x) equals any of the other coordinates [39].

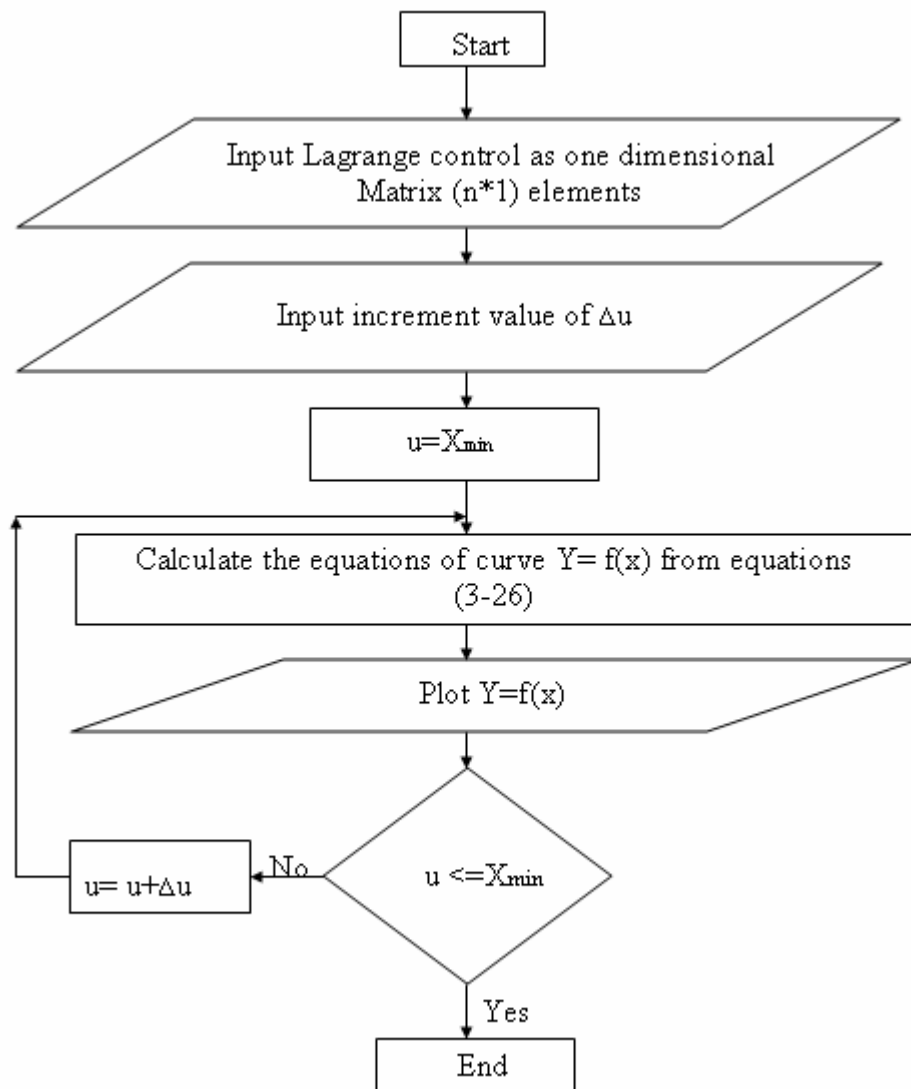


Figure (3-16): The flowchart to represent a Lagrange curve.

3.7.2.2 -Lagrange Interpolation ($Z=F(x, y)$):

In this work, adopted (2D Lagrange interpolation) of surface data generation has been implemented, tested, and evaluated. The adopted method is an extension to the earlier interpolation method (1D) by computing both (x) and (y) data to derive the (z) data as general form of $z=F(x, y)$.

The interpolating polynomial of n^{th} degree can be formulated as:

$$F(x, y) = \sum_{i=1}^n L_i(x) * \sum_{k=1}^m L_k(y) * F(x_i, y_k) \dots \dots \dots (3-27)$$

where:

$$L_i(x) = \sum_{\substack{j=1 \\ j \neq i}}^n \frac{x - x_j}{x_i - x_j}$$

$$L_k(y) = \sum_{\substack{l=1 \\ l \neq k}}^m \frac{y - y_l}{y_k - y_l}$$

The determination of Lagrange coefficient in both direction (x,y) can be invested to determine the interior data of the desired surface depending on a few initial data [12].

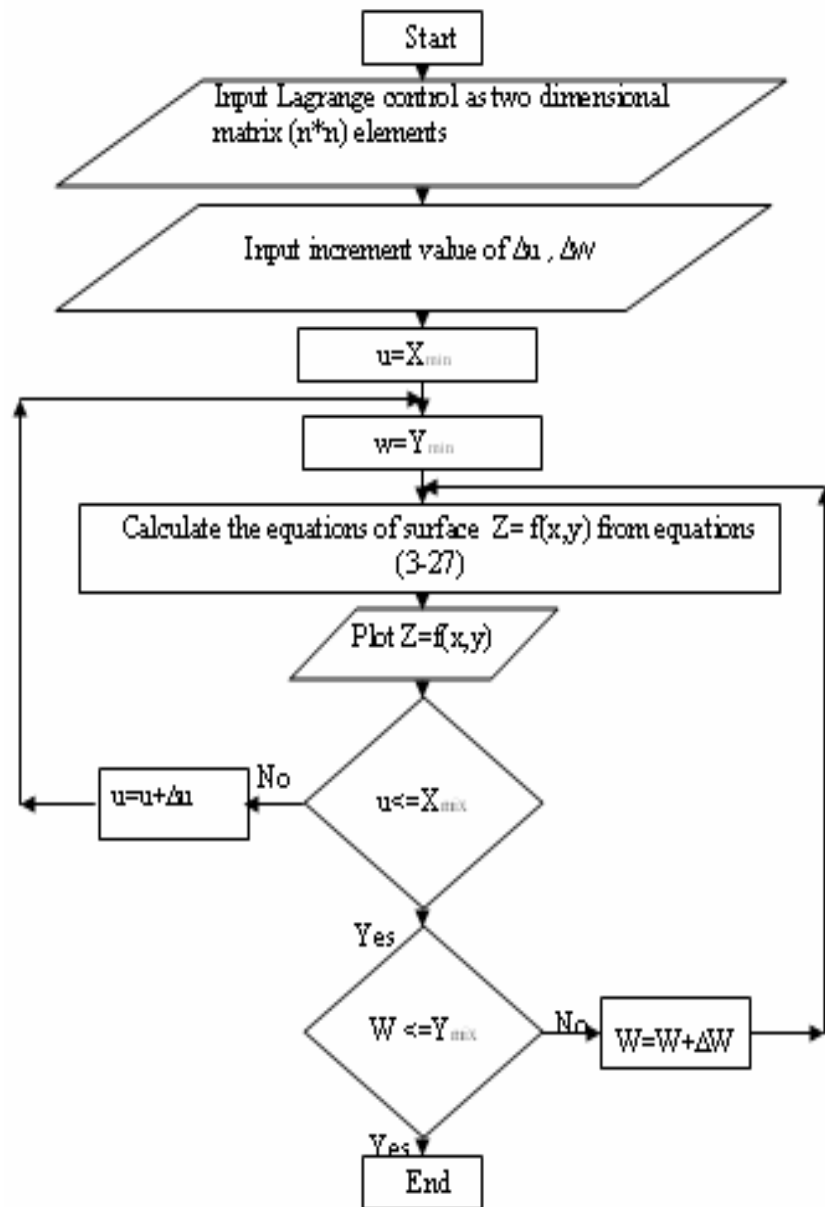


Figure (3-17): The flowchart to represent a Lagrange surface.

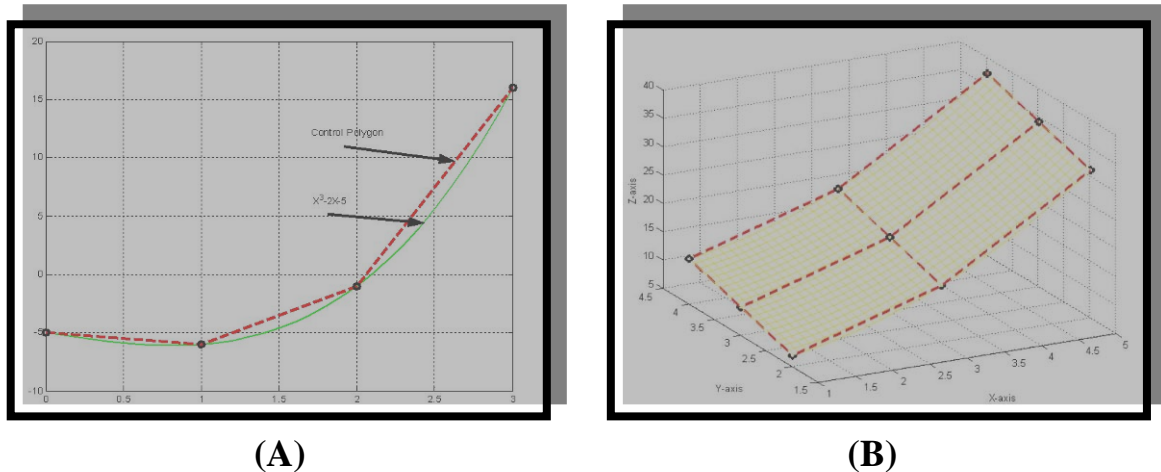


Figure (3-18): Represent Lagrange interpolation. (A) For curve. (B) For surface.

3.8 Chapter Summaries:

In this chapter, we have explained and discussed the parametric and implicit equations curves, parametric representation curve and surface for selecting better and easier method in order to be used in this research and proposed algorithms is applied. We have used MATLAB (V 7.4) software to represent different curves and surfaces. We have explained and constructed the represent the following entities in geometric modeling:

- Surface patch.
- Bezier curve and surface.
- B-spline curve and surface.
- NURBS curve and surface.

Also, we have explained and discussed the interpolation of the curve and surface representation:

- Linear interpolation of curve and surface.
- Lagrange interpolation of curve and surface.

CHAPTER FOUR

AUTOMATIC GENERTION OF PART PROGRAM AND THE PROPOSED SYSTEM

4.1 Introduction:-

This chapter presents a new approach for the determination of efficient parameters in the machining of an extrusion profile die using a 3-axis ball end mill cutter. Figure (4-1) shows a block diagram for the basic modes of the proposed modified system in this work in order to develop curve interpolator for CNC milling machine.

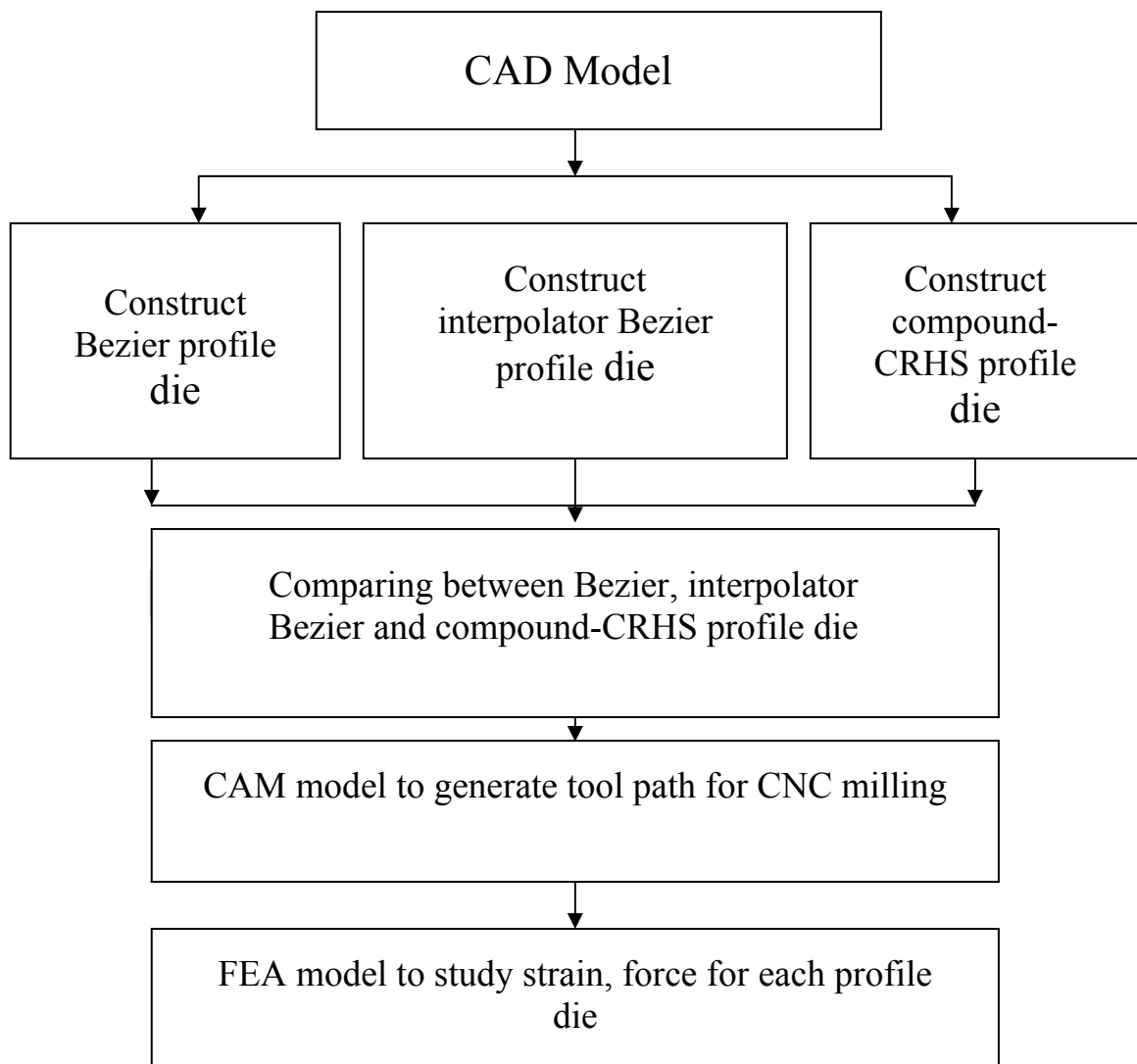


Figure (4-1): Steps followed for visualization to study interpolator curve.

4.2 Manufacturing Conditions:-

In order to minimize the cutting time of the manufacturing process and to obtain dimensional accuracy in accordance with product specifications, the most suitable manufacturing conditions for each operation must be carefully selected. Generally the cutting conditions parameter (feedrate, depth of cut, cutting speed,.....,etc) are taken into account. Each element involved in the machining process has some influence on the final result of the process. The cutting tool is another key element in machining. The term “high-speed milling” is generally used to describe end milling with a small diameter tool, less than or equal to 10 mm, at a high rotation speed greater than 10,000 rpm. Under these conditions, and given the high propensity for vibration, tool rigidity is a critical issue. Numerical control is another important element in machining. With regard to the machine tool and control, the type of position sensor must also be taken into account, given its significant influence on the quality of the final part [43]. The type of interpolation used for tool path generation introduces variety, and although linear interpolation is used in most situations, when milling sculptured surfaces, the possibility of using circular or polynomial interpolations should be considered to reduce the size of the programmers and improve the dimensional accuracy. The factors considered in the analysis of machining are:

- The type of tool holder, since good tool balance is critical to avoiding premature failure of the tool and to obtaining a good surface finish.
- The cutting conditions especially the programmed feedrate is the parameter that in this case ensures that the process is high-speed milling.

- The type of interpolation used to create the programmers, distinguishing specifically between linear and circular interpolation.

In addition to those variable factors, there are some other factors that can be considered as fixed factors by using the same configuration in all the experiments, for instance, the tool used, the execution mode, the controller type, the thermal expansion of the spindle and tool wear. The effect of tool vibration can also be minimized by using a not very long tool with a large enough diameter to assure rigidity [43].

4.3 The Major Motion Type of CNC Machines:-

Numerically controlled machine axes mainly provide two types of motions [9]:-

4.3.1. Point-to-Point Positioning:-

Point-to-point positioning is the process of positioning from one coordinate (x,y) position or location to another , performing the machining operation and continuing this pattern until all the operation is completed and continuing this pattern have been completed at all programmed locations [8].

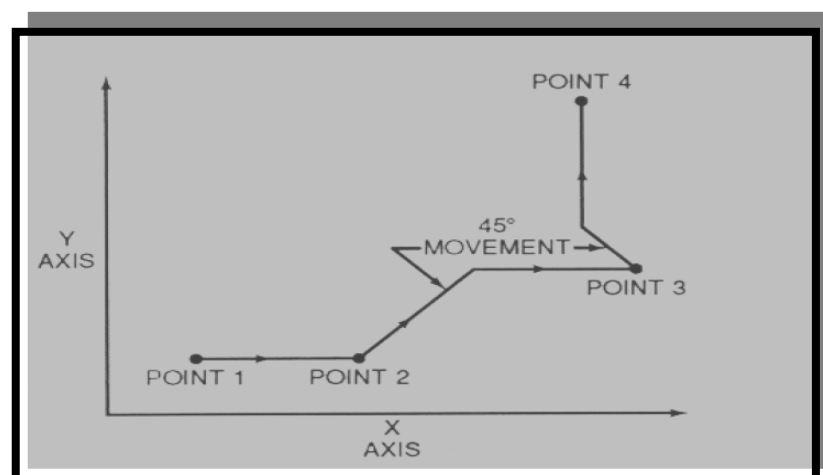
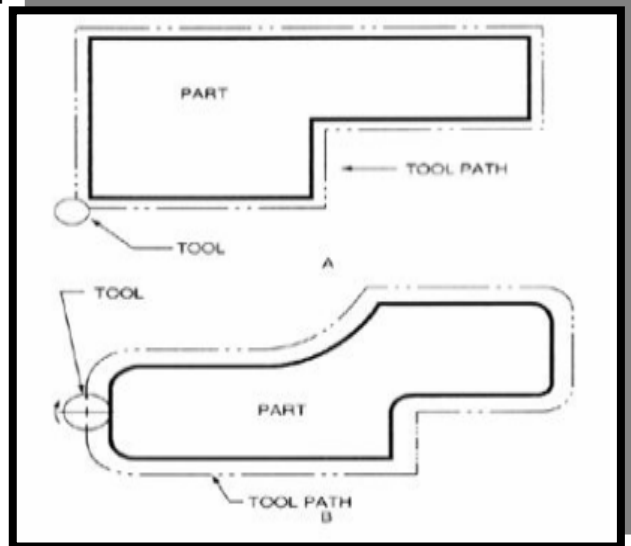


Figure (4-2): The path followed by point-to point positioning reach various programmed points (machining locations) on the XY axis [8].

4.3.2. Continuous Path (Contouring):-

Contouring or continuous path machining involves work as produced by a lathe or milling machine, where the cutting tool is in contact with workpiece as it travels from one programmed point to the next. Continuous path positioning is the ability to control motions on two or more machine axes simultaneously to keep a constant cutter-workpiece relationship. The programmed information in the CNC program must accurately path at a programmed feedrate in order to produce the form or contour required [9].



**Figure (4-3): Types of contour machining (A) Simple contour;
(B) Complex contour [9].**

4.4 Automatic Generation of Part Program:

Before automatic generation of a part program for machining a free form surface a number of parameters should be taken into consideration which are introduced here [33].

4.4.1 Tool Selection:

The developed software is capable of graphically representing three milling tools to the user namely ball nose cutters, filleted cutters, and flat end mill cutters. Ball end have been most widely used in

curved-surface machining because historically these have been easy to position with three-axis machines and require simple cutter compensation. However compared to flat end-mills, ball mills produce poor geometry matching between cutter and surface and have zero cutting speed at the axis of rotation [44]. Upon selection of the cutter depending on the shape and size of the surface created in the CAD system, the user should introduce the dimensions of the selected tool to the developed software [33].

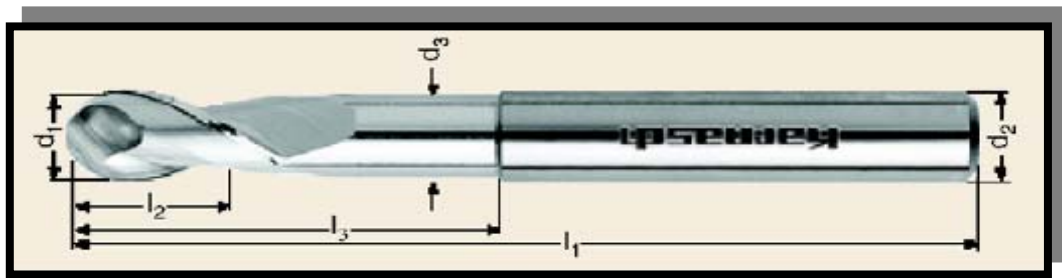


Figure (4-4): Cutting tool used in this work [43].

4.4.2 Automatic Calculation of Tool Offset:-

In many machining operations, the coordinates of the tool path are calculated with respect to the center of cutter while in machining sculptured surfaces coordinates of tool paths are calculated with respect to the tip of the tool [32]. Figure (4-5) shows that the offset surface can be obtained by taking the envelope of the inverse of the tool in the Z- direction, with the center of the inverted tool moving on the design surface [3].

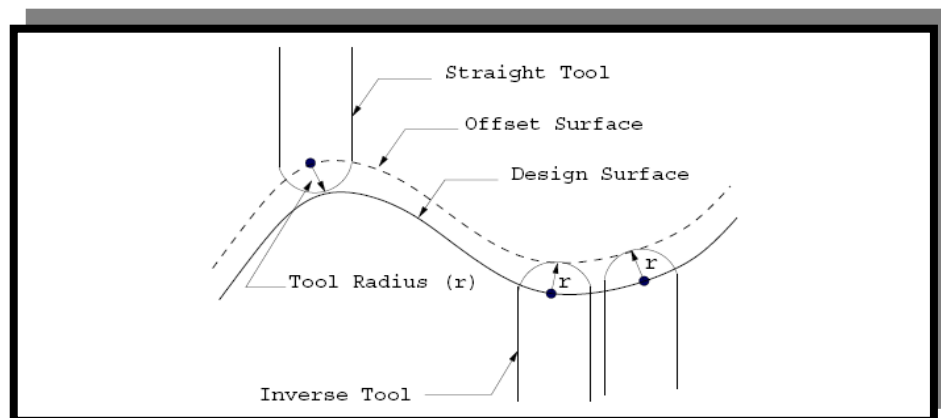


Figure (4-5): Inverse tool offset algorithm [3].

4.4.3 Automatic Calculation of Side Step:-

The side step (g) is a function of the scallop height (h), tool radius and the local radius of the curvature (ρ); therefore three different cases are considered to calculate side-step size (g) [45]:

1- A flat surface as shown in figure (4-6A):

$$\begin{aligned} h &= r - \sqrt{r^2 - \left(\frac{g}{2}\right)^2} \\ g^2 &= 4r^2 - 4(r-h)^2 \\ g &= 2\sqrt{r^2 - (r-h)^2} \dots\dots\dots(4-1) \end{aligned}$$

2- A convex curvature is shown in figure (4-6B). To find the side step for a convex surface we find (δ), the difference between a designed curve and a linear tool path, is as shown in figure (5-5).

$$\begin{aligned} \delta &= OB - OA \\ OA &= \sqrt{r^2 - p^2} \\ OB &= \rho \\ h &= r - \sqrt{r^2 - p^2 + \delta} \\ g &= 2 - \sqrt{r^2 - (r + \delta - h)^2} \dots\dots\dots(4-2) \end{aligned}$$

3- For a concave curvature we calculate the step size for concave surface:

$$\begin{aligned} \delta &= OB - OA \\ OA &= \sqrt{r^2 - p^2} \\ OB &= \rho \\ h &= r - \sqrt{r^2 - p^2 - \delta} \\ g &= 2 - \sqrt{r^2 - (r - \delta - h)^2} \dots\dots\dots(4-3) \end{aligned}$$

where (ρ) is the local radius of the curvature surface .Using the above equations, (g) is calculated at each point on the current curve [45].

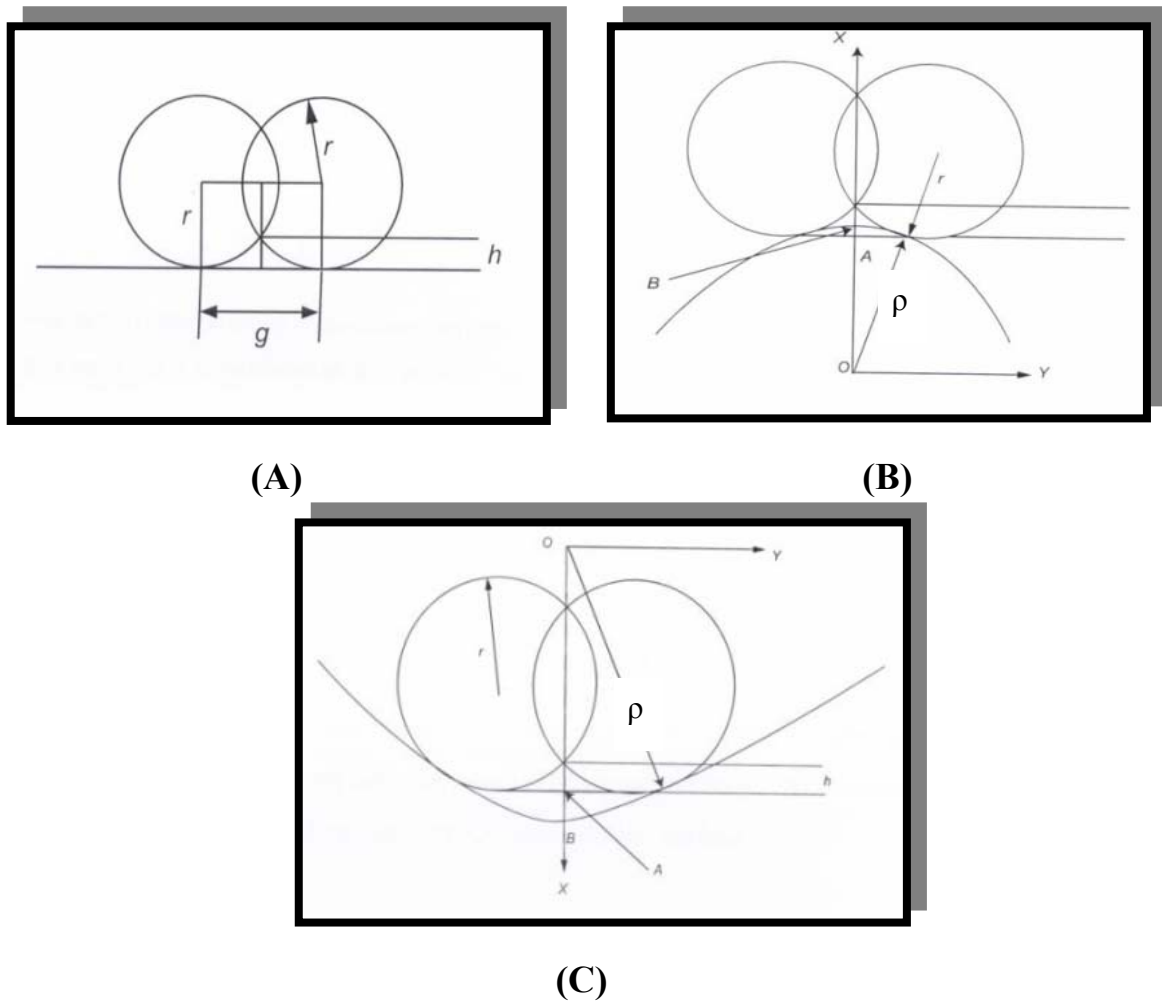


Figure (4-6): Represent tool position on the: (A) Flat surface. (B) Convex surface. (C) Concave surface [45].

4.4.4 Curvature and Radius of Curvature:-

One of the properties in which engineers are interested is curvature: whether, or how much a curve "bends" at some point. Curvature is defined quantitatively in the following way. Curvature (ρ) at the point (m) on the surface is expressed as [47]:

$$\rho = \frac{L(du/dv)^2 + 2M(du/dv) + N}{E(du/dv)^2 + 2F(du/dv) + G} \dots\dots\dots(4-4)$$

where:

$$L = n. S_{ww} \\ G = S_u, s_u$$

$$M = n. S_u w \\ F = S_u. S_w$$

$$N = n. S_{uu} \\ E = S_w. S_w$$

S_u = the first partial derivative of the surface equation with respect to u .

S_w = the first partial derivative of the surface equation with respect to w .

S_{uu} = the second partial derivative of the surface equation with respect to u .

S_{ww} = the second partial derivative of the surface equation with respect to w .

If ($\rho > 0$) points (m) is located in a convex domain of the surface.

If ($\rho = 0$) points (m) is an inflection points on the surface.

If ($\rho < 0$) points (m) is located in a concave domain of the surface.

4.4.5 Gouge-Free Machining:-

The gouging problem is the most critical problem faced in sculptured surface machining. Gouging occurs on concave areas of the surface when the radius of the tool is larger than the radius of the local surface curvature as shown in figure (4-7). To ensure machined surface quality any potential gouging problems need to be deleted before the feasible cutter paths can be generated. For this reason sculptured surface machining is a time-consuming task that requires a lot of efforts in both programming as well as machining [48].

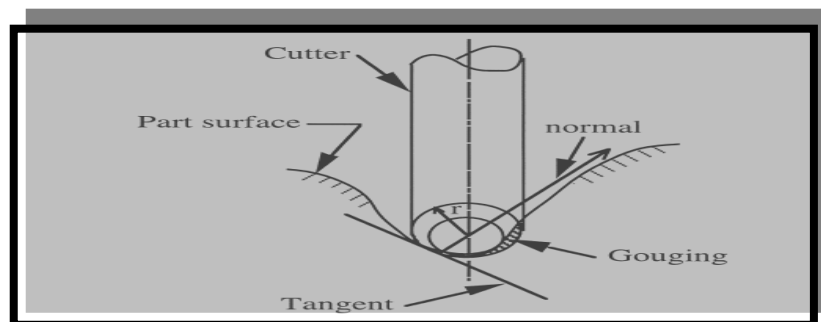


Figure (4-7): Local gouging on concave region [48].

4.5 Tool Path Generation:-

In machining, the tool path should be as smooth and steady as possible to guarantee the machining quality and to protect the spindle [49].

Due to the inherent nature of the motion of the tool paths are always a series of straight lines/arcs whereas the actual sculptured surface is a surface of varying slope and curvature. Thus, the sculpture surface is approximated by a series of straight lines and arcs for machining and the machining goal is to get as close as possible to the design surface [3]. There exist several approaches of distributing the tool path in the domain of the designed part. The goal of the tool path distribution strategies is to span the entire design part. The commonly used tool path distribution strategies are [45]:

1-Zig- Zag tool path generator.

2-Isoparametric tool path generator.

The most commonly used tool path distribution strategies is the zig-zag strategy due to the simple algorithm involved in calculating the spanning elements [45]. The boundary of the center-line path is determined by offsetting the merchantable ordered tree contour inwards by the radius of the tool [50]. In the case of the zig-zag tool paths it is desired that the tool moves in a straight line in the feed forward direction. Planning tool motion on the design surface guarantees straight line motion of the tool contact point but the tool center may not move in a straight line [3].

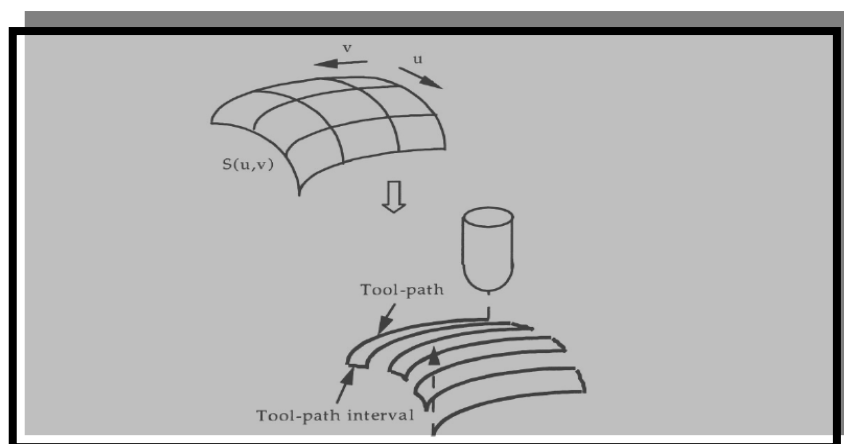


Figure (4-8): Illustration of the tool-paths and the parametric surface [51].

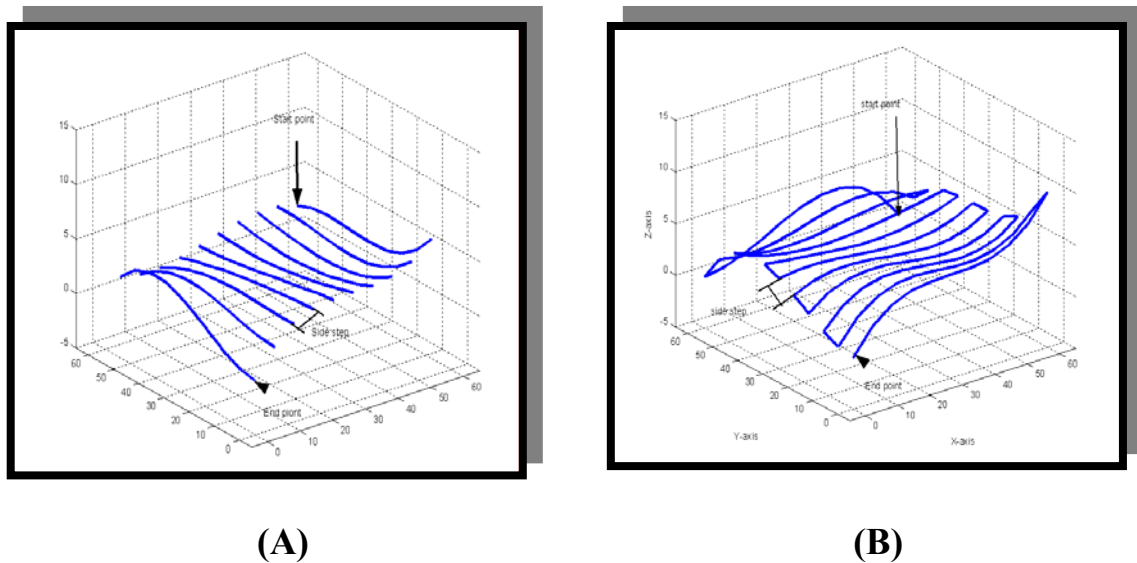


Figure (4-9): Representation of tool path generation: (A) Isoparametric tool path generation. (B) Zig-Zag tool path generation.

4.6 Milling Process:-

Sculptured surfaces are relatively difficult to machine due to their complex geometry. Sculptured surface machining primarily has two stages [21]:

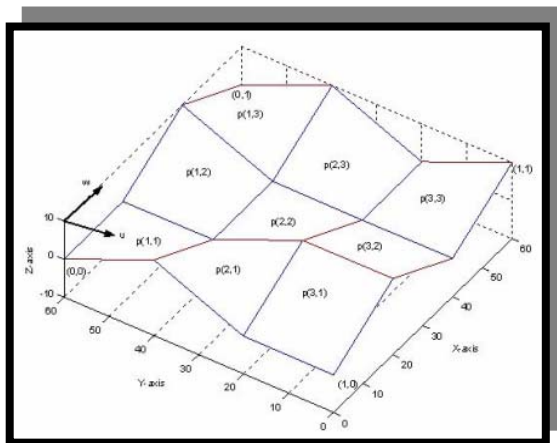
- The first being roughing
- The second being finishing

Most frequently, the Milling is done in the two phases roughing and finishing. Excessive materials are removed as rapidly as possible in roughing. During roughing high metal removal rates are used to minimize the processing times. The final surface quality is not important as layer of material to obtain a surface within a certain distance on, with appropriate surface quality cutter interference has to be controlled. Cutter interference may occur when the sculptured surface has high curvature variation [43]. If the local radius of curvature is less than the tool radius then the locus of the cutter location points can produce gouging. Finishing process is usually done by tracing curves or contours on the surface as accurately and

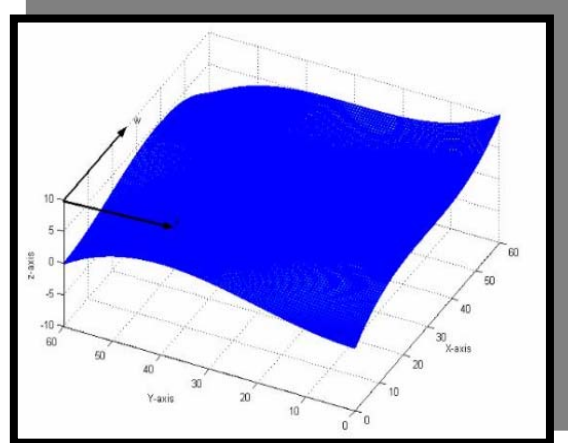
precisely as possible with limitations set by the cutter size tolerance and machine capability.

There are two ways to avoid cutter interference [43]:

- The first is to choose the appropriate cutter (a smaller cutter).
- The second method is to remove the gouging cutter path skipping the gouging segment along the cutter path.



(A)



(B)

Figure (4-10): Represents the: (A) Finish milling. (B) Rough milling.

4.7 Code Generation:-

After selecting the correct machining direction and machining side of surface in order to generate the machining codes as the tool moves along a direction each successive tool path is divided into a number of straight segments. So machining of each segment could be represented by (G01) code. Each program consists of a large number of (G01) codes as selected tool moves across either simple or free form surface [33].

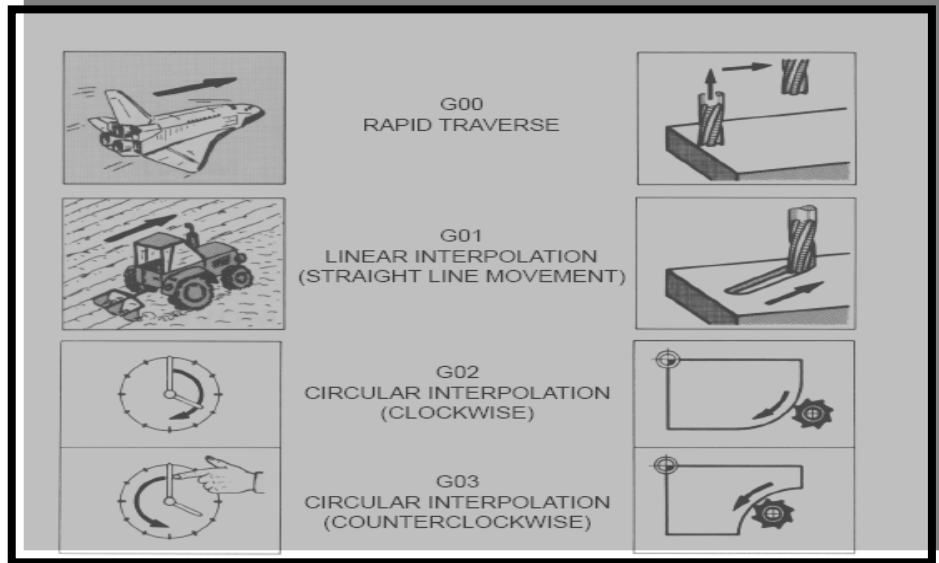


Figure (4-11): The functions of a few common G-codes [9].

4.8 (CRHS) Dies:-

The principles and techniques used in the design of tools according to the CRHS concept are discussed below. Four basic rates of deformation (S) for CRHS profile dies are adopted in this investigation [52]:

- S= 0.8 for decelerated rate of deformation.
- S = 1 for uniform rate of deformation.
- S = 1.2 for accelerated rate of deformation.
- S= (0.8 + 1 + 1.2) compound rate of deformation.

The concept of the (CRHS) depends on homogenous strain and neglected elastic strain because elastic strain is little mounted

$$d \epsilon_h = \frac{\sqrt{2}}{3} [(d \epsilon_x - d \epsilon_y)^2 + (d \epsilon_y - d \epsilon_z)^2 + (d \epsilon_z - d \epsilon_x)^2]^{\frac{1}{2}} \dots \dots \dots (4-5)$$

where

$d \epsilon_h$ = total homogenous strain.

ϵ_x = longitudinal strain.

ϵ_y = radial strain.

ϵ_z = circumferential strain.

$$d\epsilon_x + d\epsilon_y + d\epsilon_z = 0 \dots\dots\dots(4-6)$$

$$\epsilon_x + \epsilon_y + \epsilon_z = 0$$

Substituting (4-5) in (4-6) gives:

$$\epsilon_h = \sqrt{\frac{2}{3}}(\epsilon_x^2 + \epsilon_y^2 + \epsilon_z^2) \dots\dots\dots(4-7)$$

Equation (4-7) is used for calculating homogenous strain (ϵ_h) for product in the concept (CRHS) and it consists of three components of the Homogenous strain.

where:

ϵ_h = homogenous strain at any section (n)

S = the rate of deformation (constant)

For solving equation (4 – 7) at any section (n):

$$\epsilon_{hn} = Ln(Zn) \dots\dots\dots(4-8)$$

where:

Zn = a function that reflects the dimension of workpiece of the pass

n = 0, 1, 2

To obtain the design equation appropriate for (Zn) substitute equation (4– 7) in (4 – 8):

$$\frac{Zn}{Zn-1} = (Z1)^{Sn-1} \dots\dots\dots(4-9)$$

The solution of equation (4-9) provides the required outline of the pass geometry therefore the tool profile for extrusion die design with concept (CRHS) will follow steps for finding geometrical extrusion die design. Divide the dimension of the workpieces section (n) of the pass to find $\epsilon_x, \epsilon_y, \epsilon_z$.

$$d \epsilon_x = \frac{dA}{A} \dots\dots\dots(4-10)$$

Where:

A= area at any section.

$$d \epsilon_x = \frac{2\pi R dR}{\pi R^2} = \frac{2.dR}{R} \dots\dots\dots(4-11)$$

Integrating equation (4-11) we obtain:

$$\epsilon_{x_n} = \int_{R_o}^{R_n} d \epsilon_x = 2 \ln\left(\frac{R_o}{R_n}\right) \dots\dots\dots(4-12)$$

where:

R_o=initial radius of rod.

R_n=radius of work piece (rod) at any pass.

With constant equation volume:

$$\epsilon_{x_n} + \epsilon_{y_n} + \epsilon_{z_n} = 0$$

For circular shape:

$$\epsilon_{y_n} = \epsilon_{z_n}$$

$$\epsilon_{x_n} = -2 \epsilon_{y_n}$$

$$\epsilon_{y_n} = -\frac{1}{2} \epsilon_{x_n} \dots\dots\dots(4-13)$$

Substituting equation (4-13) in equation (4-12) we will obtain:

$$\epsilon_{y_n} = \epsilon_{z_n} = -\ln\left(\frac{R_o}{R_n}\right) \dots\dots\dots(4-14)$$

And substituting equation (4-10), (4-14) in equation (4-7) will obtain yield:

$$\epsilon_{ln} = Ln\left(\frac{R0}{Rn}\right)^2 \dots\dots\dots(4-15)$$

To obtain the dimension of the magnitude (Zn) we equation (4-15) with equation is compared with equation (4-9):

$$z_n = \left(\frac{R0}{Rn}\right)^2 \dots\dots\dots(4-16)$$

To obtain the dimension of extrusion die design (deformation pass), equation (4-9) will be used to determine (Z1):

$$z_1 = \left(\frac{R0}{Rn}\right)^2 \dots\dots\dots(4-17)$$

$$z_n = (z_1)^{s^{(n-1)}} * (z_{n-1})$$

$$z_n = (z_1)^{s^1} * z_1$$

$$z_3 = (z_1)^{s^2} * z_2 = (z_1)^{s^2} * (z_1)^{s^1} * z_1 = z_1^{s^2+s+1} \dots\dots\dots(4-18)$$

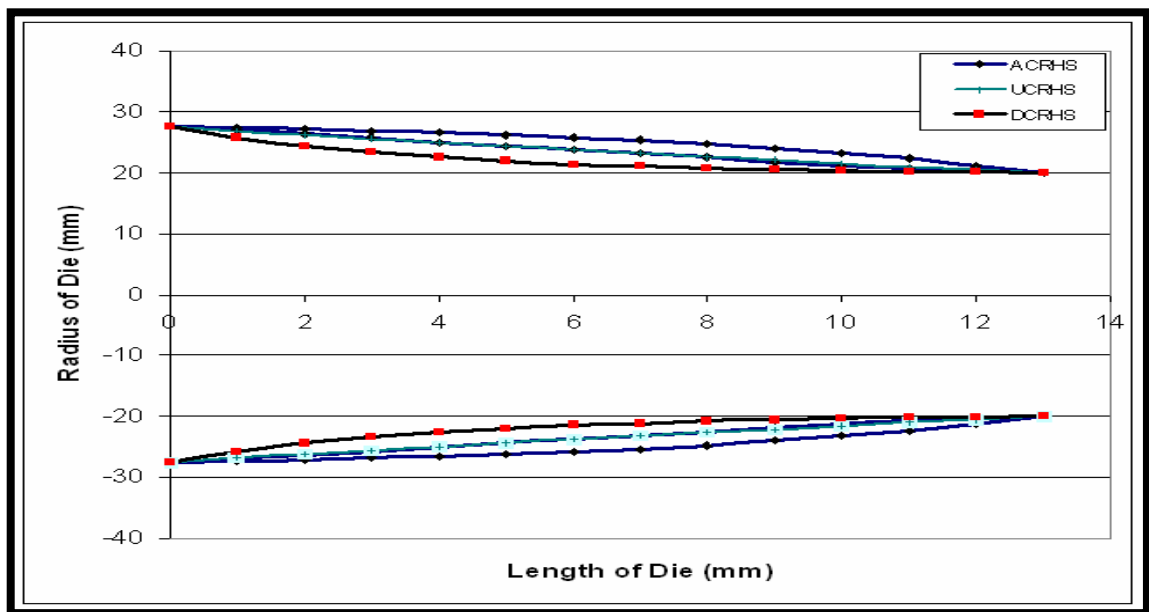


Figure (4-12): The geometric shape (for the Forward Extrusion) dies profile designed by CRHS.

4.9 Finite Element Analysis Using ANSYS9.0 Package:

ANSYS is a commercial finite element analysis, the package is with capability to analyze a wide range of different problems. There are two ways to use ANSYS. Interactively through the graphical user interface GUI, and through the use of batch files and ANSYS commands [52,53]. The input data for an ANSYS analysis are prepared using a preprocessor. The general preprocessor contains powerful solid modeling and mesh generation capabilities, and is also used to define all other analysis data of geometric properties (real constants), material properties, constraints, loads, etc., with the benefit of database definition and manipulation of analysis data. The analysis results are reviewed using postprocessors, which have the ability to display distorted geometries, stress and strain contours, flow fields, safety factor contours, contours of potential field results (thermal, electric, magnetic), vector field displays mode of shapes and time history graphs [52,53].

4.9.1 Choosing Element Type:

The ANSYS element library contains more than sixty elements for static and dynamic analyses, over twenty for heat transfer analyses, and includes numerous magnetic, field, and special purpose elements. In this study the element SOLID 45 is selected. SOLID 45 is used for the 3-D modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node translations in the nodal x, y, and z directions. Within ANSYS, two different methods used to generate a model solid modeling and direct generation [52,53].

4.9.2 Defining the Material Properties:

Most element types require material properties. Depending on the application, material properties may be;

- Linear or nonlinear.
- Isotropic, orthotropic, anisotropic.
- Constant temperature or temperature-dependent.
- **Table (4-1) represents material properties of materials used in this research [52].**

<i>Properties of materials</i>	<i>DIE</i>	<i>BILLET</i>
Material	H13	Aluminum
Modulus of Elasticity (E) GPa	220	68.94
Tangent Modulus (E_t) GPa		0.1
Yield stress (σ_Y) MPa	900	70
Poisson's ratio (ν)	0.3	0.33

4.9.3 Meshing Model:

In addition to specifying element shape, one may also want to specify the type of meshing (mapped) that should be used to mesh your model [52,53].

4.9.4 Defining the Contact Surfaces:

Contact problems are highly nonlinear and require significant computer resources to solve. Contact problems present two significant difficulties. Generally, the regions of contact are not known until the problem is running.

Depending on the loads, material, boundary conditions, and other factors, surfaces can come into and go out of contact with each other in a largely unpredictable and abrupt manner. Second, most contact problems need to account for friction. There are several friction laws and models to choose from, and all are nonlinear. Frictional response can be chaotic; making solution convergence difficult. ANSYS supports three contact models: node-to-node, node-to-surface, and surface-to-surface. Each type of model uses a different set of ANSYS contact elements [52,53].

4.9.4.1 Contact Pair:

In studying the contact between two bodies, the surface of one body is conventionally taken as a contact surface and the surface of the other body as a target surface. The “contact -target” pair concept has been widely used in finite element simulations. For rigid-flexible contact, the contact surface is associated with the deformable body; and the target surface must be the rigid surface. For flexible-flexible contact, both contact and target surfaces are associated with deformable bodies. The contact and target surfaces constitute a “contact Pair” [52,53].

4.9.4.2 Surface-to-Surface Contact Elements:

ANSYS supports both rigid-to-flexible and flexible-to-flexible surface-to-surface contact elements. These contact elements use a "target surface" and a "contact surface" to form a contact pair [52,53].

- The target surface is modeled with either TARGE169 or TARGE170 (for 2-D and 3-D, respectively).
- The contact surface is modeled with elements CONTA171, CONTA172, CONTA173, and CONTA174.

4.9.5 Defining the Analysis Type and Applying Loads:

In this step, we will define the analysis type (i.e. static, transient,..., etc.) analysis options (large deflection, large strain, large displacement), then apply load steps, we can apply loads either to the solid model (key points, lines, and areas) or to the finite element model (nodes and elements) [52,53].

4.9.6 Controlling the Motion of the Rigid Target Surface (Rigid-to-Flexible Contact):

Rigid target surfaces are defined in their original configuration, and the motion of the entire surface is then defined by the imposed displacements on the pilot node (or the different nodes of the target surface if no pilot node was defined) [52,53]. We must use a pilot node in any of the following situations to control the boundary conditions (and motion) of the entire target surface:

- The target surface is subject to applied forces.
- The target surface is subject to rotations.
- The target surface is connected to other elements (e.g., structural mass element).
- The motion of the target surface is adjusted by the equilibrium condition.

The degrees of freedom of the pilot node represent the motion of the entire rigid surface, including two translational and one rotational degree of freedom in 2-D, three translational and three rotational degrees of freedom in 3-D. We can apply boundary conditions (displacement, initial velocity), concentrated loads, rotations, etc. to the pilot node [52,53].

4.10 Algorithms Proposed For Representing Interpolator

Curve for CNC System Approach:-

In this section, we will summarize algorithms proposed that can be used to calculate optimum length of line segment with tolerance given and calculating better side step with given height scallop. Length line segment can be represented by G01 functions.

4.10.1 Defining the Designed Surface in the (u,w) Direction:

The designed part is represented by Cubic Bezier surface. The surface is represented by parametrized over a domain (u,w) and defined by parallel curves called isoparametric curves. Boundary of curves must be equal to the boundaries of the surface.

4.10.2 Calculating the Radius of Curvature:

On the designed part, we calculate the radius of curvature at each point on the surface to obtain the minimum radius of curvature. Calculating the radius of curvature very important because it is used to determine the length of line segment and determining better cutter radius must be equal to or smallest than the minimum radius of curvature for the parametric surface.

4.10.3 Calculating The Optimum Line Segment in (u,w) Direction With Scallop Height and Tolerance Given:

During surface machining, the surface part is approximated by series of line segments. Therefore in this thesis, we calculate the length of line segment in (u) and (w) direction. We approximate the tool path by better length segment (linear interpolation). The better length segment is the distance between (CC) points during current tool path with in the limited given tolerance. This work will determine the length line segments for forward step (L).

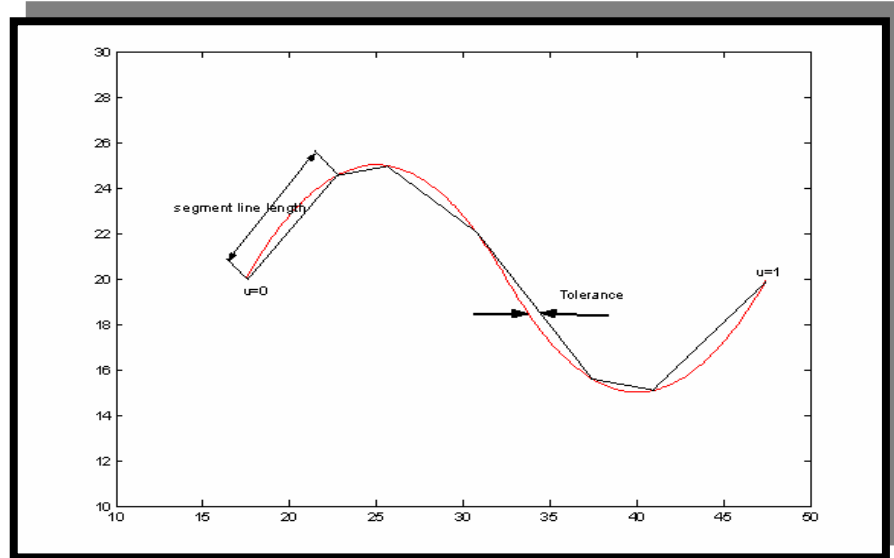


Figure (4-13): Represent line segment and tolerance.

After calculating length line segment in (u) direction, we calculate the better length segment in (w). Length line segment in (w) direction is the better distance between two adjacent tool paths which can keep the height scallop (h) given. Hence the radius of tool must be less than or equal to the minimum radius of curvature.

4.10.4 Converting the Length Line Segment in (u,w) Direction into Parametric Domain:

The length line segment in (u,w) direction is determined by a physical unit, therefore it must be converted into the parametric system (u,w) to represent different surface in the machining.

4.10.5 Converting (CC) Point to (CL) Points:

The (CC) points must be converted to the (CL) points to generate tool path and manufacture part. (CL) are stored as a (CL) data file. After these steps we calculate strains and forces for interpolator Bezier profile die then compare the results with cubic Bezier and compound-CRHS profile die.

4.10.6 Procedure for Studying Curve Interpolator for CNC

System Algorithms:-

The following steps are constructed for building interpolator surface:

- 1- Input control points of the surface as matrix ($n \times n$).
- 2- Input increment value in (u and w).
- 3- Input $u=0$.
- 4- Input $w=0$.
- 5- Calculate the X , Y and Z coordinate of each point on the surface.
- 6- Plot each X , Y and Z point for surface.
- 7- Check the magnitude of ($w \leq 1$).
- 8- No: Goto step (4).
- 9- Yes: Goto step (13).
- 10- Check the magnitude of ($u \leq 1$).
- 11- No: Goto step (3).
- 12- Yes: Goto step (13).
- 13- Calculate the radius of curvature of each point (X, Y, Z) on the surface as matrix ($n \times n$).
- 14- Select the minimum radius of curvature.
- 15- Input tolerance between the segments line and the curve.
- 16- Input the height scallop.
- 17- Calculate the best line direction (u) or forward direction with tolerance given.
- 18- Calculate the best line indirection (w) or side step direction with height scallop given.
- 19- Input control point of surface as matrix (n, n).
- 20- Input increment value (line segment) in (u and w) direction.
- 21- Input ($X=X_{min}$).
- 22- Input ($Y=Y_{min}$).
- 23- Calculate the X , Y and Z coordinate of each point on the surface.
- 24- Plot each X , Y , and Z for surface.
- 25- Check the magnitude of ($Y=Y_{max}$).
- 26- No: Goto step (22).
- 27- Yes: Goto step (31).
- 28- Check the magnitude of ($X=X_{max}$).
- 29- No: Goto step (21).
- 30- Yes: Goto step (31).
- 31- Represent the interpolator surface by (X, Y, Z) coordinate.
- 32- DXF code file.
- 33- G-code program for interpolator cubic Bezier surface.
- 34- Controller plus driver.
- 35- X-Y table.

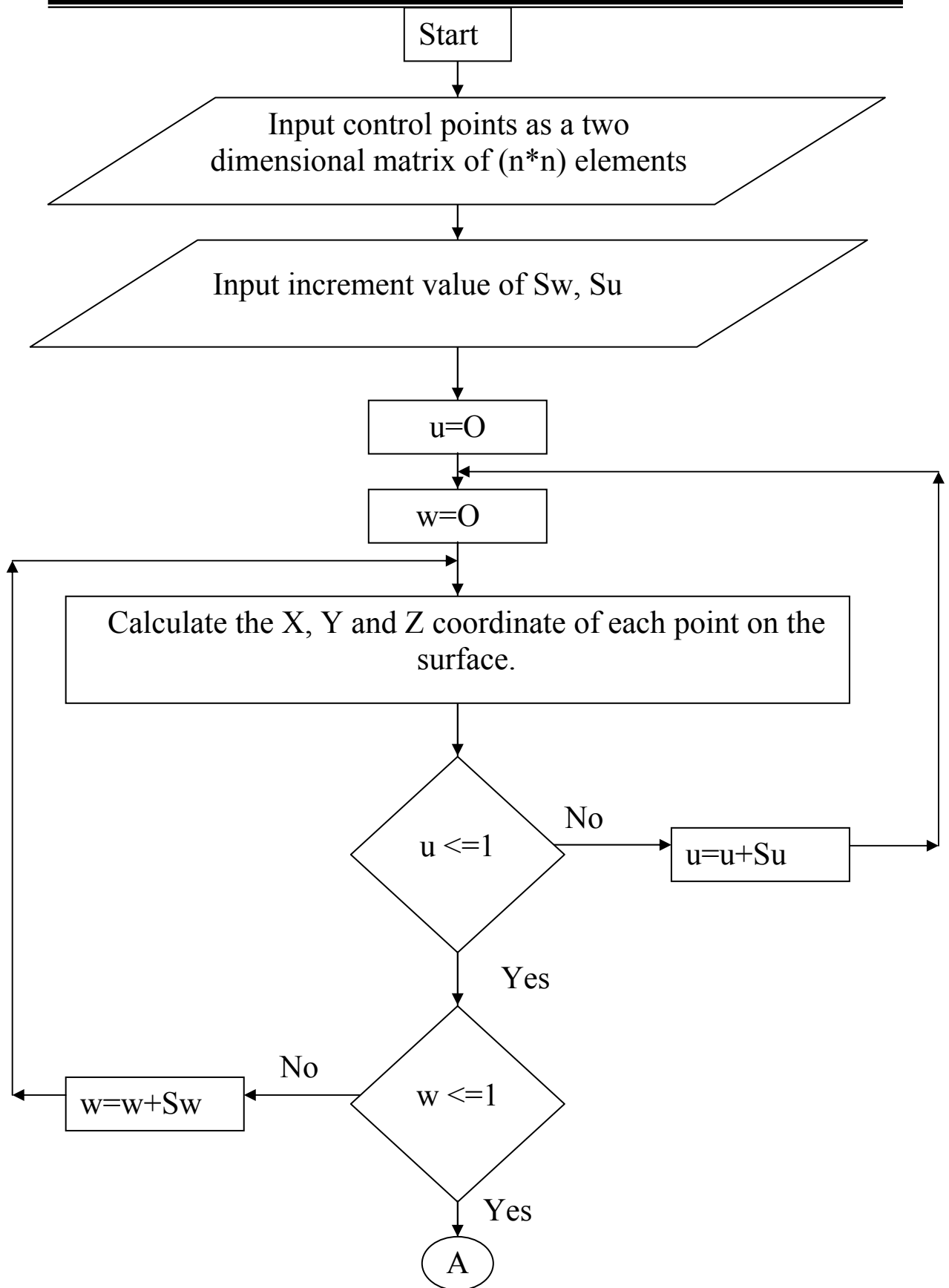
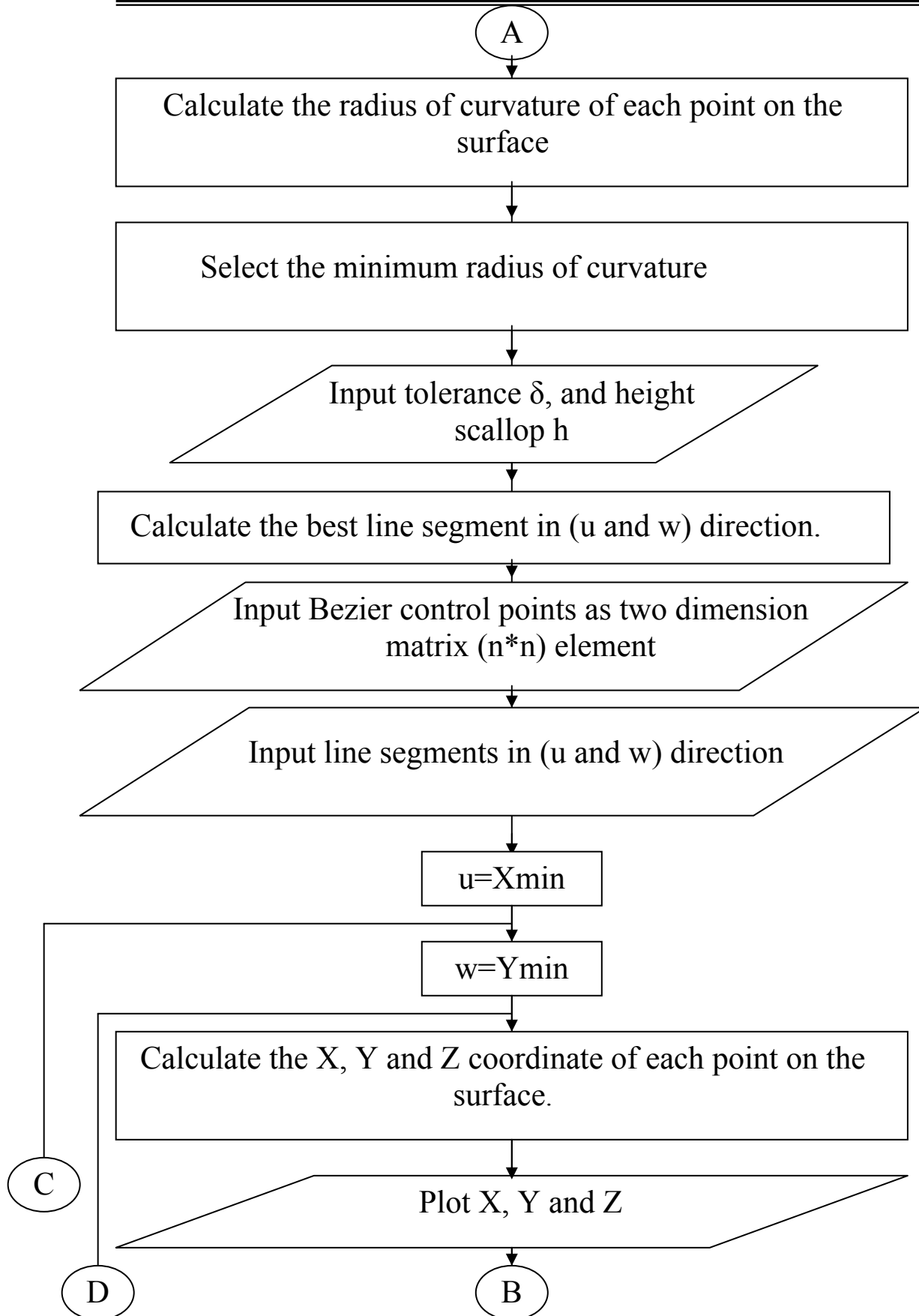
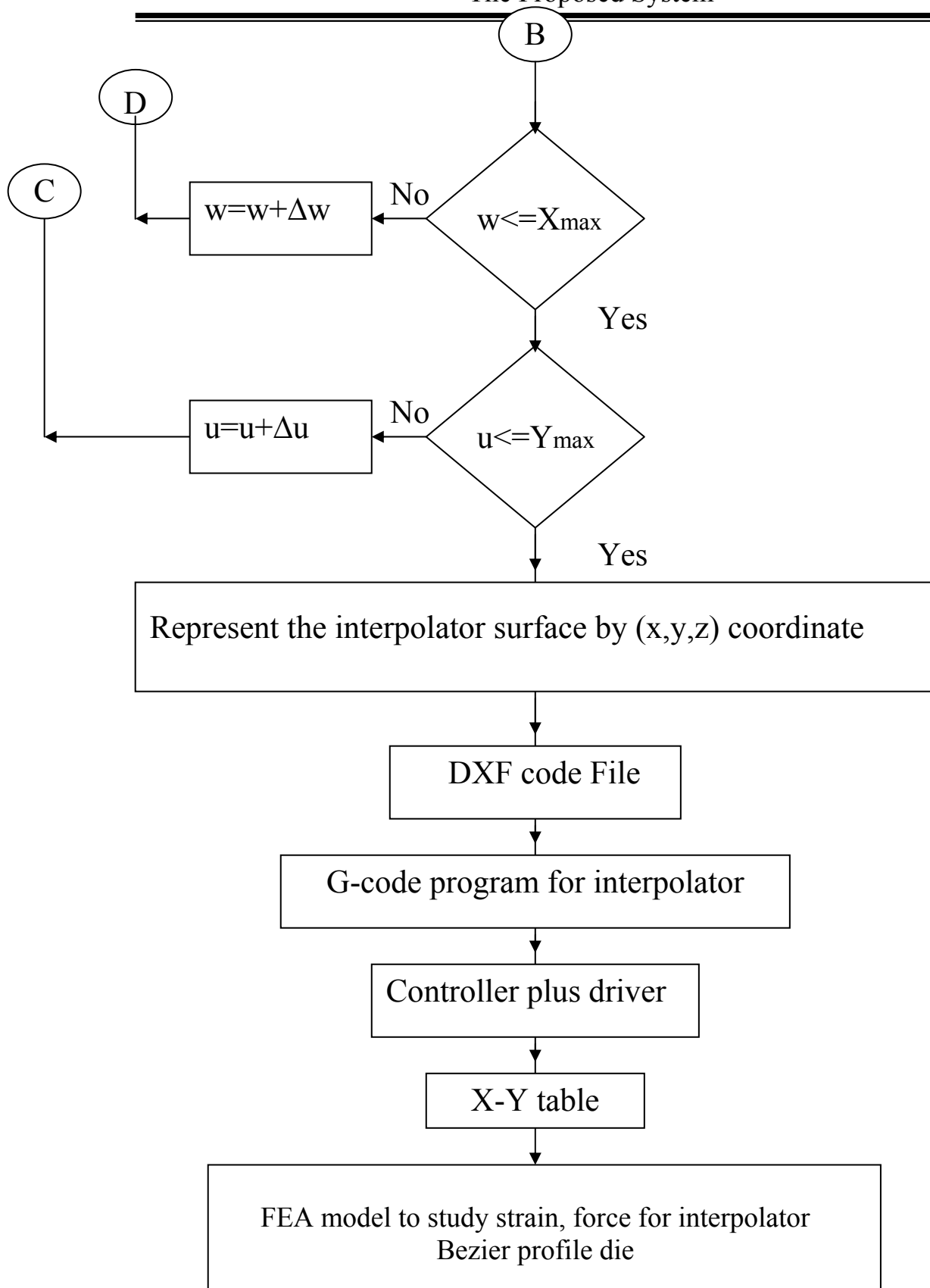


Figure (4-14): The flowchart that represents the algorithm proposed.



Continue of Figure (4-14)



Continue of Figure (4-14)

4.11 Summary:

This chapter has covered the following topics:

- The tool path generation strategies as well as the main parts of machining process (roughing and finishing).
- A discussing the equation modeling the extrusion die design using FEM. The package is ANSYS 9.0.
- The system algorithms and block diagram for the system are proposed.

CHAPTER FIVE

THE PROPOSED ALGORITHM APPLCATION SYSTEM

Chapter Five

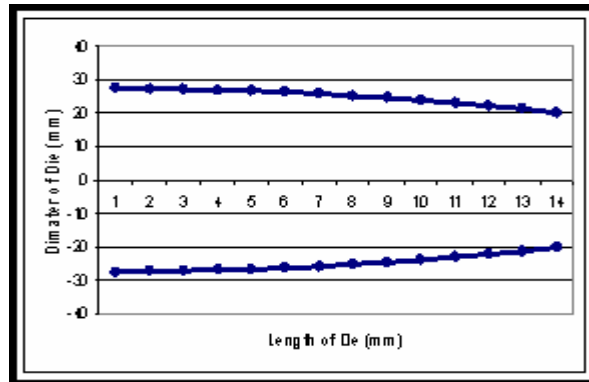
5.1 Introduction:

The input to which system will be two (2D) or three dimension (3D) model. The model of the input contains not only dimensions of the shape but also the tolerance, height scallop, better length segment and special features. To facilitate a CAD, CAM system in the manufacturing process, we generate a NC program containing the all features being mentioned. In this work (DXF-file) shall be converted from MATLAB to SURFCAM software to visualize the product before machining. In this work, we propose a modified methodology will be proposed to calculate segments of appropriate length in (u,w) directions that are within the tolerance, height scallop and ultimately generate the tool path for extrusion die design. The algorithm is applied to the extrusion die and the proposed algorithms (interpolator Bezier profile die) will be compared with cubic Bezier and component (CRHS) profile die. A real part is machined using SURFCAM software to simulate the part machining before machining on the CNC machine. G-codes are the machine language output from SURFCAM software in this research. After determining the length line segment and comparing between cubic Bezier, interpolator cubic Bezier and component (CRHS) profile die, we calculate the homogenous strain and force required for extrusion die utilizing the ANASYS 9.0 software.

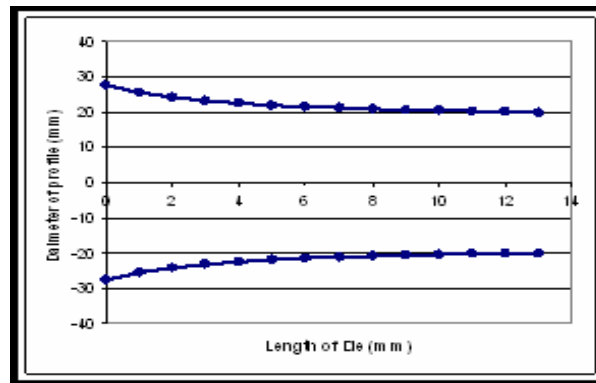
5.2 Extrusion Profiles Die:

In the thesis, CRHS concept profiles dies are shown in the figure (5-1). There are four basic rates of deformation ($S=0.8, 1, 1.2$) CRHS profile dies used in this research. From equation (4-9,.....) extrusion die (circular rod) will be design with internal radius (20mm) and external radius (27.5mm) and extrusion die design is checked from the constant rate

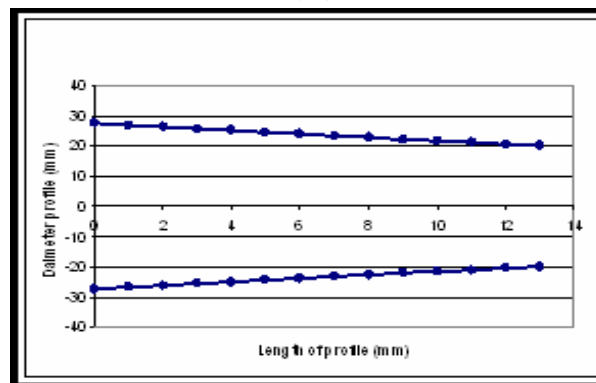
of deformation (S). Figure (5-1) shows different profile dies (ACRHS, DCRHS and UCRHS).



(A)



(B)



(C)

Figure (5-1): Represents profile die for: (A) Accelerated profile die (ACRHS). (B) Decelerated profile die (DCRHS). (C) Uniform profile die (UCRHS).

5.3 Tool Path Design:

The cutter in the CNC machine moves along specified coordinates to get on the desired machining, the cutter moves to the new locations by using linear or circular interpolations. The design of the tool path depends mainly on the underlying geometry of the part to be machined, as well as the size and shape of the selected tool. Figure (5-2) shows a zig-zag tool path is better tool path after studying different tool path design (zigzag, isoparametric and isoscallop).

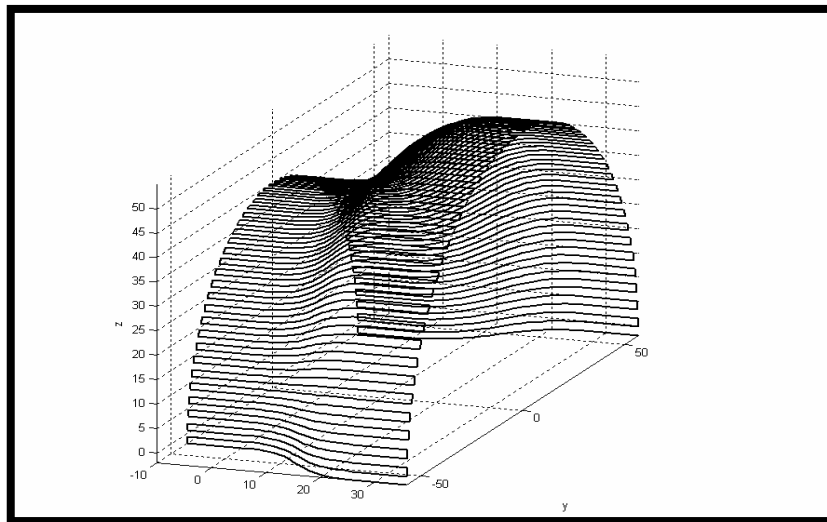


Figure (5-2): Representation of zig-zag tool path.

5.4 The Proposed Algorithms:

Subsequently, we explain the steps of the proposed algorithms as applied in the production process.

5.4.1 Determining of Length Segment (in U direction):

Each curve is approximated by a series of line segments and length of line segments it is controlled by tolerance given. There are two line segments, one in (u) and one in (w) directions. The forward step size (Length line segment) depends on the tolerance (δ) given and radius of curvature (ρ).

5.4.2 Determining of Length Segment (in W direction):

The length of a line segment in (W) direction is function of the height scallop (h), the radius of the cutter and tolerance. We will use the equation (4-2) to calculate the length of line segments in (W) direction with the given height scallop (h). There are three different cases used to calculate the length of a line segments in (W) direction depending on the convex, concave and flat surface. The length segments in (w) directions is described by the equations that represent the Bezier profile die using (u) and (w) parameters.

5.4.3 Example of Proposed Algorithm:-

The proposed algorithm must be implemented and tested with another case study (cubic Bezier, interpolate Bezier with component-CRHS profile die) and we calculate the appropriate (CC) points by using proposed algorithm. The software used in this proposed algorithm is:

- MATLAB 7.4.
- SURFCAM.
- ANSYS 9.0.

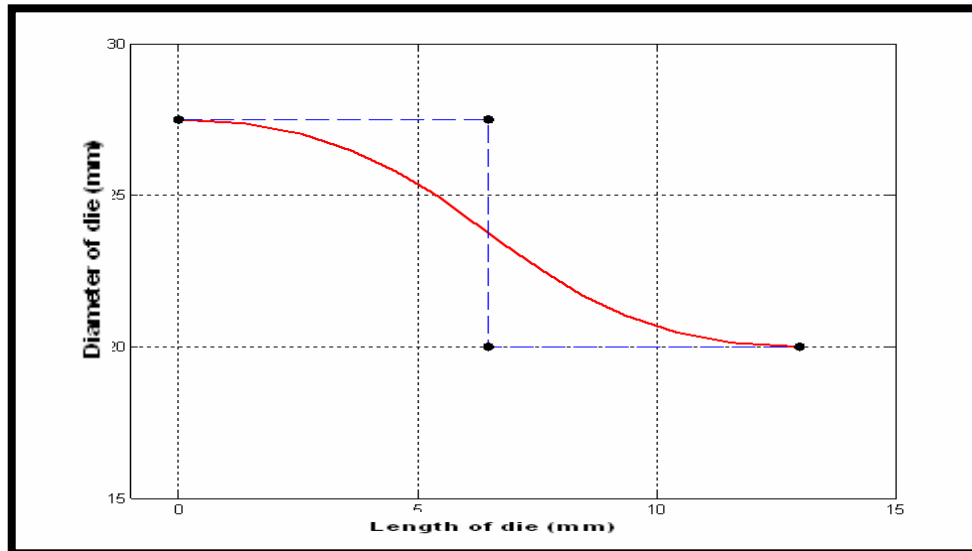
The proposed algorithms are performed on a personal computer (Core, 1.663 2CPU, 512 Mb of Physical Memory) with Microsoft XP professional. The desired surface was generated by MATLAB (7.4) software.

5.4.3.1 Case Study:

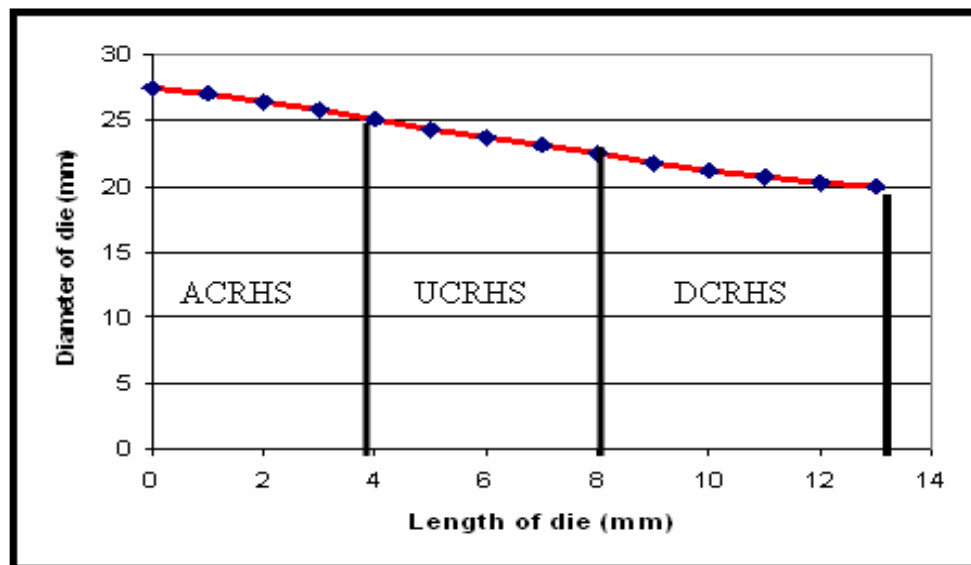
A cubic Bezier surface is defined by a grid of (4*4) control points to represent extrusion die design and matrix control points as shown below:

(3.75, 0, 0)	(3.75, 0, 20)	(23.75, 0, 20)	(23.75, 0, 0)
(3.75, 6.5, 0)	(3.75, 6.5, 20)	(23.75, 6.5, 20)	(23.75, 6.5, 0)
(0, 6.5, 0)	(0, 6.5, 20)	(27.5, 6.5, 20)	(27.5, 6.5, 0)
(0, 13, 0)	(0, 13, 20)	(27.5, 13, 20)	(27.5, 6.5, 0)

Figure (5-3) represents cubic Bezier and compound-CRHS profile die; to layout the tool paths for each profiles die. The Bezier curves consist of four control points and compound –CRHS consists of three zones that are ACRHS, UCRHS and DCRHS.



(A)



(B)

Figure (5-3): Representation of profile die. (A) Cubic Bezier curve.(B) Compound-CRHS curve.

Table (5-1) and figure (5-4) show the difference between interpolator Bezier and compound –CRHS profile die. Figure (5-4) shows the difference in the radius along length of die for interpolator Bezier and compound-CRHS profile die and the maximum difference between interpolator Bezier and compound-CRHS profile die equals (0.81 mm). The purpose of figures (5-4) and (5-5) is to demonstrate the difference between interpolator Bezier and compound –CRHS profile die.

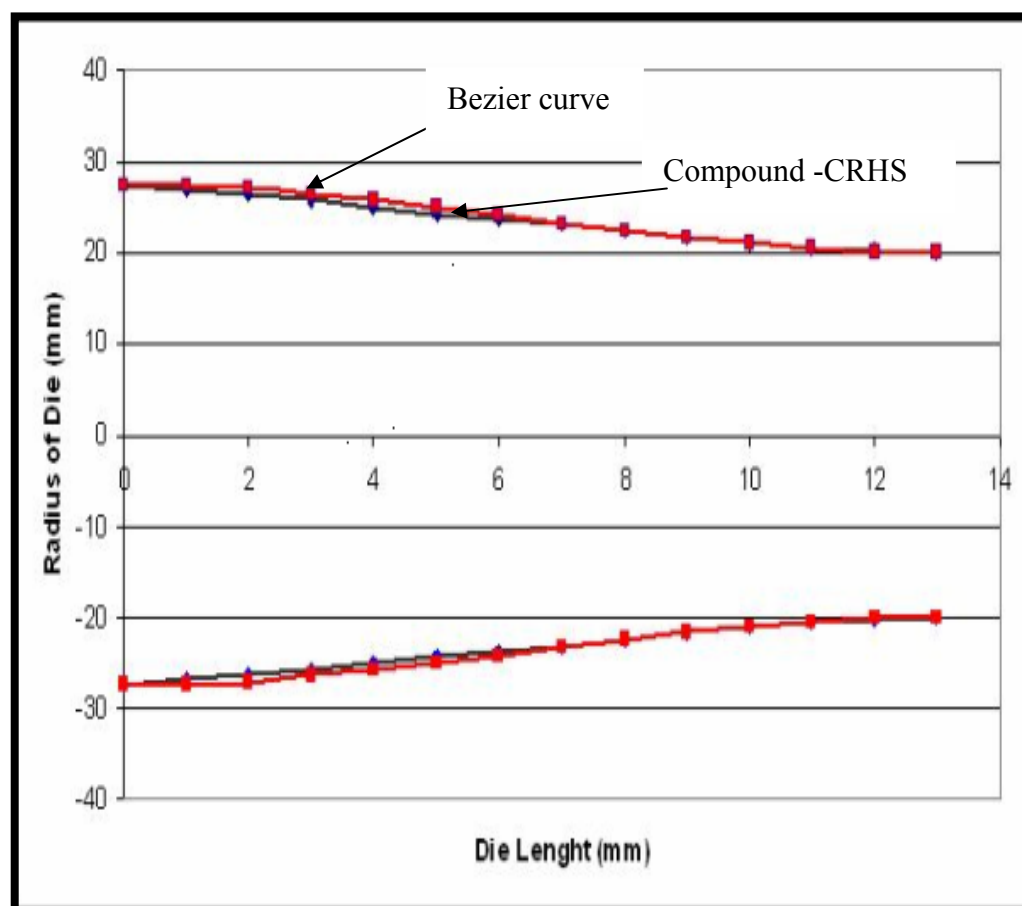


Figure (5-4): Representation of difference between compound-CRHS and Bezier profile die.

- Table (5-1) Difference between interpolator Bezier curve and compound-CRHS die profile:

X	Bezier Curve	Compound CRHS	Difference
0	27.5	27.5	0
1	27.37	27.016	0.354
2	27.02	26.4478	0.5722
3	26.49	25.7811	0.7089
4	25.81	25	0.81
5	25.03	24.3502	0.6798
6	24.18	23.7191	0.4609
7	23.32	23.1035	0.2165
8	22.48	22.5	-0.02
9	21.7	21.7253	-0.025
10	21.02	21.1263	-0.01063
11	20.48	20.658	-0.178
12	20.13	20.291	-0.161
13	20	20	0

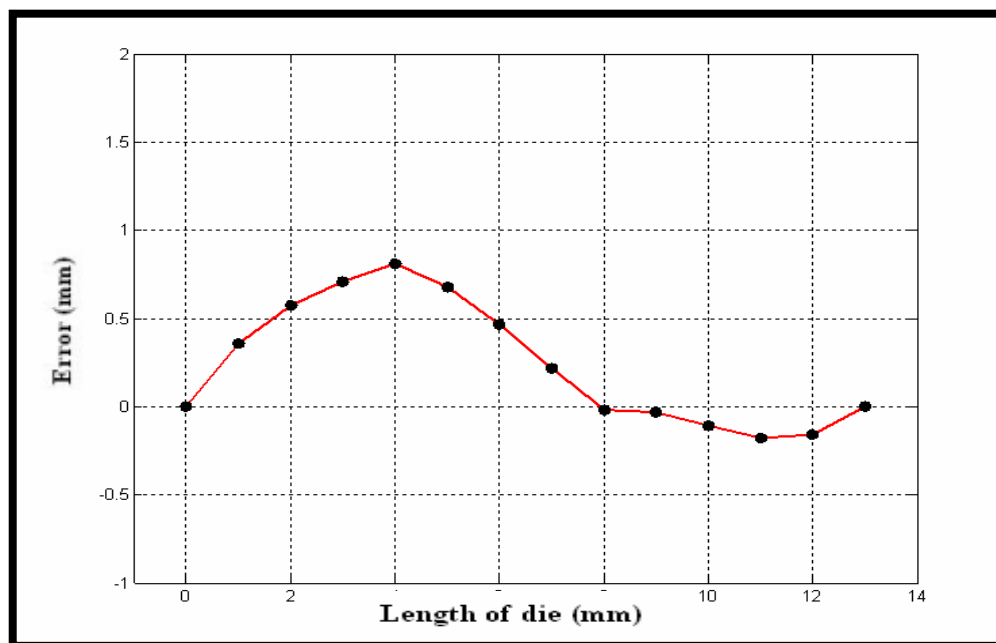
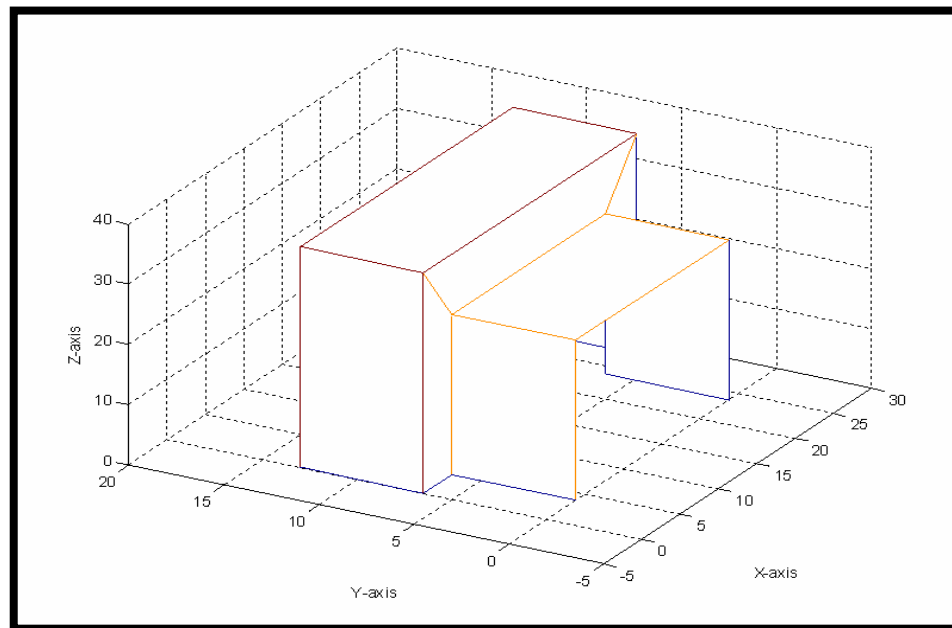


Figure (5-5): Shows error between interpolator Bezier and compound-CRHS profile die.

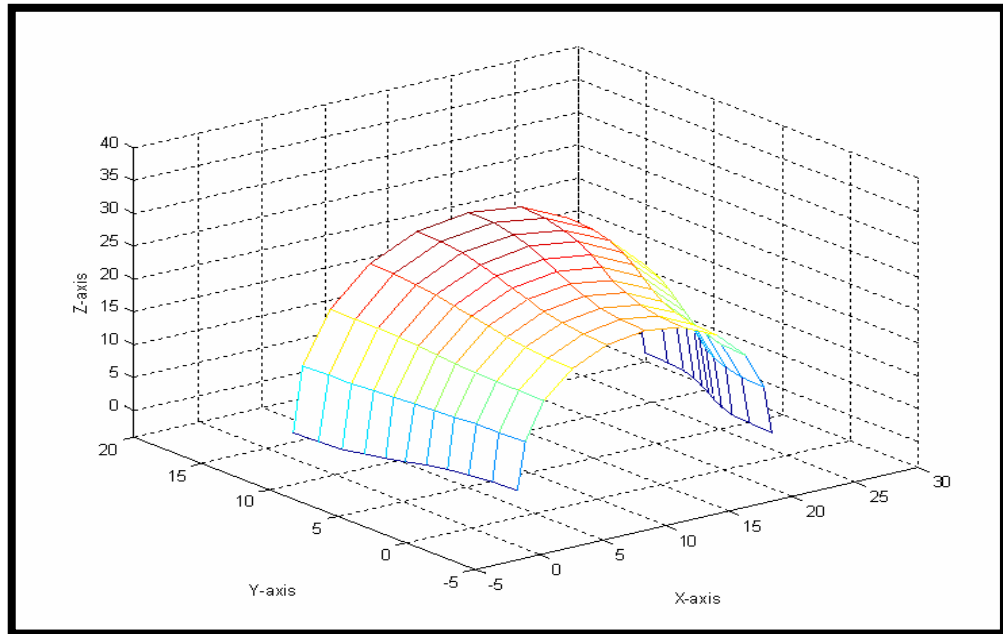
5.4.3.1.a Case Study (Cubic Bezier Profile Die):

Tool path resolution (length line segment) is related to machining tolerance. The machining efficiency of tool paths is directly related to the machining time. Machining time is typically proportional to manufacturing costs. Figure (5-6) shows control polygon, cubic Bezier profile die, and represents zig-zag tool path. Figure (5-11) shows machining extrusion die (Cubic Bezier profile die) by using SURFCAM software. Figure (5-11A) shows workpiece (cibatool) before machining, Figure (5-11B) shows the roughing operation for model to reduce cost of machining, Figure (5-11C) shows the finishing operation for Cubic Bezier profile die.

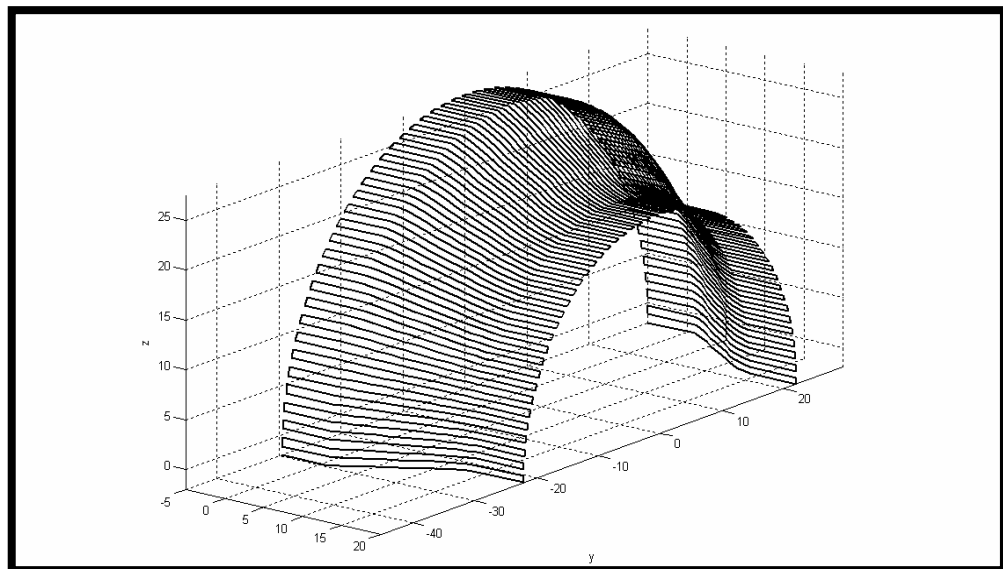


(A)

Figure (5-6): Representation of profile die by using cubic Bezier surface (By using approximation length segment): (A) Control polygon. (B) Bezier profile die. (C) Tool path for Bezier profile die.



(B)



(C)

After we explain and visualize of cubic Bezier profile die SURFCAM software will be used to simulate machining of Bezier profile die and tool path achieved by MATLAB (7.4) software. DXF-file is used to convert profile die and tool path from MATLAB (7.4) to SURFCAM. Figure (5-7) shows the successful translation between MATLAB and SURFCAM to apply simulation machining to the case study used (cubic Bezier surface, interpolator Bezier surface and compound-CRHS profile die).

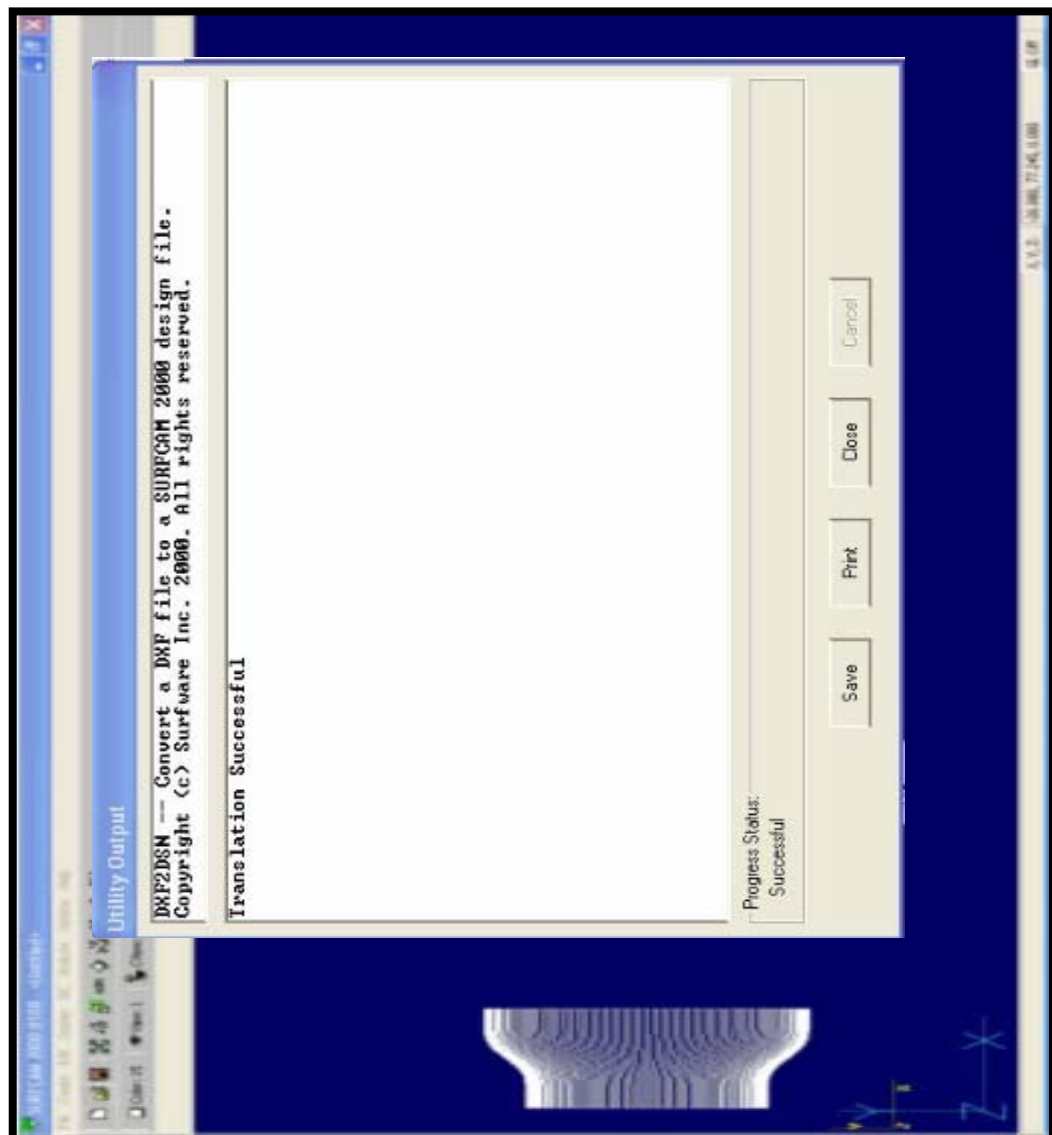


Figure (5-7): Successful translation between MATLAB and SURFCAM software.

Figure (5-8) shows different milling cutter radius used in SURFCAM to simulate machining case study being used. Two milling cutters are used in roughing process; the cutter diameter is (16 mm) to reduce machining time. After this process better cutter radius (cutter radius doesn't exceed the minimum radius of curvature) is used to apply finishing process by using (5mm) cutter diameter.

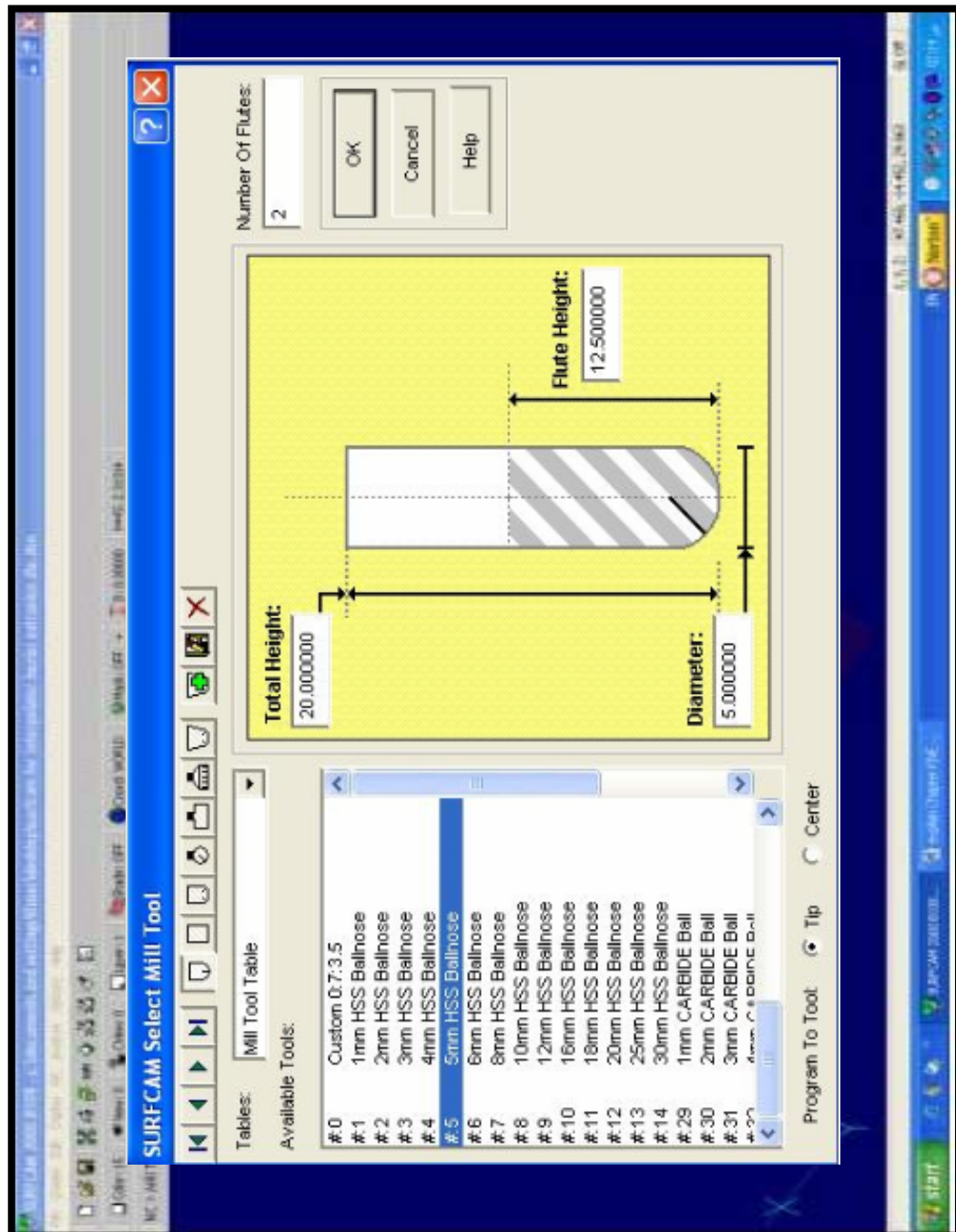


Figure (5-8): Selection of better cutter radius.

Figure (5-9) shows different workpiece materials used in machining. Cibatool is the material selected in this research.

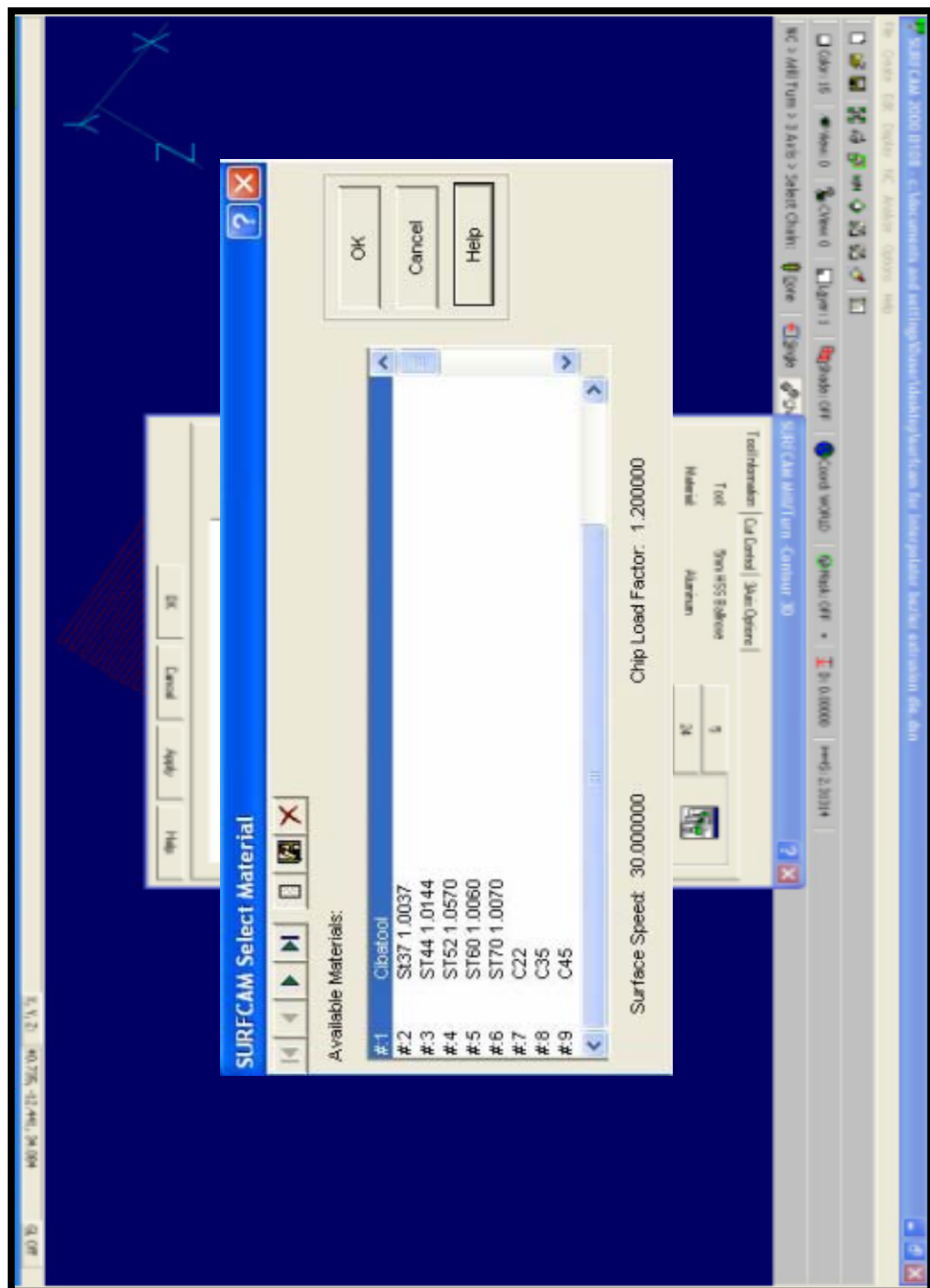


Figure (5-10) shows parameters of machining used in the SURFCAM. In our case study, ball end mill (16mm & 5mm) cutter diameter, cibatool workpiece materials is selected, feedrate, spindle speed, etc... are calculated automatically by the SURFCAM software.

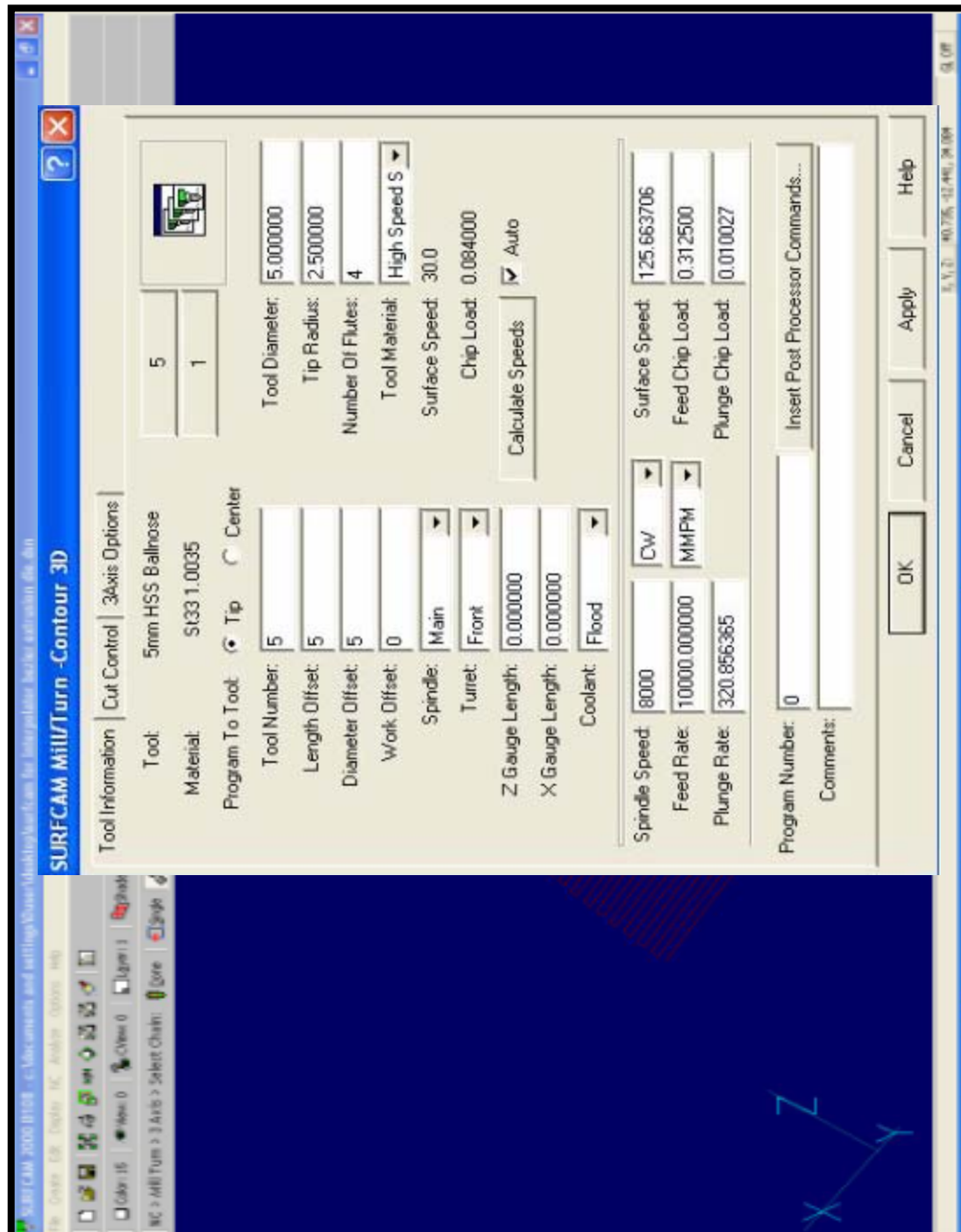
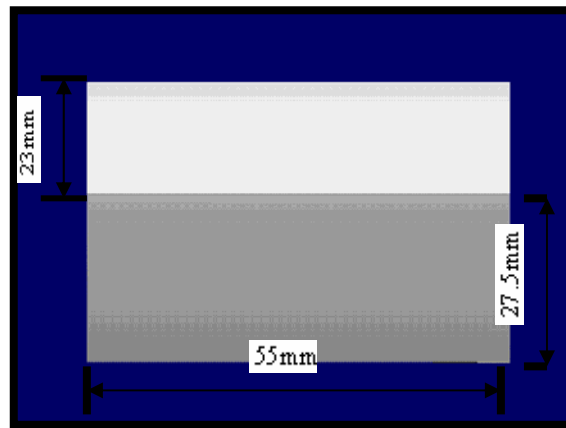
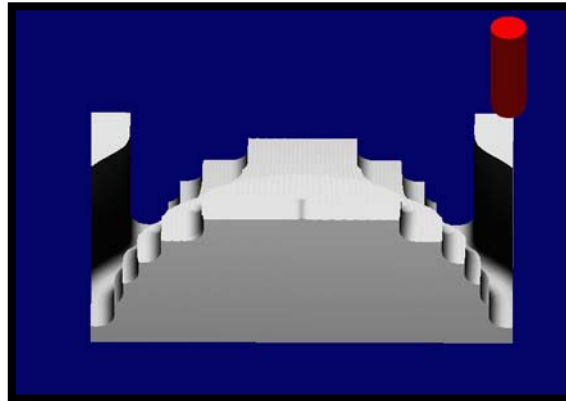


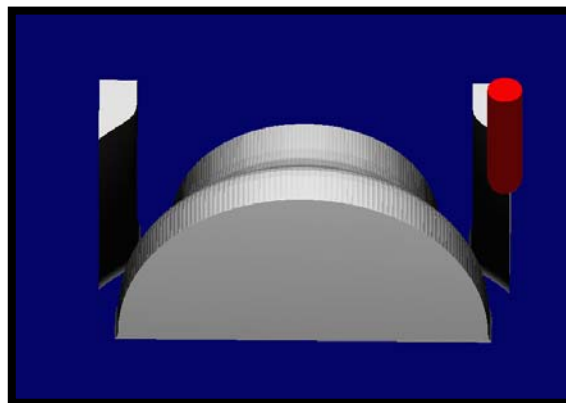
Figure (5-10): Parameters machining for Bezier profile die.



(A)



(B)

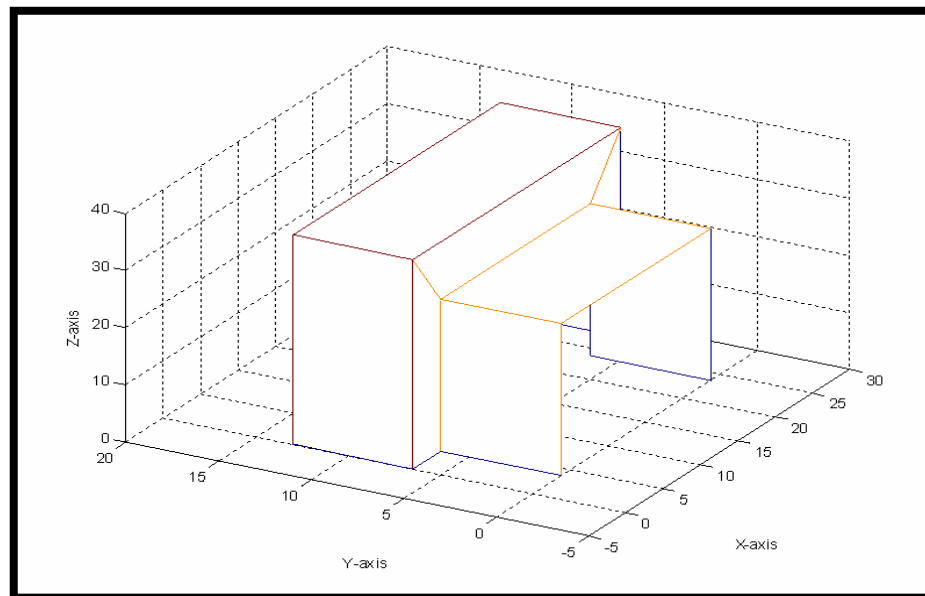


(C)

Figure (5-11): Using SURFCAM software to simulate the machining of cubic Bezier profile die. (A) Workpiece (cibatool). (B) Roughing process. (C) Finishing process.

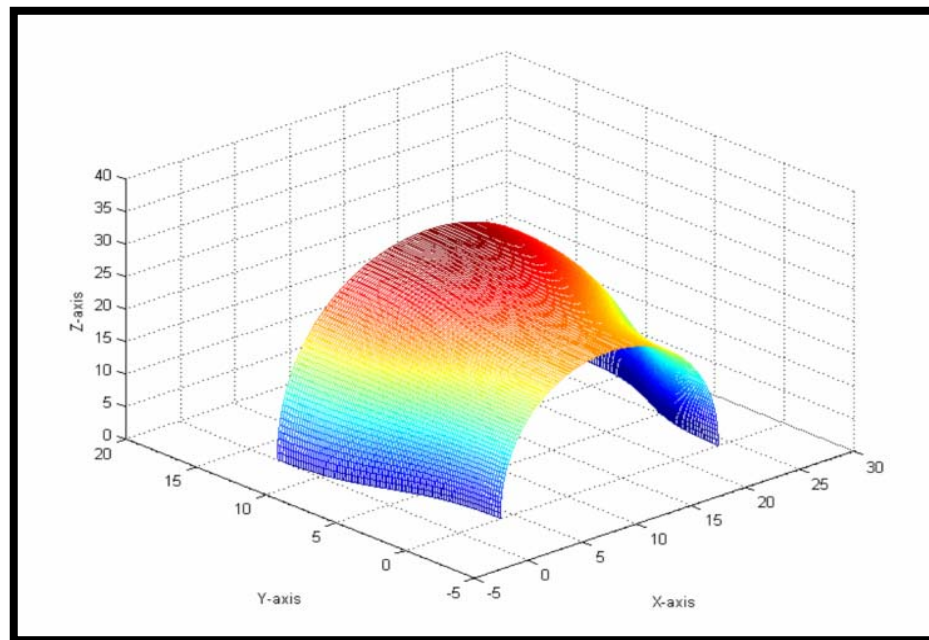
5.4.3.1.b Case Study (Interpolator Cubic Bezier Profile Die):

Figure (5-12) represents interpolator Bezier (representing extrusion profile die), and represents the tool paths for interpolator Bezier surface with allowed tolerance, height scallop and length line segment. After determining length line segment for interpolator Bezier profile SURFCAM will be used to simulate machining for proposed algorithms. Figure (5-13) shows machining extrusion die (interpolator Bezier surface) by using SURFCAM. Figure (5-13A) shows the workpiece (cibatool) before machining (block), Figure (5-13B) shows the roughing operation for model (using 16mm cutter diameter) and Figure (5-13C) shows the finishing operation for the designed model (using 5mm cutter diameter).

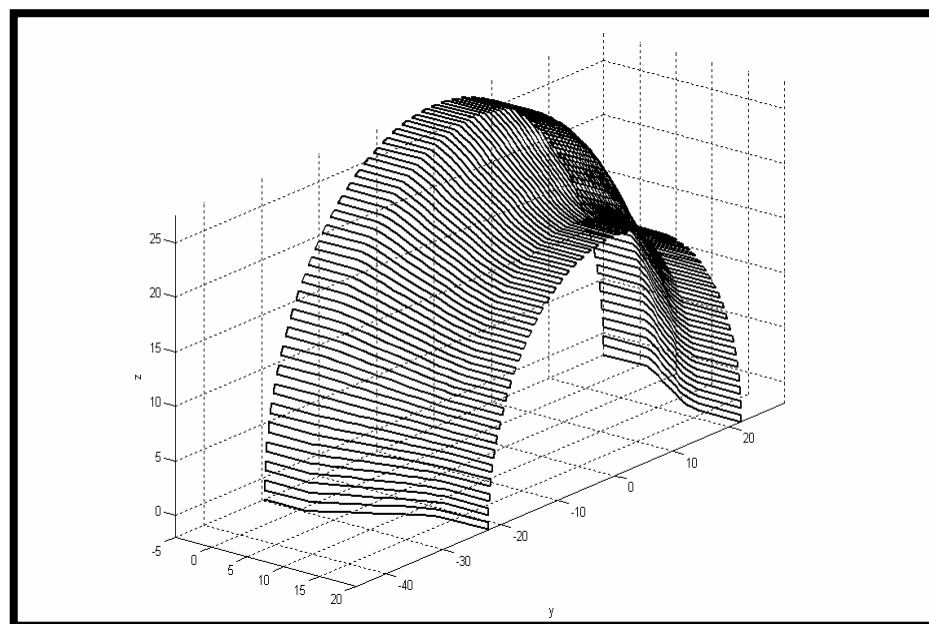


(A)

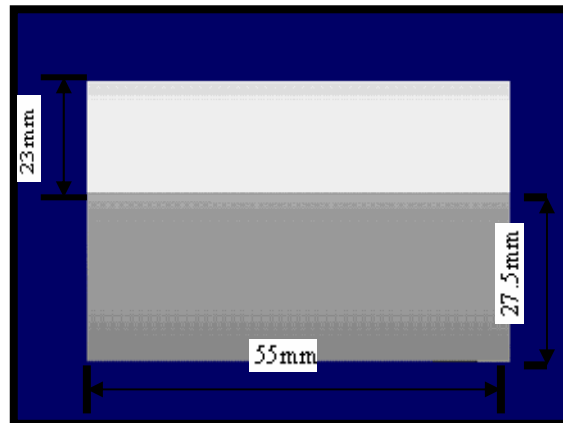
Figure (5-12): Represents profile die by using interpolator Bezier surface (By using better length segment). (A)Control polygon. (B) Bezier profile dies. (C) Tool path for Bezier profile die.



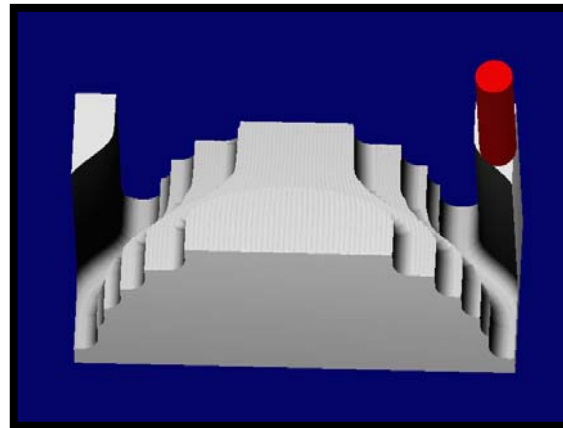
(B)



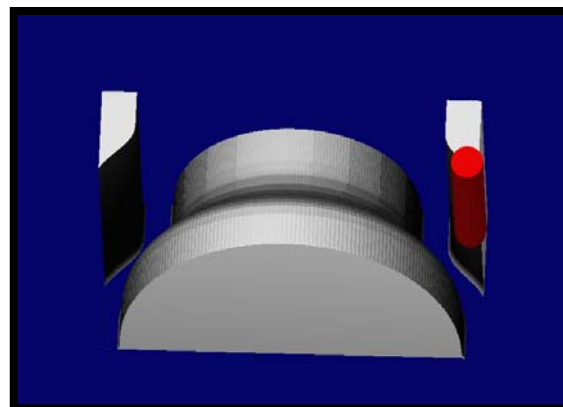
(C)



(A)



(B)



(C)

Figure (5-13): Using SURFCAM software to simulate the machining of interpolator Bezier surface (A) Workpiece (cibatool). (B) Roughing process. (C) Finishing process.

5.4.3.1.c Case Study (Compound-CRHS Profile Die):

After the use of a cubic Bezier surface and interpolator Bezier surface for extrusion die design, we will now focus on compound-CRHS dies design. Compound-CRHS consists of three sections, of which the first section is designed according to the (ACRHS) concept, while the mid of the die is designed according to the (UCRHS) concept. And the end section is designed according to the (DCRHS) concept as shown below.

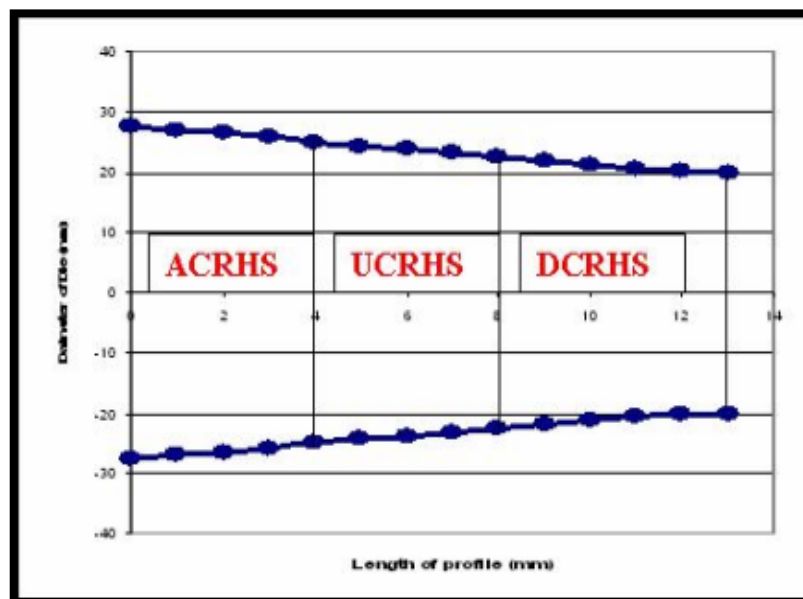
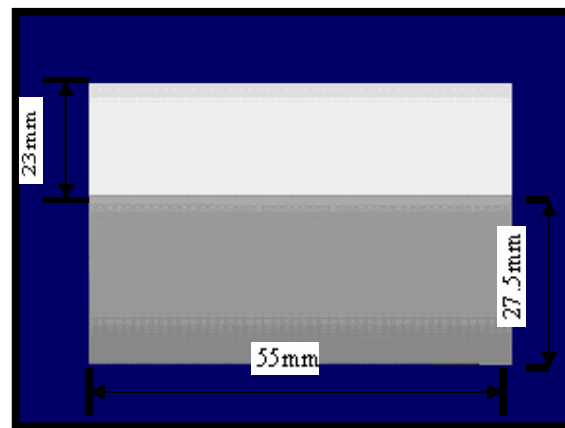
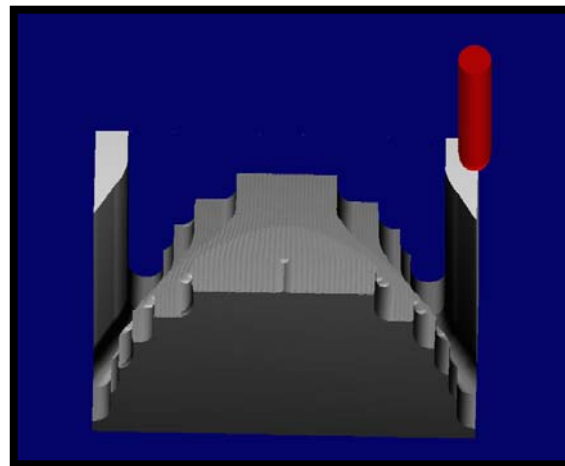


Figure (5-14): Profile die by using compound-CRHS.

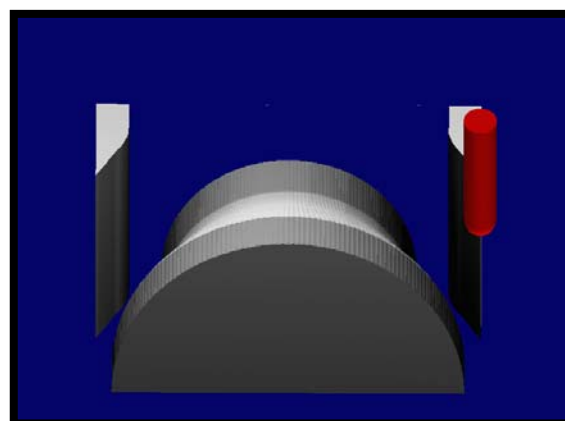
After explaining the approximated length segment for compound-CRHS, SURFCAM will be used to simulate machining after representing the tool path by MATLAB (7.4) software. DXF-file will be used to convert the profile die and the tool path from MATLAB (7.4) to SURFCAM software. Figure (5-15), shows machining extrusion die (compound-CRHS) by using SURFCAM. Figure (5-15A) shows the workpiece before machining (block), Figure (5-15B) shows the roughing operation for model (using 16mm cutter diameter) and Figure (5-15C) shows the finishing operation for design model (using 5mm cutter diameter).



(A)



(B)



(C)

Figure (5-15): Using SURFCAM program to simulate the machining of compound-CRHS profile die. (A) Workpiece (cibatoool). (B) Roughing process. (C) Finishing process.

5.4.5 Estimate Error for the Proposed Algorithm:-

Deviation will be explained between the desired surface and the machining surface. Deviation on the surface machining increases at the side of the die because the cutter is not perpendicular on the (CC) point but cutting is inside the cutter as shown in figure (5-16). Figure (5-17) shows the error between the desired surface and the machining surface. The maximum error occurs at the sides of the manufactured part. The deviation is calculated for each line segment on the surface and each line segment is processed by a linear interpolator. Deviation is explained as follows:

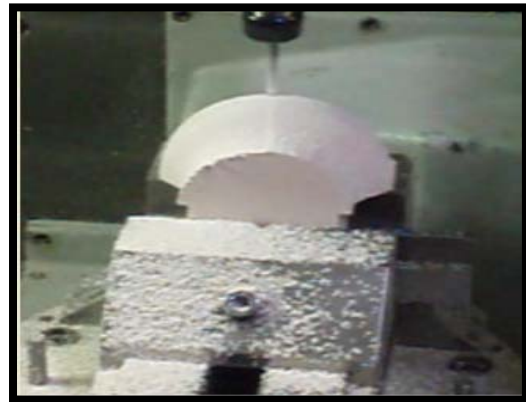
$$\text{Deviation} = Z_f - Z_a \dots\dots\dots (5-1)$$

Z_f =value for the desired surface in (z-deliration).

Z_a =value for machined surface in (z-deliration).



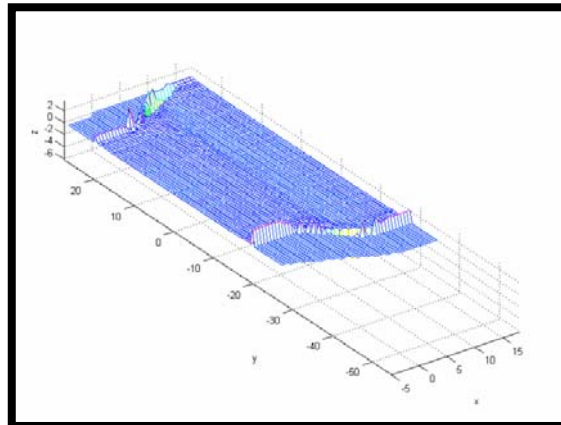
(A)



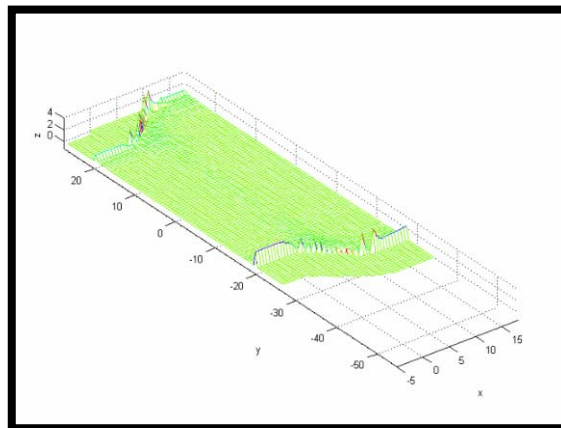
(B)

Figure (5 -16): Location of the cutter with respect to the workpiece.(A)

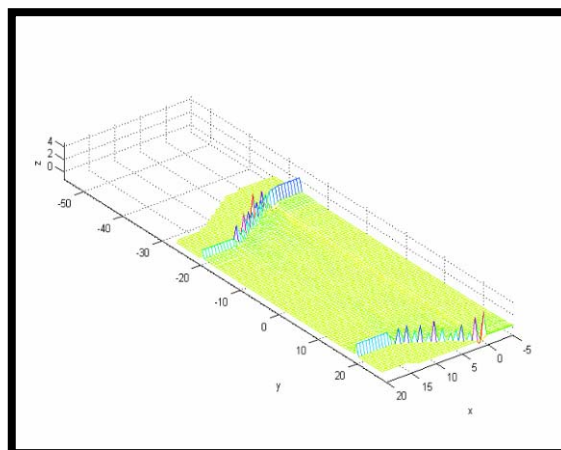
Cutter right side of the workpiese.(B) cutter perpendicular to the workpiese.



(A)



(B)



(C)

Figure (5-17): Represents error between different profile die for:
(A) Cubic Bezier profile die. (B) Interpolator Bezier profile die (C)
Compound-CRHS profile die.

5.4.6 Cutter Contact Points:

During machining, the cutting occurs at around the cutter contact (CC). The efficiency and quality of CNC machining can be improved significantly, if the machining parameter on the surface is kept constant. In our research, the better line segment between two cutter contact (CC) points will be determined. Figure (5-18) shows a number of segments with angles between segments profile die and the purpose of this figure is to visualize the number of segments with angles between segments for cubic Bezier profile die. The number of segments for Bezier profile dies equals (1295) segments.

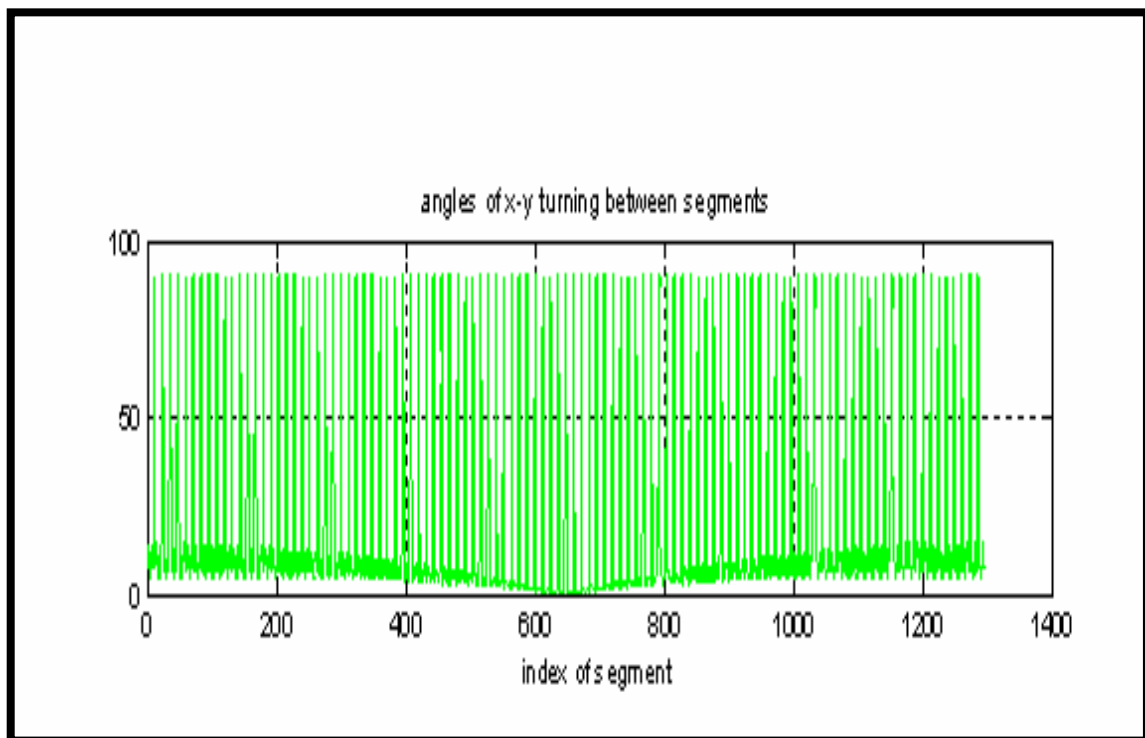
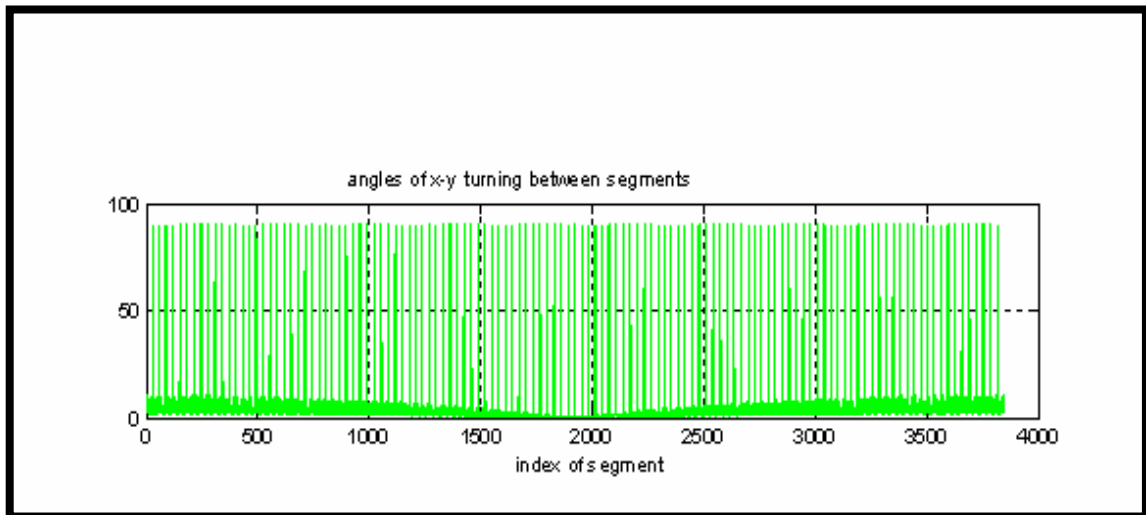
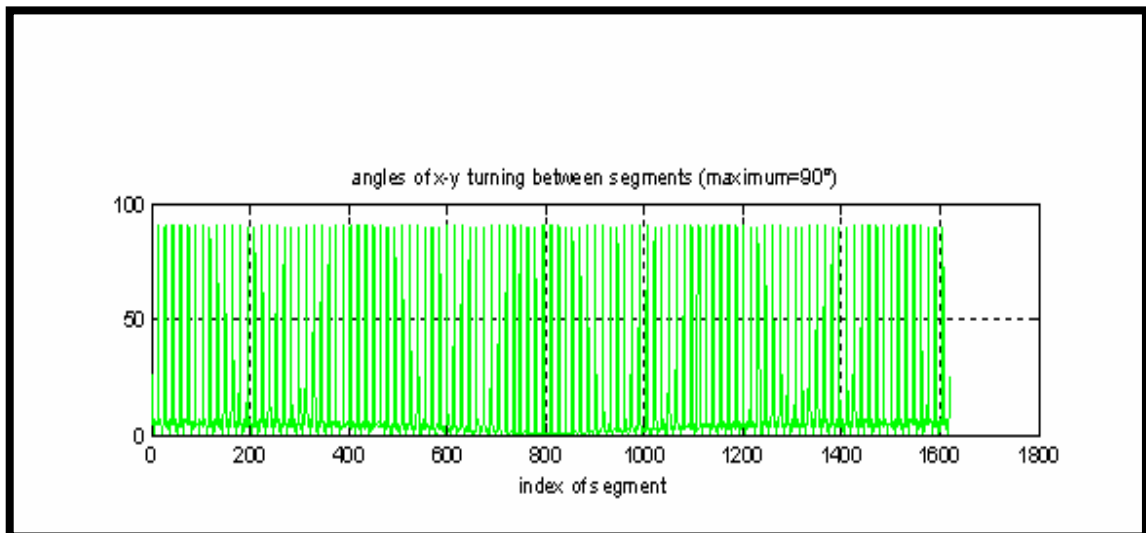


Figure (5-18): Represents line segment with angles for cubic Bezier profile die.

Figure (5-19) shows the number of segments with angles between segments for interpolator Bezier profile die and compound-CRHS, the numbers of segments for interpolator Bezier profile die equal (3843) segments and the numbers of segments for compound-CRHS profile die equal (1619) segments.



(A)



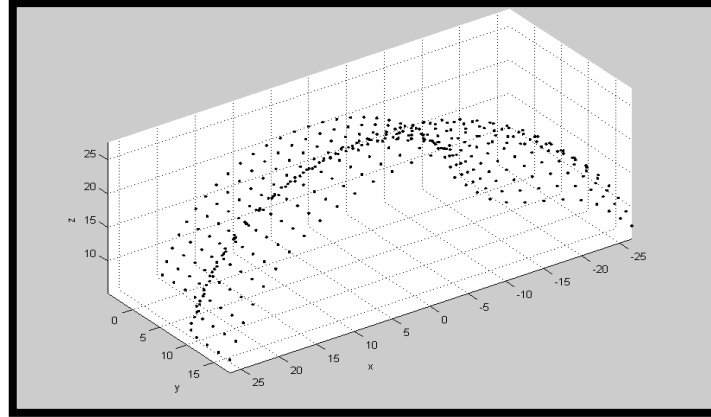
(B)

Figure (5-19): Represents line segment with angles for

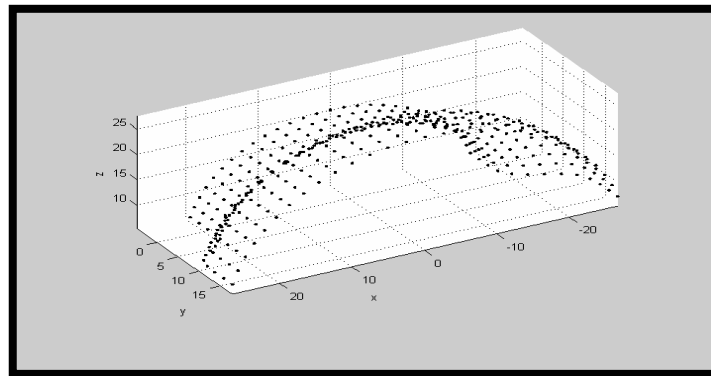
(A) Interpolator Bezier profile dies.

(B) Compound-CRHS profile dies.

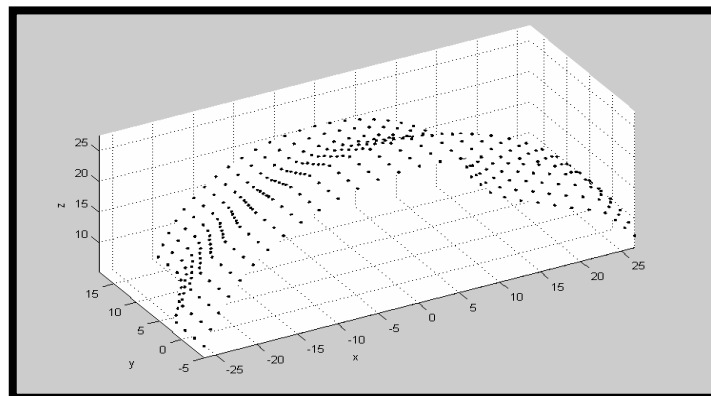
Figure (5-20) shows cutter contact (CC) points for cubic Bezier, interpolator Bezier and compound-CRHS profile die.



(A)



(B)



(C)

Figure (5-20): Represents profile die by (CC) points for (A) Cubic Bezier profile die. (B) Interpolator Bezier profile die. (C) Compound-CRHS profile die.

5.4.7 Extrusion Strain:

Strain and force required in each extrusion die will be calculated to determine better extrusion die (strain and force needed to extrude billet). For simulation of the extrusion dies process by using commercial ANSYS 9.0 software we used element SOLID 45, aluminum material properties, model generation within ANSYS (direct generation used in this research), meshing model (mapped), contact surface (target surface TARGET 170 and contact surface CONTA 174 used in this research), extrusion velocity (25mm/min) pilot point to control the boundary conditions and motion of the entire target surface. Extrusion die processes consist of four parts they are Rim, billet, container and die as shown in figure (5-21).

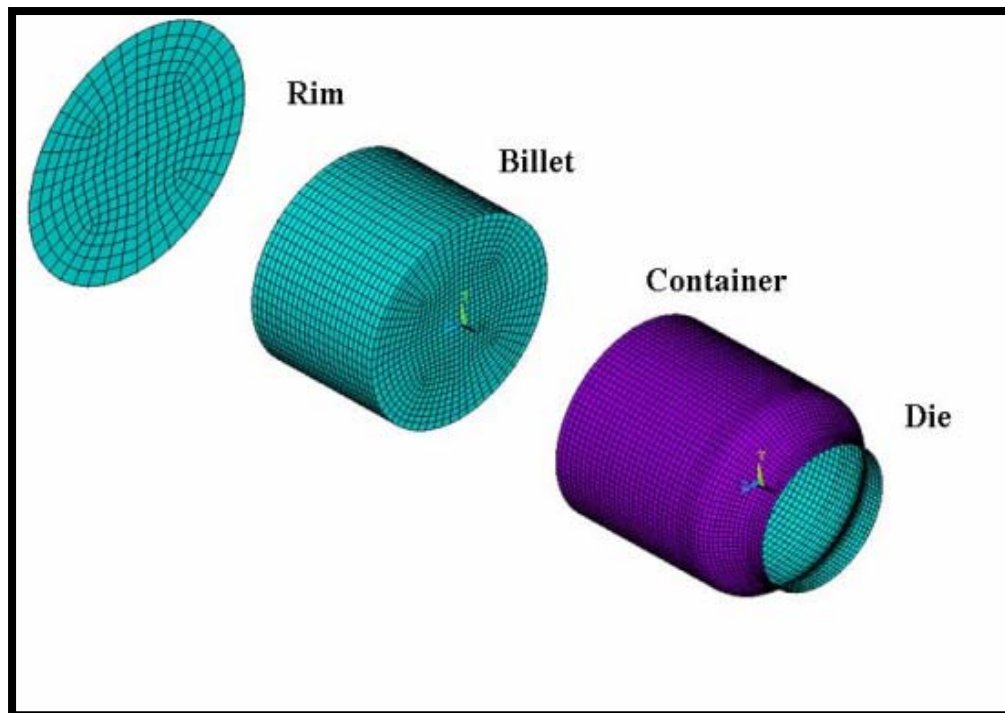


Figure (5-21): Finite element model of the billet material and extrusion die.

Figure (5-22) shows the steps of extrusion process during quarter die.

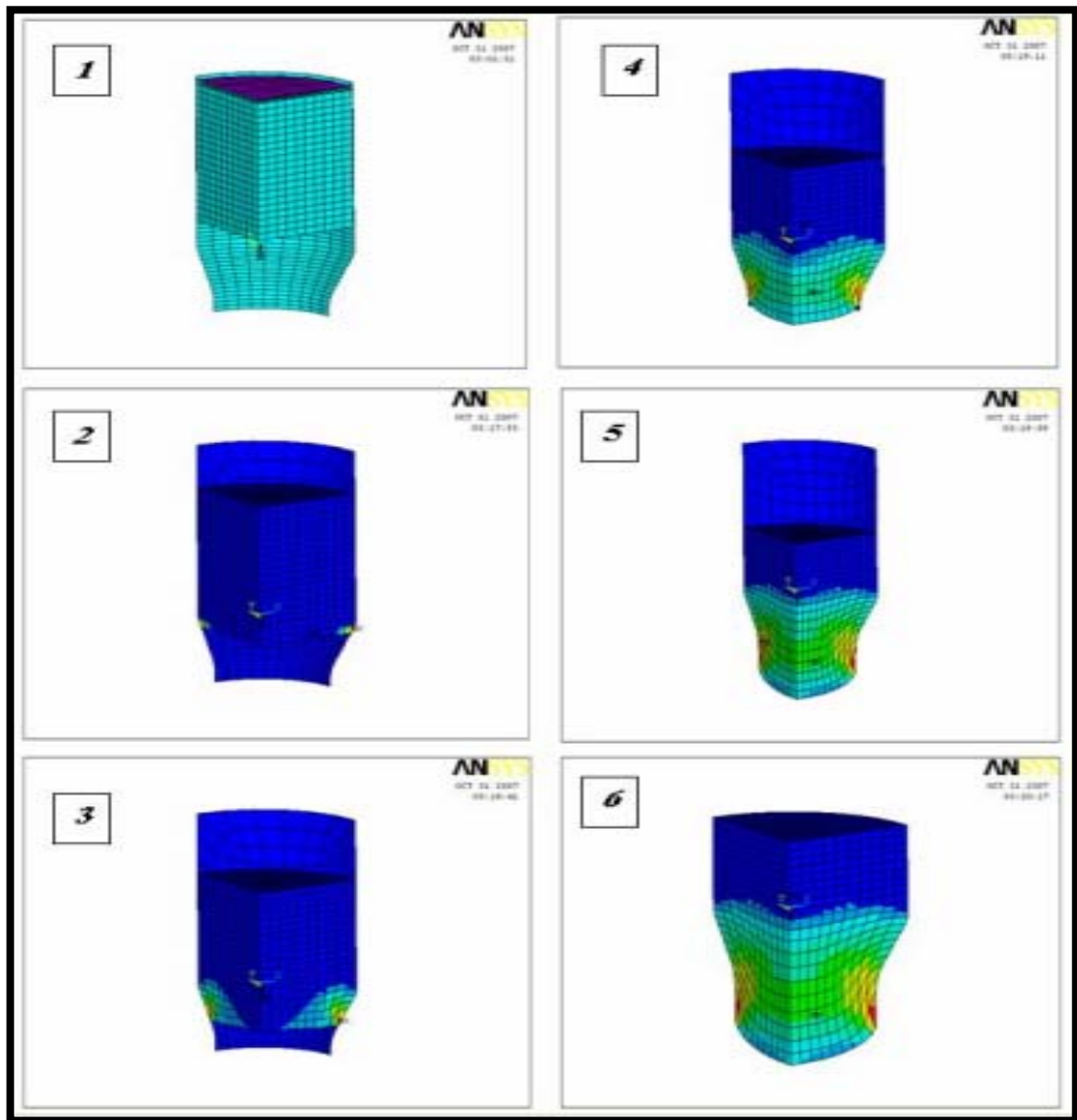
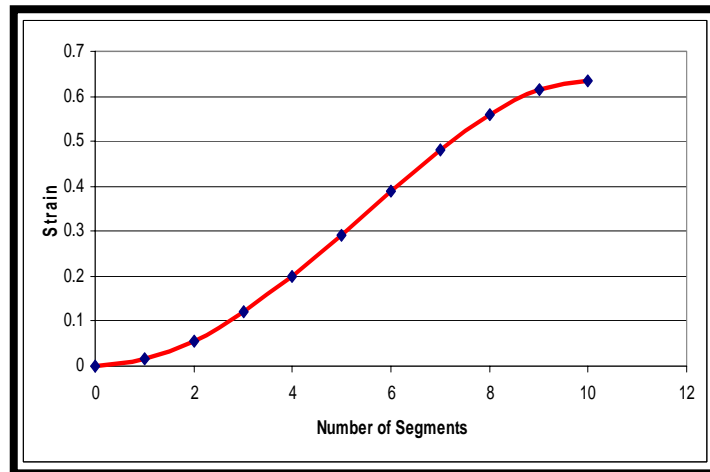
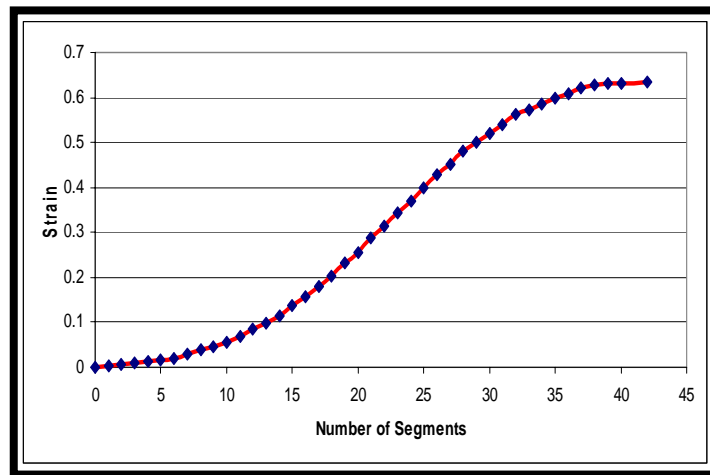


Figure (5-22): Sequences of extrusion process in FEM using ANSYS9.0.

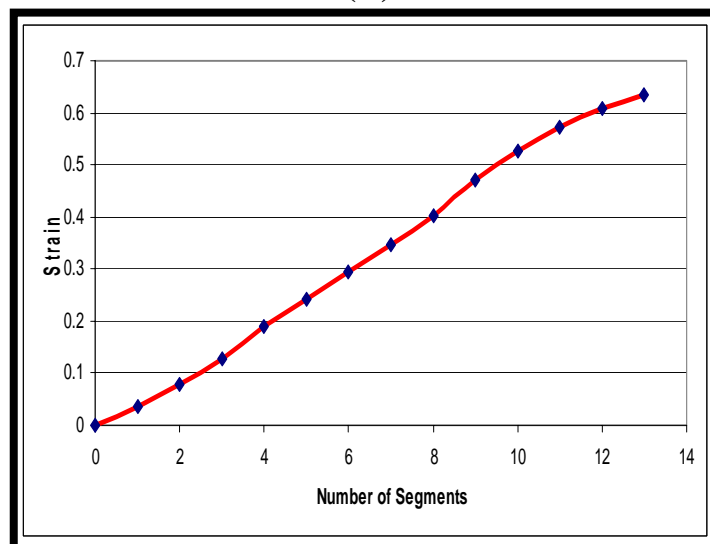
Figure (5-23) shows the strain with length of die (mm) for algorithm being proposed compared with cubic Bezier and compound-CRHS profile die.



(A)



(B)



(C)

Figure (5-23): Represents strain with length of die (mm) for (A) Cubic Bezier profile die. (B) Interpolator Bezier profile die. (C) Compound-CRHS profile die.

5.4.8 Extrusion Force:

The force required for extrusion depends on the flow stress of the billet container interface, the friction condition at the die material interface, and the other process variables, such as initial billet temperature and speed extrusion. The required extrusion force (F) is given by:

$$F = P \cdot A \dots\dots\dots (5-1)$$

where:

- **P**= extrusion pressure.
- **A**= area of the container bore.

Figure (5-24), (5-25) and (5-26) show the force (N) with displacement (mm) for proposed algorithm compared with cubic Bezier and compound-CRHS profile die.

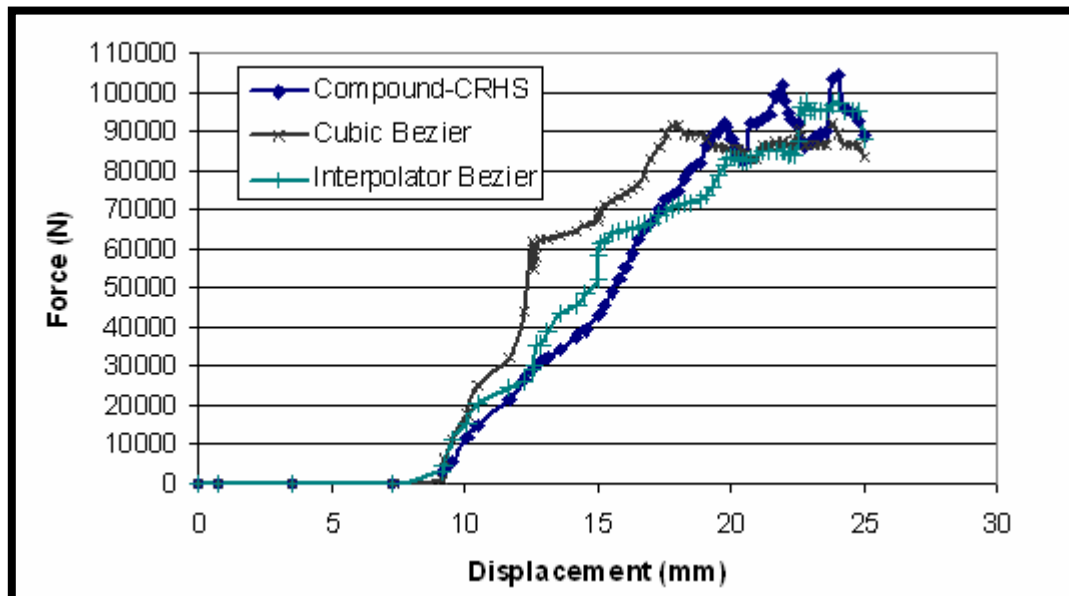


Figure (5-24): Represents force (N) with displacement (mm) for Cubic Bezier profile die, Interpolator Bezier profile die, Compound-CRHS profile die.

- Table (5-2) Shows summary of machining parameters for cubic Bezier, interpolator Bezier and compound-CRHS profile dies.

No.	Profile Die			
	Properties	Bezier Profile Die	Interpolator Bezier Profile Die	Compound-CRHS Profile Die
1	Tolerance in (u)and(w) direction	0.064 & 0.2 mm	0.01 & 0.01 mm	0.0833 & 0.2 mm
2	Height Scallop	0.06 mm	0.04 mm	0.06 mm
3	Minimum Radius of Curvature	1.948 mm	1.948 mm	1.949 mm
4	Radius of Cutter (Roughing)	8 mm	8 mm	8 mm
5	Radius of Cutter (Finishing)	2.5 mm	2.5 mm	2.5 mm
6	Length Line Segment in (w) Dir.	0.8 mm	0.7 mm	0.8 mm
7	Length Line Segment in (u) Dir.	variable	0.3 mm	1 mm
8	(CC) Points	1080	4216	1404
9	Number of Segment For Tool Path	1295	3843	1619
10	Number of Tool Path	108	124	108
11	Length of Tool Path	330 m	377.8 m	333.8 m
12	Size Store in Memory in (Bytes)	1229914 Bytes	148738 Bytes	131406 Bytes
13	Number of G-code	5515 Blocks	6569 Blocks	4442 Blocks
14	Numbers of Cutter Flutes	4	4	4
15	Total Time of Machining (min.)	197.471	226.074	199.745
16	Time Of finishing machining (min.)	59.301	74.440	65.8836
17	Max. Strain	0.636	0.636	0.636
18	Max. Force to Extrude Billet (N)	92191	100786	104617

5.4.9 Cutting Conditions for Interpolator Extrusion Die:

Our fabricating work is of experimental nature. The material that was used is (cibatoool) .The tool used in this work is tip ball mill cutter, tool material is (HSS) with Ø16mm roughing process and Ø5mm to finishing process applied to interpolator Bezier profile die, the machining was achieved on CNC machine (Okuma VH-40-HS dynamic 5-axis CNC machine, with specification of linear motor drives (10.000 m/min), motor spindle 7.5kW 8000 rpm), machine control OSP 7000 M. The machine is operated in (Finland) as shown in Figure (5-27), and the G-codes applied to the CNC machine were achieved by using SURFCAM. The G-code was designed by 3-axis FANUC 15 MB system, and the machining process was done without a lubricant.



Figure (5-25): 5-axis CNC machine Okuma VH-40-HS dynamic machine which belongs to company in the (Finland).

Table (5-3) shown Coordinate workpiece.

NO.	Coordinate of Workpiece	Magnitude
1	Min. X for Workpiece	0
2	Min. Y for Workpiece	0
3	Min. Z for Workpiece	0
4	Max. X for Workpiece	27.5
5	Max. Y for Workpiece	23
6	Max. Z for Workpiece	55

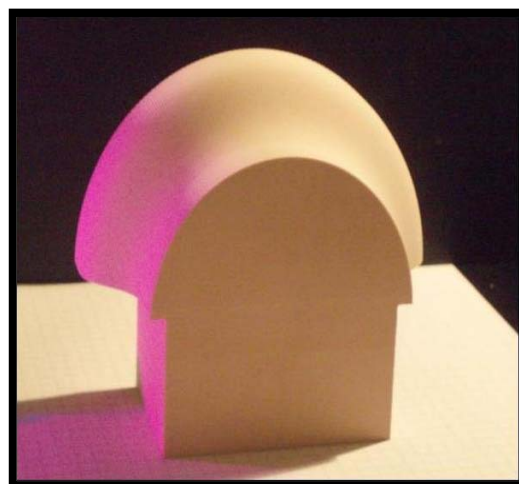


Figure (5-26): The machined models produced by CNC milling machine (3-axis). Sample designed by interpolator Bezier profile and machined with cutter diameter equal (roughing=16mm and finishing=5mm).

CHAPTER SIX

DISCUSSION, CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

6.1 Introduction:

This chapter bundles the results of the work carried out for the thesis. Part designed 3-D surfaces using MATLAB (7.4), then studying prepare tool path generation strategies based on the modified interpolation methods. Finally, simulate the machining process using SURFCAM.

6.2 General Discussion:

1- The Bezier technique a good and easy method used in this research after studying different parametric technique to represent curve and surface (Bezier, B-Spline (uniform and non-uniform), NURBS and Lagrange), proposed algorithms applied to the Bezier technique by using MATLAB (7.4) software. Figure (6-1) compares the mentioned methods to represent the extrusion profile die. The figure below shows that the Bezier technique is regular and better than the other techniques to represent the extrusion profile die since it is easily derived and applied.

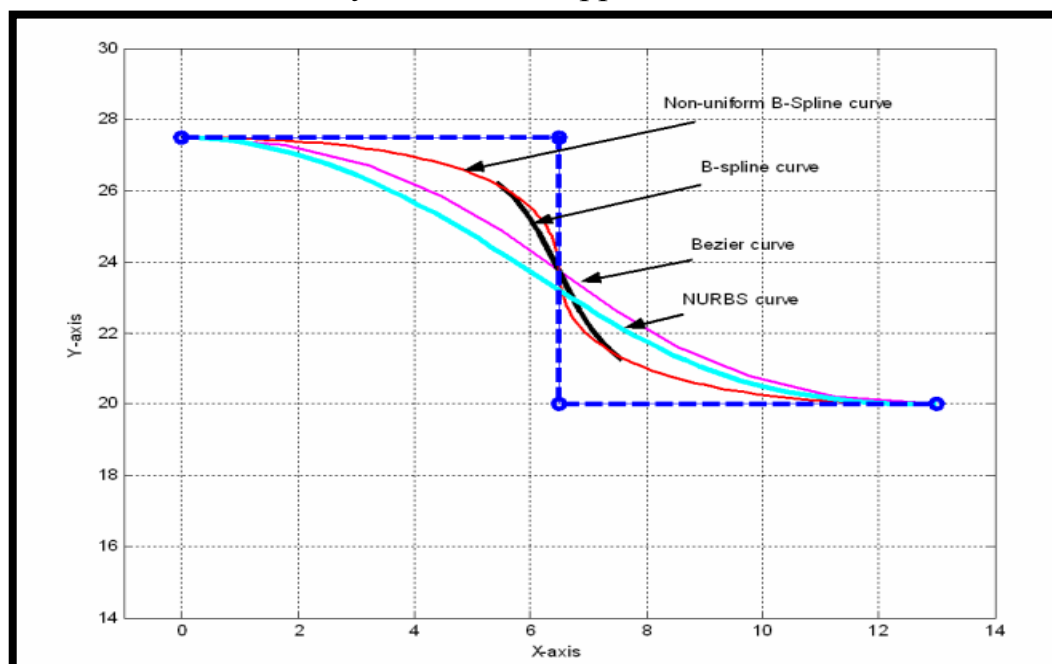


Figure (6-1): Representation of the profile die by using the difference curve technique.

2- We applying the proposed algorithms in production field by designing the extrusion die after discussing the equations of extrusion die (ACRHS, UCRHS, DCRHS and compound-CRHS). Figure (6-2) shows that the maximum difference between interpolator and compound-CRHS profile die is within (0.81mm). Consequently, this value is accepted from the point of view that this value is approaching the optimum value.

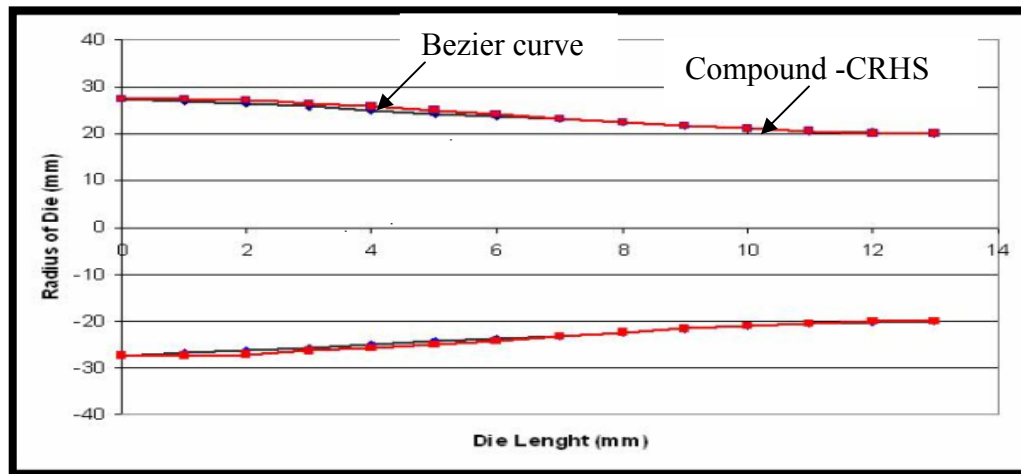
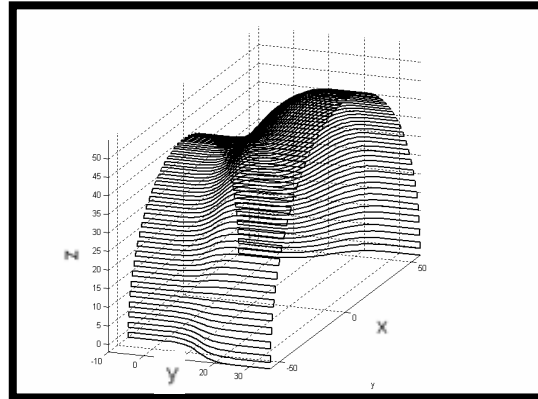


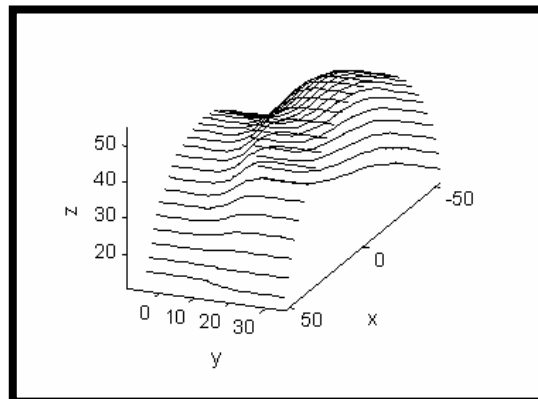
Figure (6-2): Representation of difference between compound-CRHS and Bezier profile die.

3- The surface part is approximated by a series of line segment. Therefore in our work we will calculate the length of line segment in (u) and (w) direction. The better length line segment is the distance between (CC) points during current tool path within the limited given tolerance. Interpolator Bezier profile die has a tolerance of (0.01mm) in (u) direction, it has a tolerance less than cubic Bezier profile die within (%84.375) and within (%87.99) for compound-CRHS profile die. Interpolator Bezier profile die has a tolerance of (0.01mm) in (w) direction, it has tolerance less than cubic Bezier and compound-CRHS profile die within (%95). Interpolator Bezier profile die has height scallop (0.04mm), it has height scallop less than cubic Bezier and compound-CRHS profile die within (%33).

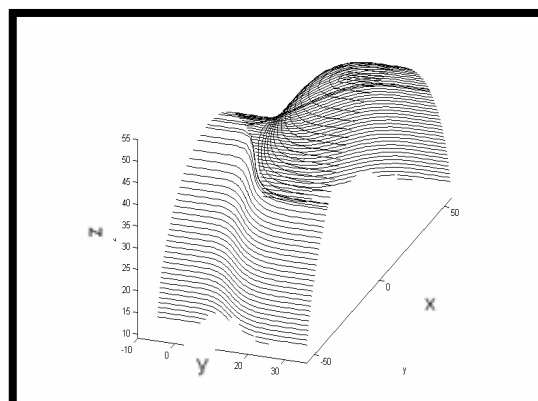
4- The tool path should be as smooth and steady as possible to guarantee the machining quality. Figure (6-3) shows different tool paths. Zig-zag tool path is better than isoparametric, and isoscallop tool path since it has less rapid motion and has simplicity in path planning.



(A)



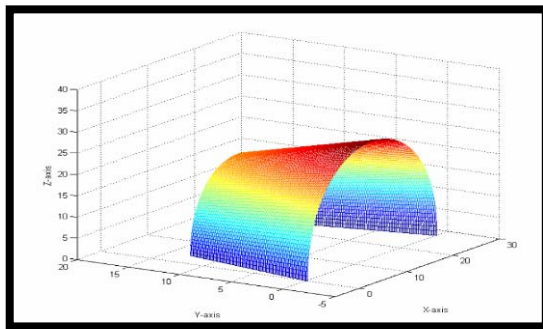
(B)



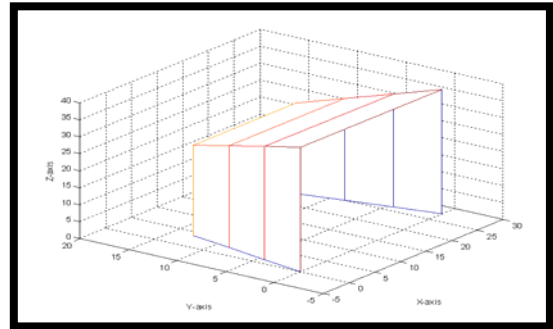
(C)

Figure (6-3): Tool path type representation. (A) Zig zag tool path. (B) Isoparametric tool path. (C) Isoscallop tool path.

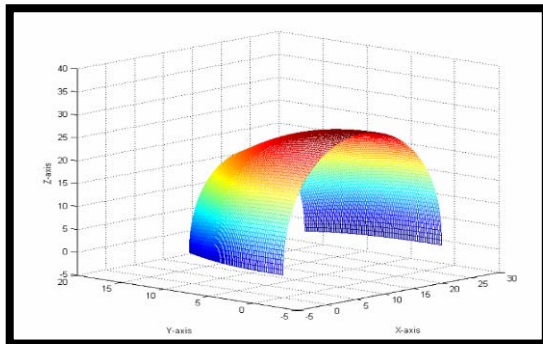
5- Figure (6-4) shows that we can use the control point to surface representation in order to get a variety of extrusion dies compared with order CRHS methods being mentioned.



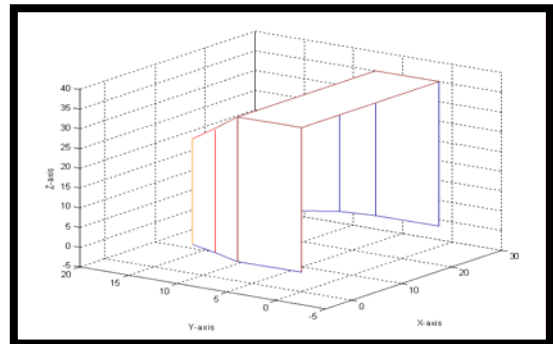
(A)



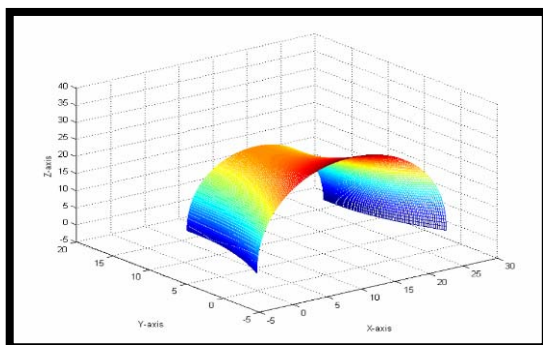
(B)



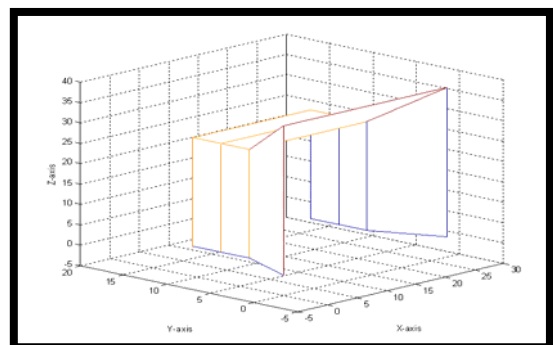
(C)



(D)



(E)



(F)

Figure (6-4): Representation of cubic Bezier profile dies comparable to CRHS profile die. (A) Bezier profile dies comparable to UCRHS profile die. (B) Control polygon. (C) Bezier profile dies comparable to ACRHS profile die. (D) Control polygon. (E) Bezier profile dies comparable to DCRHS profile die. (F) Control polygon.

6- During machining, the cutting occurs around the cutter contact (CC) which has effects on the surface quality; therefore we must determine the number of line segments with angles. The numbers of segments for interpolator Bezier profile die equal is (3813). As shown in the figure (6-5), it is better than cubic Bezier profile die within (%66) and it is good for compound-CRHS profile die within (%57).

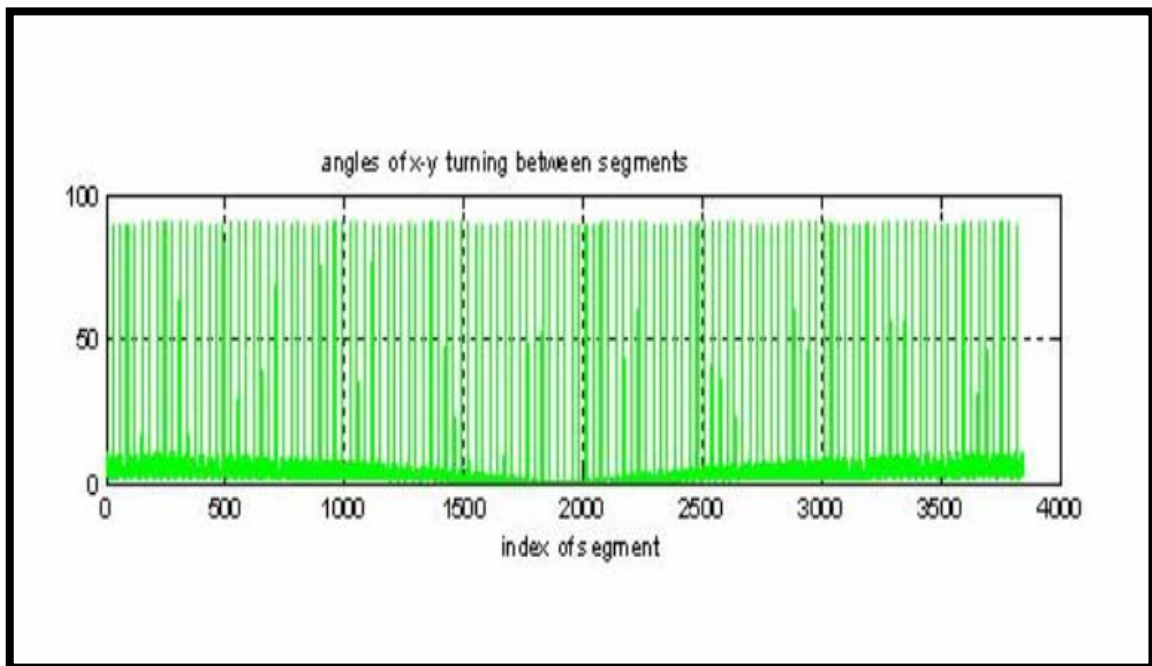


Figure (6-5): Represents line segment with angles.

7- We use the software SURFCAM for presentation, of machining simulation (workpiece, roughing process, and finishing process) before the goes into manufacturing. Figure (6-6) shows DXF-file for the integration process between CAD and CAM systems. This is achieved by converting the design point data sets from MATLAB 7.4 to SURFCAM software to allow tool path generation. Then, we generate and simulate the G-code functions from SURFCAM software to operate in the CNC milling machine. The algorithms proposed result in (6569) G-code blocks, which is more than cubic Bezier profile die within (%16) and within (%32.37) for compound-CRHS profile die.

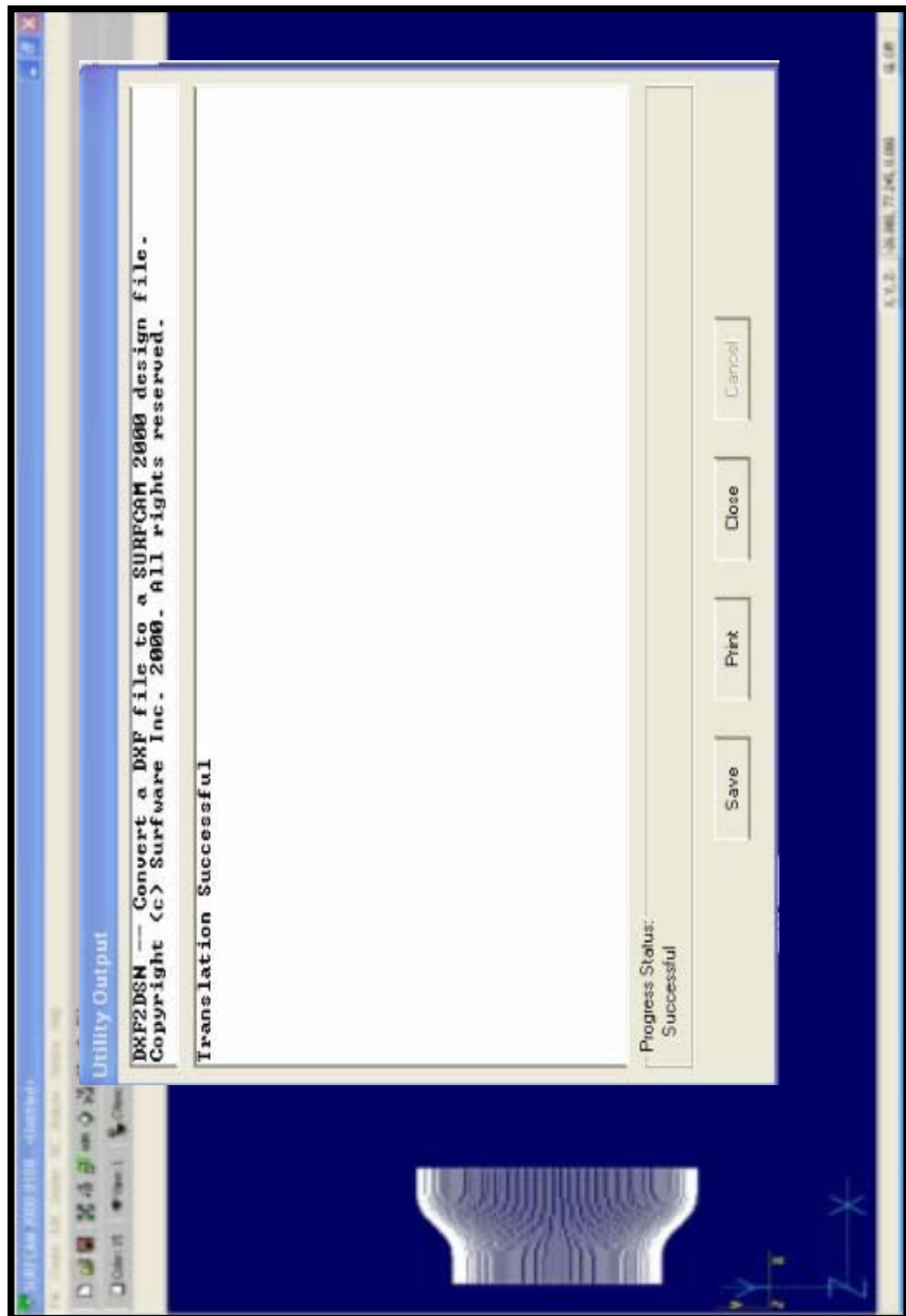
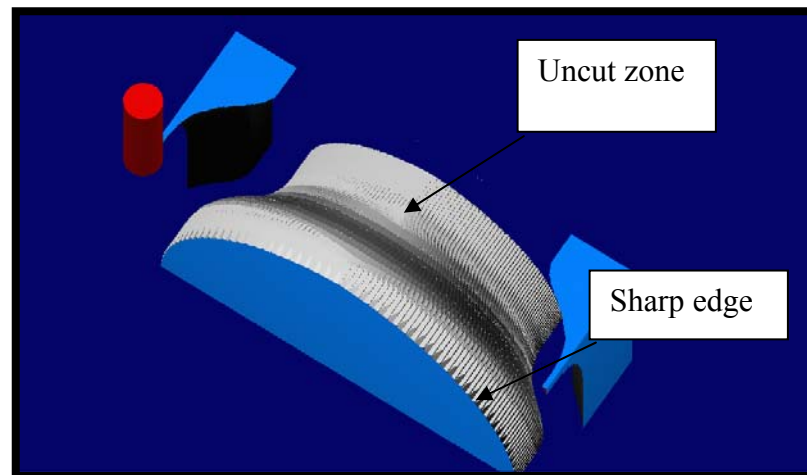


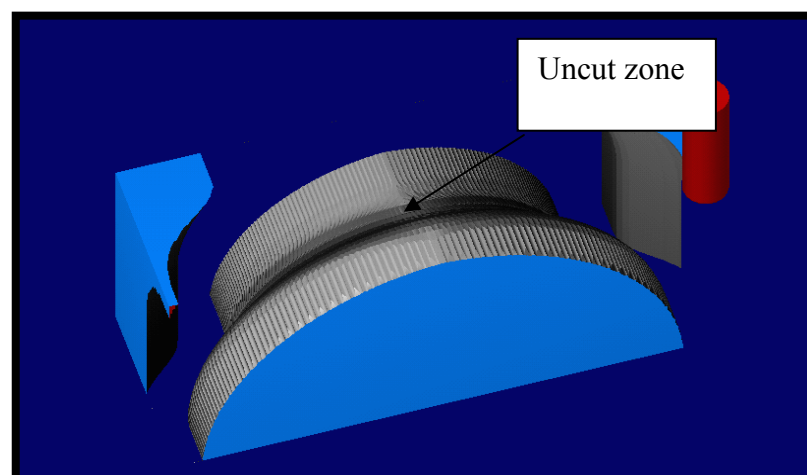
Figure (6-6): Successful translation between MATLAB and SURFCAM software.

8- The modified method of our research indicates developing program by using MATLAB 7.4 software for the determination of better cutter radius for roughing and finishing process. Cutter radius must be equal to or smaller than minimum radius of curvature for the surface extrusion die (cubic Bezier, interpolator Bezier, compound -CRHS).

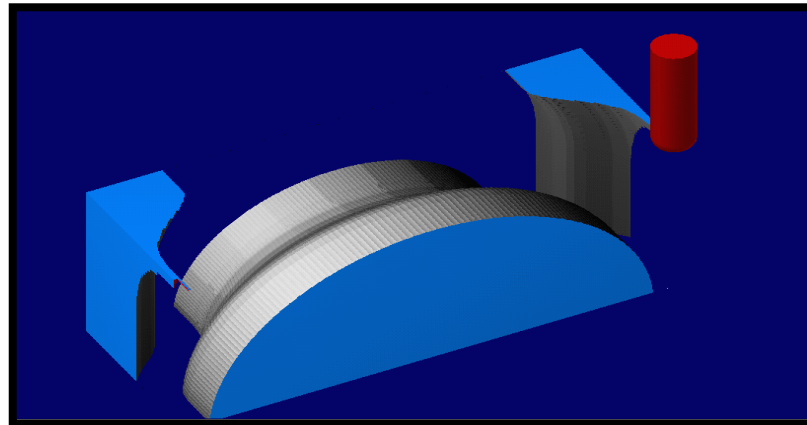
9- Figure (6-7) shows machining by using ball, flat and bullnose end-mill in order to select a better end mill tool, therefore after comparing machining we use a ball end-mill because flat and bullnose end-mill produces poor surface geometry.



(A)



(B)



(C)

Figure (6-7): Machining by using deference end-mill tool.(A) Flat end-mill tool. (B) Bullnose end-mill tool. (C) Ball end-mill tool.

10- Figure (6-8) shows the error (deviation) between the desired surface and the machining surface, which increases on the side of the die because the cutter isn't perpendicular on the (CC) points but cutting occurs inside the cutter. We can reduce the error to a minimal value by using a 5-axis machine because machining is perpendicular on the (CC) points. Interpolator Bezier has an error less than cubic Bezier profile die within (%1.5) and more than within (%45.65) for compound-CRHS profile die.

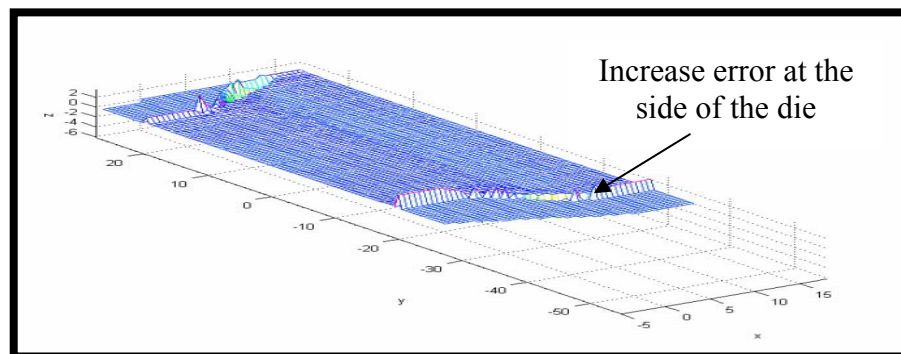


Figure (6-8): Represents error between desired surface and machining surface.

11- Studying aims to define the better extrusion die, therefore using ANSYS9.0 software to define strain and force required to get better extrusion die.

6.3 Conclusions:

The proposed algorithm for interpolator cubic Bezier surface developed and implemented successfully through the integration of mathematical modeling used for calculations near optimum length line segment for free form surface with given tolerance and height scallop.

The advantages of the proposed system are summarized as follows:

- 1- The Bezier technique is regular, easy to derive and by changing control points to represent different types of extrusion dies comparable to CRHS profile dies.
- 2- Interpolator Bezier profile die has a tolerance (0.01mm) in (u) direction, which is less than for the cubic Bezier profile die within (%84.375) and within (87.99) for the compound-CRHS profile die.
- 3- Interpolator Bezier profile die has a tolerance (0.01mm) in (w) direction, it has a tolerance less than cubic Bezier and compound-CRHS profile die within (%95).
- 4- Interpolator Bezier profile die has height scallop (0.04mm), it has less height scallop than cubic Bezier and compound-CRHS profile die within (%33).
- 5- The selection of better cutter radius depends on the minimum radius of curvature (not to exceed the minimum radius of curvature).
- 6- Zig-zag tool path generation is the better tool path compared to isoparametric and isoscallop tool paths.

7- We employ DXF-files to convert cubic Bezier, interpolator Bezier and compound-CRHS profile die from MATLAB (as CAD tool) to SYRFCAM (as CAM tool) and to obtain the G-code functions and simulate the machining process. The algorithms proposed generate (6569) blocks of G-code, which is has more than for cubic Bezier profile die within (%16) and within (%32.37) for compound-CRHS profile die.

8- A ball end-mill is a better tool in machining profile die compared to a flat and a bullnose end-mill.

9- Time secondary operations (grinding and polishing) are reduced through determining the appropriate line segment.

10- We can reduce the error during machining by using a 5-axis machine.

11- Interpolator Bezier profile die gives better surface quality because it is better than cubic Bezier profile die within (%74) and than compound-CRHS within (%66).

12- Force required to extrude the metal (aluminum) during interpolator Bezier profile die is equal to (100786 N), it has more than cubic Bezier profile die within (%8.5) and less than compound-CRHS within (%3.8).

6.4 Suggestions for Future Works:

The more research works could be conducted future continuation and expansion in this filed:

- 1- Studying the surface scallop generating mechanism in the ball end milling and flat end milling.
- 2- Studying the difference between machining of sculptured surfaces using multi axis milling CNC machines (like 4 axes, 5 axes and 6 axes).
- 3- Concentrating should be placed on the computational methods (like Genetic, Neural methods) and the interference with the CAD/CAM systems in the process of tool path generation.

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APPENDICES

APPENDIX (A)

Appendix A

A.1 Equation to Represent B-splines:

The basis function to ($k=3$) and given control points ($n=4$) we compute $N_{i,l}(u) = (N_{i,3}, N_{i,1+3}, N_{i,2+3})$ then and select value boundary (i) from ($K \leq i \leq n$) to find knot vector (t_i) from:

$$N_{i,k} = \frac{(u - t_i)N_{i,k-1}(u)}{t_{i+k-1} - t_i} + \frac{(t_{i+k} - u)N_{i+1,k-1}}{t_{i+k} - t_{i+1}} \dots\dots\dots(A-1)$$

Where

K = Equation class

$K - 1$ = Equation degrees

t_i = Knot values

T = Knot vector

$$t_i = i - (k - 1)$$

$$T = [i-2, i-1, i, i+1, i+2, i+3, i+4]$$

-When $K=1$

$$\left. \begin{array}{ll} N_{i,1}(u) = 1 & \text{for } i-2 \leq u \leq i-1 \\ = 0 & \text{otherwise} \\ \\ N_{i+2,1}(u) = 1 & \text{for } i \leq u \leq i+1 \\ = 0 & \text{otherwise} \\ \\ N_{i+3,1}(u) = 1 & \text{for } i+1 \leq u \leq i+2 \\ = 0 & \text{otherwise} \\ \\ N_{i+4,1}(u) = 1 & \text{for } i+2 \leq u \leq i+3 \\ = 0 & \text{otherwise} \\ \\ N_{i+5,1}(u) = 1 & \text{for } i+3 \leq u \leq i+4 \\ = 0 & \text{otherwise} \end{array} \right\} (A-2)$$

Appendix A

When K=2

$$\left. \begin{aligned} N_{i,2}(u) &= (u - i + 2)N_{i,1}(u) + (i - u)N_{i+1,1}(u) \\ N_{i+1,2}(u) &= (u - i + 1)N_{i+1,1}(u) + (i + 1 - u)N_{i+2,1}(u) \\ N_{i+2,2}(u) &= (u - i)N_{i+2,1}(u) + (i + 2 - u)N_{i+3,1}(u) \\ N_{i+3,2}(u) &= (u - i - 1)N_{i+3,1}(u) + (i + 3 - u)N_{i+4,1}(u) \end{aligned} \right\} \dots \text{(A-3)}$$

When K=3:

$$\left. \begin{aligned} N_{i,3}(u) &= \frac{1}{2}[(u - i + 2)^2 N_{i,1}(u) + (u - i + 2)(i - u)N_{i+1,1}(u) \\ &\quad + (i + 1 - u)(u - i + 1)N_{i+1,1}(u) + (i + 1 + u)^2 N_{i+2,1}(u)] \\ N_{i+1,3}(u) &= \frac{1}{2}[(u - i + 1)^2 N_{i+1,1}(u) + (u - i + 1)(i + 1 - u)N_{i+2,1}(u) \\ &\quad + (i + 2 - u)(u - i)N_{i+2,1}(u) + (i + 2 + u)^2 N_{i+3,1}(u)] \\ N_{i+2,3}(u) &= \frac{1}{2}[(u - i)^2 N_{i+2,1}(u) + (u - i)(i + 2 - u)N_{i+3,1}(u) \\ &\quad + (i + 3 - u)(u - i - 1)N_{i+3,1}(u) + (i + 3 + u)^2 N_{i+4,1}(u)] \end{aligned} \right\} \text{(A-4)}$$

From equations (A-3) we can find p(u) for any curves during ($i \leq u \leq i+1$) depending on ($N_{i,1}(u)$) during denote equation we will find ($N_{i+2,1}=1$) only.

$$\begin{aligned} -P(u) &= \frac{1}{2}(i + 1 - u)^2 P_i + \frac{1}{2}[(u - i + 1)(i + 1 - u) + (i + 2 - u)(u - i)]P_{i+1} + \frac{1}{2}(u - i)^2 P_{i+2} \\ -P(u) &= \frac{1}{2}[(1 - u)^2 P_i + (-2u^2 + 2u + 1)(i + 1 - u)P_{i+1} + u^2 P_{i+2} + 2] \dots \dots \dots \text{(A-5)} \end{aligned}$$

$$-P(u) = \frac{1}{2} \begin{bmatrix} u^2 & u & 1 \end{bmatrix} \begin{bmatrix} 1 & -2 & 1 \\ -2 & 2 & 0 \\ 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} P_{i-1} \\ P_i \\ P_{i+1} \end{bmatrix} \dots \dots \dots \text{(A-6)}$$

Appendix A

-With K=4 (third degree):

$$P_i(u) \frac{1}{6} \begin{bmatrix} u^3 & u^2 & u & 1 \end{bmatrix} \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix} \begin{bmatrix} P_{i-1} \\ P_i \\ P_{i+1} \\ P_{i+2} \end{bmatrix} \dots\dots\dots (A-7)$$

$$\therefore P_i(u) = V Mbs \begin{bmatrix} P_{i-1} \\ P_i \\ P_{i+1} \\ P_{i+2} \end{bmatrix} \quad for \quad i \in [1 : n-2]$$

-With K=5 [fourth degree]:

$$P_i(u) \frac{1}{24} \begin{bmatrix} u^4 & u^3 & u^2 & u & 1 \end{bmatrix} \begin{bmatrix} 1 & -4 & 5 & 0 & 0 \\ -4 & 12 & -8 & 0 & 0 \\ 6 & -6 & 9 & 0 & 0 \\ -4 & -12 & -60 & 1 & 0 \\ 1 & 1 & 75 & 0 & 1 \end{bmatrix} \dots\dots\dots (A-8)$$

Appendix A

A.2 Equation to Represent Non-uniform B-Splines:

To find the equation of a non-uniform cubic B-spline curve by the four control points when $k=3$ and $n=3(0, 1, 2, 3)$

- $T=n+k+1=6$(A-9)

$$T = [0 \ 0 \ 0 \ 1 \ 1 \ 1]$$

- When $K=1$, $i+k \leq 6$

$$\left. \begin{array}{ll} \bullet N_{0,1} = 1 & \text{for } u = 0 \\ & = 0 \\ \bullet N_{1,1} = 0 & \text{for } u = 0 \\ & = 1 \\ \bullet N_{2,1} = 1 & \text{for } u = 0 \leq u \leq 0.5 \\ & = 0 \end{array} \quad \begin{array}{ll} \bullet N_{3,1} = 1 & \text{for } u = 0.5 \leq u \leq 1 \\ & = 0 \\ \bullet N_{4,1} = 1 & \text{for } u = 1 \\ & = 0 \\ \bullet N_{5,1} = 1 & \text{for } u = 1 \\ & = 0 \end{array} \right\} \dots (A-10)$$

- Where $K=2$, $i+k \leq 6$

$$\left. \begin{array}{l} \bullet N_{0,2} = (u - u_0) \frac{N_{0,1}}{u_1 - u_0} + (u_2 - u) \frac{N_{1,1}}{u_2 - u_1} = 0 \\ \bullet N_{1,2} = (u - u_1) \frac{N_{1,1}}{u_2 - u_1} + (u_3 - u) \frac{N_{2,1}}{u_3 - u_2} = (1 - 2u)N_{2,1} \\ \bullet N_{2,2} = (u - u_2) \frac{N_{2,1}}{u_3 - u_2} + (u_4 - u) \frac{N_{3,1}}{u_4 - u_3} = (2u)N_{2,1} + (2 - 2u)N_{3,1} \\ \bullet N_{3,2} = (u - u_3) \frac{N_{3,1}}{u_4 - u_3} + (u_5 - u) \frac{N_{4,1}}{u_5 - u_4} = (2u - 1)N_{3,1} \\ \bullet N_{4,2} = (u - u_4) \frac{N_{4,1}}{u_5 - u_4} + (u_6 - u) \frac{N_{5,1}}{u_6 - u_5} = 0 \end{array} \right\} \dots (A-11)$$

Appendix A

Where $K=3$, $i+k \leq 6$

$$\left. \begin{aligned} \bullet N_{0,3} &= (u - u_0) \frac{N_{0,2}}{u_2 - u_0} + (u_3 - u) \frac{N_{1,2}}{u_3 - u_1} = (1 - 2u)N_{1,2} \\ \bullet N_{1,3} &= (u - u_1) \frac{N_{1,2}}{u_3 - u_1} + (u_4 - u) \frac{N_{2,2}}{u_4 - u_2} = (2u)N_{1,2} + (1 - u)N_{2,2} \\ \bullet N_{2,3} &= (u - u_2) \frac{N_{2,2}}{u_4 - u_2} + (u_5 - u) \frac{N_{3,2}}{u_5 - u_3} = (u)N_{2,2} + (2 - 2u)N_{3,2} \\ \bullet N_{3,3} &= (u - u_3) \frac{N_{3,2}}{u_5 - u_3} + (u_6 - u) \frac{N_{4,2}}{u_6 - u_4} = (2u - 1)N_{3,2} \end{aligned} \right\} \dots\dots\dots (A-12)$$

$$P_1(u) = (1 - 2u)^2 p_0 + (4u - 6u^2) p_1 + (2u)^2 p_2 \dots\dots\dots (A-13)$$

$$P_2(u) = (2u^2 - 4u + 2) p_1 + (-6u^2 + 8u - 2) p_2 + (4u^2 - 4u + 1) p_3 \dots\dots\dots (A-14)$$

A.3 Case Study to Represent Lagrange Interpolation Curve:-

Compute the curve equation for Lagrange interpolation for through four control points. $P_1(0,-5)$ $P_2(1,-6)$ $P_3(2,-1)$ $P_4(3,16)$.

An:-

$$L_i(x) = \sum_{\substack{j=1 \\ j \neq i}}^n \frac{x - x_j}{x_i - x_j}$$

$$F(x) = L_1 * Y_1 + L_2 * Y_2 + L_3 * Y_3$$

$$F(x) = X^3 - 2X + 5$$

We can represent the curve equation using MATLAB software Figure (3-18A).

Appendix A

A.4 Case Study to Represent Lagrange Interpolation Surface:

We compute the surface equation for Lagrange interpolation through the initial control points of a desired surface arc $p_1(1,2,7)$, $p_2(1,3,10)$, $p_3(1,4,13)$, $p_4(3,2,15)$, $p_5(3,3,18)$, $p_6(3,4,21)$, $p_7(5,2,31)$, $p_8(5,3,34)$, $p_9(5,4,37)$

An:-

$$p_{11}(1,2,7) \quad p_{12}(1,3,10) \quad p_{13}(1,4,13)$$

$$p_{21}(3,2,15) \quad p_{22}(3,3,18) \quad p_{23}(3,4,21)$$

$$p_{31}(5,2,31) \quad p_{32}(5,3,34) \quad p_{33}(5,4,37)$$

$$\begin{aligned} \bullet z = f(x, y) &= \sum_{j=1}^n \sum_{i=1}^m L_{ij}(y) * L_i(x) * f(x, y) \\ &= Lx_1[Ly_1, z(x_1, y_1) + Ly_2, z(x_1, y_2) + Ly_3, z(x_2, y_3)] \\ &= Lx_3[Ly_1, z(x_3, y_1) + Ly_2, z(x_3, y_2) + Ly_3, z(x_3, y_3)] \end{aligned}$$

• We determine the Lagrange coefficient in both (x) and (y) direction:-

$$L_i(x) = \sum_{\substack{j=1 \\ j \neq i}}^n \frac{x - x_j}{x_i - x_j}$$

$$L_k(y) = \sum_{\substack{j=1 \\ j \neq k}}^m \frac{y - y_j}{y_k - y_j}$$

$$\begin{aligned} Z=f(x,y)= & (0.35*y^2+0.125x^2)+(-3xy-x)+(5.625y+1.875)+(-0.75y^2- \\ & 2.25x^2)+(4.5y+13.5x)+(-3.75y-11.25)+(0.375x^2y+3.125x^2)+(-1.5xy- \\ & 12.5x)+(1.125y+9.375) \end{aligned}$$

Appendix A

The mathematical representation of the desired surface is $Z=f(\mathbf{x},\mathbf{y})=\mathbf{x}^2+3\mathbf{y}$. Then we can represent the surface equation by using MATLAB software Figure (3-18B).

APPENDIX (B)

Appendix B

- Table (B-1) represent data ACRHS profile die:

X(mm)	Zn	Rn
0	1	27.5
1	1.0132	27.320
2	1.0292	27.1061
3	1.0488	26.8514
4	1.0729	26.5489
5	1.1025	26.1903
6	1.1390	25.767
7	1.1845	25.267
8	1.2415	24.6803
9	1.3135	23.9942
10	1.4055	23.1960
11	1.5244	22.2731
12	1.6804	21.2141
13	1.8888	20

- Table (B-2) represent data DCRHS profile die:

X(mm)	Zn	Rn
0	1	27.5
1	1.1443	25.7076
2	1.2745	24.3582
3	1.3894	23.3299
4	1.4887	22.5386
5	1.561	21.9249
6	1.6442	21.4461
7	1.7033	21.0706
8	1.7521	20.775
9	1.7921	20.541
10	1.8270	20.3450
11	1.8514	20.2102
12	1.8730	20.093
13	1.8904	20

Appendix B

- **Table (B-3) Represent data UCRHS profile die:**

X(mm)	Zn	Rn
0	1	27.5
1	1.0502	26.8345
2	1.1029	26.1854
3	1.15822	25.5519
4	1.1643	24.9938
5	1.2774	24.3305
6	1.3416	23.7419
7	1.4089	23.1682
8	1.4797	22.6070
9	1.5539	22.0601
10	1.6319	21.5264
11	1.7139	21.0056
12	1.7999	20.4974
13	1.8903	20

- **Table (B-4) Shows data Compound-CRHS profile die:**

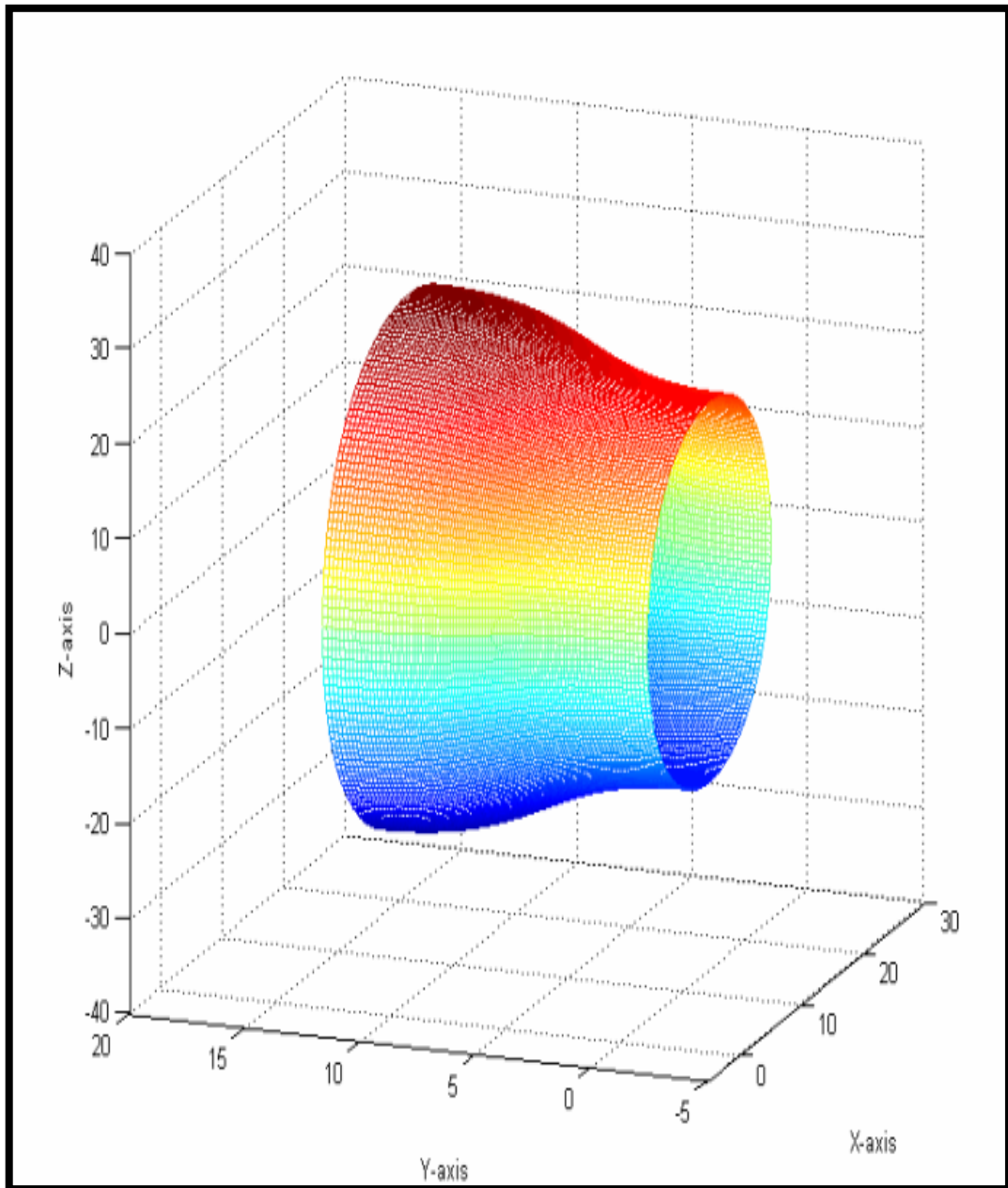
X(mm)	Zn	Rn
0	1	27.5
1	1.0361	27.016
2	1.0811	26.4478
3	1.1377	25.7811
4	1.2096	25
5	1.2345	24.3502
6	1.1109	23.7191
7	1.1709	23.1035
8	1.2341	22.5
9	1.0725	21.7253
10	1.1342	21.1263
11	1.1862	20.658
12	1.2295	20.291
13	1.2652	20

APPENDIX (C)

Appendix C

- Table (C-1) shows machining parameters for Bezier surface (By using approximation length segment).

1	<i>Tolerance in (u)and(w) direction</i>	<i>0.064&0.02(mm)</i>
2	Height Scallop	0.06(mm)
3	Minimum Radius of Curvature	1.948(mm)
4	Radius of Cutter(Roughing)	8(mm)
5	Radius of Cutter(finishing)	2.5(mm)
6	Side step	0.8(mm)
7	Forward step	variable
8	(CC) Points	1080
9	Number of Segment For Tool Path	1295
10	Number of Tool Path	108
11	Length Of Tool Path	330 (m)
12	Number of G-code	5515 Blocks
13	Store Size in Memory in (Bytes)	1229914 Bytes



**Figure (C-1): Represent extrusion die design by using interpolator
Bezier profile die.**

Appendix C

- Table (C-2) shows summary of machining parameters for interpolate Bezier surface (By using better length segment).

1	<i>Tolerance in (u)and(w) direction</i>	<i>0.01&0.01(mm)</i>
2	Height Scallop	0.04(mm)
3	Minimum Radius of Curvature	1.948(mm)
4	Radius of Cutter(Roughing)	8(mm)
5	Radius of Cutter(finishing)	2.5(mm)
6	Side step	0.7(mm)
7	Forward step	0.3(mm)
8	(CC) Points	4216
9	Number of Segment For Tool Path	3843
10	Number of Tool Path	124
11	Length Of Tool Path	377.8 (m)
12	Number of G-code function	6569 Blocks
13	Size Store in Memory in (Bytes)	148738 Bytes

Appendix C

- Table (C-3) shows a summary of machining parameters for Compound-CRHS Profile dies.

1	<i>Tolerance in (u)and(w) direction</i>	<i>0.0833&0.02(mm)</i>
2	Height Scallop	0.06(mm)
3	Minimum Radius of Curvature	1.949(mm)
4	Radius of Cutter(Roughing)	8(mm)
5	Radius of Cutter(finishing)	2.5(mm)
6	Side step	0.8(mm)
7	Forward step	1(mm)
8	(CC) Points	1404
9	Number of Segment For Tool Path	1619
10	Number of tool Path	108
11	Length Of Tool Path	333.8 (m)
12	Size Store in Memory in (Bytes)	131406
13	Number of G-code	4442 Blocks

APPENDIX (D)

FOR CUBIC BEZIER PROFILE DIE

Appendix D

Curvatures for Cubic Bezier Profile Die:

[illegible]

Appendix D

Radiuses of Curvatures for Cubic Bezier Profile Die:

[illegible]

Appendix D

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N0001 00	N0060 X23.
N0002 (Surfware, Inc.)	N0061 X21.23 Y15.9118
N0003 (5703 Corsa Ave)	N0062 X19.776 Y16.4778
N0004 (Westlake, Ca. 91311)	N0063 X18.554 Y17.3121
N0005 G17 G40 G80 G90	N0064 X17.488 Y18.325
N0006 T5 M6	N0065 X15.512 Y20.5297
N0007 M3 S4775	N0066 X14.446 Y21.5427
N0008 G00 G54 X28. Y15.5	N0067 X13.224 Y22.3769
N0009 G43 Z50. H5	N0068 X11.768 Y22.943
N0010 M8	N0069 X10. Y23.1515
N0011 G00 Z27.4968	N0070 X5.
N0012 G01 Z24.9968 F835.6	N0071 Y23.2366
N0013 X23. F1671.1	N0072 X10.
N0014 X21.23 Y15.71	N0073 X11.768 Y23.0289
N0015 X19.776 Y16.28	N0074 X13.224 Y22.465
N0016 X18.554 Y17.12	N0075 X14.446 Y21.6341
N0017 X17.488 Y18.14	N0076 X15.512 Y20.625
N0018 X15.512 Y20.36	N0077 X17.488 Y18.4289
N0019 X14.446 Y21.38	N0078 X18.554 Y17.4199
N0020 X13.224 Y22.22	N0079 X19.776 Y16.5889
N0021 X11.768 Y22.79	N0080 X21.23 Y16.0251
N0022 X10. Y23.	N0081 X23. Y15.8173
N0023 X5. Y23.0095	N0082 X28.
N0024 X10.	N0083 Y15.9566
N0025 X11.768 Y22.7996	N0084 X23.
N0026 X13.224 Y22.2298	N0085 X21.23 Y16.1633
N0027 X14.446 Y21.3902	N0086 X19.776 Y16.7245
N0028 X15.512 Y20.3706	N0087 X18.554 Y17.5515
N0029 X17.488 Y18.1516	N0088 X17.488 Y18.5557
N0030 X18.554 Y17.132	N0089 X15.512 Y20.7413
N0031 X19.776 Y16.2924	N0090 X14.446 Y21.7456
N0032 X21.23 Y15.7226	N0091 X13.224 Y22.5726
N0033 X23. Y15.5127	N0092 X11.768 Y23.1337
N0034 X28.	N0093 X10. Y23.3405
N0035 Y15.5508	N0094 X5.
N0036 X23.	N0095 Y23.463
N0037 X21.23 Y15.7605	N0096 X10.
N0038 X19.776 Y16.3295	N0097 X11.768 Y23.2574
N0039 X18.554 Y17.1681	N0098 X13.224 Y22.6994
N0040 X17.488 Y18.1863	N0099 X14.446 Y21.8771
N0041 X15.512 Y20.4025	N0100 X15.512 Y20.8786
N0042 X14.446 Y21.4207	N0101 X17.488 Y18.7053
N0043 X13.224 Y22.2593	N0102 X18.554 Y17.7068
N0044 X11.768 Y22.8283	N0103 X19.776 Y16.8844
N0045 X10. Y23.0379	N0104 X21.23 Y16.3264
N0046 X5.	N0105 X23. Y16.1209
N0047 Y23.0853	N0106 X28.
N0048 X10.	N0107 Y16.31
N0049 X11.768 Y22.8761	N0108 X23.
N0050 X13.224 Y22.3083	N0109 X21.23 Y16.5143
N0051 X14.446 Y21.4716	N0110 X19.776 Y17.0686
N0052 X15.512 Y20.4555	N0111 X18.554 Y17.8856
N0053 X17.488 Y18.2441	N0112 X17.488 Y18.8775
N0054 X18.554 Y17.2281	N0113 X15.512 Y21.0366
N0055 X19.776 Y16.3913	N0114 X14.446 Y22.0286
N0056 X21.23 Y15.8235	N0115 X13.224 Y22.8455
N0057 X23. Y15.6144	N0116 X11.768 Y23.3999
N0058 X28.	N0117 X10. Y23.6041
	N0118 X5.

Appendix D

.....	N5460 Y74.3856 Z-1.9049
.....	N5461 X23.
.....	N5462 X21.23 Y74.1765 Z-1.9234
N5403 X13.224 Y67.1545 Z0.8016	N5463 X19.776 Y73.6087 Z-1.9736
N5404 X14.446 Y67.9714 Z0.9971	N5464 X18.554 Y72.7719 Z-2.0474
N5405 X15.512 Y68.9634 Z1.2345	N5465 X17.488 Y71.7559 Z-2.1372
N5406 X17.488 Y71.1225 Z1.7512	N5466 X15.512 Y69.5445 Z-2.3325
N5407 X18.554 Y72.1144 Z1.9886	N5467 X14.446 Y68.5284 Z-2.4222
N5408 X19.776 Y72.9314 Z2.1841	N5468 X13.224 Y67.6917 Z-2.4961
N5409 X21.23 Y73.4857 Z2.3167	N5469 X11.768 Y67.1239 Z-2.5462
N5410 X23. Y73.69 Z2.3656	N5470 X10. Y66.9147 Z-2.5647
N5411 X28.	N5471 X5.
N5412 Y73.8791 Z1.5204	N5472 Y66.9621 Z-3.2089
N5413 X23.	N5473 X10.
N5414 X21.23 Y73.6736 Z1.4775	N5474 X11.768 Y67.1717 Z-3.1965
N5415 X19.776 Y73.1156 Z1.3612	N5475 X13.224 Y67.7407 Z-3.1631
N5416 X18.554 Y72.2932 Z1.1898	N5476 X14.446 Y68.5793 Z-3.1138
N5417 X17.488 Y71.2947 Z0.9816	N5477 X15.512 Y69.5975 Z-3.0539
N5418 X15.512 Y69.1214 Z0.5286	N5478 X17.488 Y71.8137 Z-2.9237
N5419 X14.446 Y68.1229 Z0.3204	N5479 X18.554 Y72.8319 Z-2.8638
N5420 X13.224 Y67.3006 Z0.149	N5480 X19.776 Y73.6705 Z-2.8145
N5421 X11.768 Y66.7426 Z0.0326	N5481 X21.23 Y74.2395 Z-2.781
N5422 X10. Y66.537 Z-0.0102	N5482 X23. Y74.4492 Z-2.7687
N5423 X5.	N5483 X28.
N5424 Y66.6595 Z-0.6444	N5484 Y74.4873 Z-3.634
N5425 X10.	N5485 X23.
N5426 X11.768 Y66.8663 Z-0.6076	N5486 X21.23 Y74.2774 Z-3.6401
N5427 X13.224 Y67.4274 Z-0.5077	N5487 X19.776 Y73.7076 Z-3.6569
N5428 X14.446 Y68.2544 Z-0.3605	N5488 X18.554 Y72.868 Z-3.6815
N5429 X15.512 Y69.2587 Z-0.1817	N5489 X17.488 Y71.8484 Z-3.7115
N5430 X17.488 Y71.4443 Z0.2073	N5490 X15.512 Y69.6294 Z-3.7767
N5431 X18.554 Y72.4485 Z0.3861	N5491 X14.446 Y68.6098 Z-3.8066
N5432 X19.776 Y73.2755 Z0.5333	N5492 X13.224 Y67.7702 Z-3.8313
N5433 X21.23 Y73.8367 Z0.6332	N5493 X11.768 Y67.2004 Z-3.848
N5434 X23. Y74.0434 Z0.67	N5494 X10. Y66.9905 Z-3.8542
N5435 X28.	N5495 X5.
N5436 Y74.1827 Z-0.1848	N5496 Y67. Z-4.5
N5437 X23.	N5497 X10.
N5438 X21.23 Y73.975 Z-0.2156	N5498 X11.768 Y67.21
N5439 X19.776 Y73.4111 Z-0.2989	N5499 X13.224 Y67.78
N5440 X18.554 Y72.5801 Z-0.4218	N5500 X14.446 Y68.62
N5441 X17.488 Y71.5711 Z-0.571	N5501 X15.512 Y69.64
N5442 X15.512 Y69.375 Z-0.8957	N5502 X17.488 Y71.86
N5443 X14.446 Y68.3659 Z-1.0449	N5503 X18.554 Y72.88
N5444 X13.224 Y67.535 Z-1.1678	N5504 X19.776 Y73.72
N5445 X11.768 Y66.9711 Z-1.2512	N5505 X21.23 Y74.29
N5446 X10. Y66.7634 Z-1.2819	N5506 X23. Y74.5
N5447 X5.	N5507 X28.
N5448 Y66.8485 Z-1.9222	N5508 G00 Z27.4968
N5449 X10.	N5509 M9
N5450 X11.768 Y67.057 Z-1.8976	N5510 G90 G00 G49 Z0 M5
N5451 X13.224 Y67.6231 Z-1.8308	N5511 X0 Y0
N5452 X14.446 Y68.4573 Z-1.7324	N5512 M30
N5453 X15.512 Y69.4703 Z-1.6129	N5513 %
N5454 X17.488 Y71.675 Z-1.3527	
N5455 X18.554 Y72.688 Z-1.2332	
N5456 X19.776 Y73.5222 Z-1.1348	
N5457 X21.23 Y74.0882 Z-1.068	
N5458 X23. Y74.2968 Z-1.0434	

APPENDIX (E)

FOR INTERPOLATOR BEZIER PROFILE DIE

Appendix E

Curvatures for Interpolator Bezier Profile Die:

[illegible]

Appendix E

Radiuses of Curvatures for Interpolator Bezier Profile Die:

[illegible]

Appendix E

%	N0060 X28.
N0001 00	N0061 Y15.6538
N0002 (Surfware, Inc.)	N0062 X23.
N0003 (5703 Corsa Ave)	N0063 X21.1 Y15.9423
N0004 (Westlake, Ca. 91311)	N0064 X19.9 Y16.4099
N0005 G17 G40 G80 G90	N0065 X18.7 Y17.2057
N0006 T10 M6	N0066 X17.5 Y18.3099
N0007 M3 S1492	N0067 X15.4 Y20.6476
N0008 G00 G54 X28. Y15.5	N0068 X14.5 Y21.5131
N0009 G43 Z50. H10	N0069 X13.3 Y22.3487
N0010 M8	N0070 X11.8 Y22.9555
N0011 G00 Z27.4976	N0071 X11.2 Y23.0351
N0012 G01 Z24.9976 F354.4	N0072 X10. Y23.1147
N0013 X23. F708.7	N0073 X5.
N0014 X21.1 Y15.79	N0074 Y23.1792
N0015 X19.9 Y16.26	N0075 X10.
N0016 X18.7 Y17.06	N0076 X11.8 Y23.0205
N0017 X17.5 Y18.17	N0077 X13.3 Y22.4154
N0018 X15.4 Y20.52	N0078 X14.5 Y21.5823
N0019 X14.5 Y21.39	N0079 X15.7 Y20.402
N0020 X13.3 Y22.23	N0080 X17.5 Y18.3885
N0021 X11.8 Y22.84	N0081 X18.7 Y17.2875
N0022 X11.2 Y22.92	N0082 X19.9 Y16.494
N0023 X10. Y23.	N0083 X21.1 Y16.0279
N0024 X5. Y23.0072	N0084 X23. Y15.7402
N0025 X10.	N0085 X28.
N0026 X11.8 Y22.8472	N0086 Y15.8457
N0027 X13.3 Y22.2374	N0087 X23.
N0028 X14.5 Y21.3977	N0088 X21.1 Y16.1323
N0029 X15.7 Y20.2081	N0089 X19.9 Y16.5968
N0030 X17.5 Y18.1788	N0090 X18.7 Y17.3874
N0031 X18.7 Y17.0691	N0091 X17.5 Y18.4844
N0032 X19.9 Y16.2694	N0092 X15.4 Y20.8069
N0033 X21.1 Y15.7995	N0093 X14.5 Y21.6667
N0034 X23. Y15.5096	N0094 X13.3 Y22.4969
N0035 X28.	N0095 X11.8 Y23.0997
N0036 Y15.5385	N0096 X11.2 Y23.1788
N0037 X23.	N0097 X10. Y23.2578
N0038 X21.1 Y15.8281	N0098 X5.
N0039 X19.9 Y16.2975	N0099 Y23.3507
N0040 X18.7 Y17.0964	N0100 X10.
N0041 X17.5 Y18.205	N0101 X11.8 Y23.1932
N0042 X15.4 Y20.5519	N0102 X13.3 Y22.593
N0043 X14.5 Y21.4208	N0103 X14.5 Y21.7664
N0044 X13.3 Y22.2597	N0104 X15.7 Y20.5953
N0045 X11.8 Y22.8689	N0105 X17.5 Y18.5977
N0046 X11.2 Y22.9488	N0106 X18.7 Y17.5054
N0047 X10. Y23.0287	N0107 X19.9 Y16.7181
N0048 X5.	N0108 X21.1 Y16.2556
N0049 Y23.0646	N0109 X23. Y15.9702
N0050 X10.	N0110 X28.
N0051 X11.8 Y22.905	N0111 Y16.1137
N0052 X13.3 Y22.2968	N0112 X23.
N0053 X14.5 Y21.4593	N0113 X21.1 Y16.3977
N0054 X15.7 Y20.2728	N0114 X19.9 Y16.8579
N0055 X17.5 Y18.2487	N0115 X18.7 Y17.6412
N0056 X18.7 Y17.142	N0116 X17.5 Y18.7281
N0057 X19.9 Y16.3443	N0117 X15.4 Y21.0293
N0058 X21.1 Y15.8757	N0118 X14.5 Y21.8812

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.....	N6539 X18.7 Y72.9309 Z-3.7865
.....	N6540 X17.5 Y71.8213 Z-3.8148
.....	N6541 X15.4 Y69.472 Z-3.8748
N6483 X21.1 Y73.9721 Z-0.7798	N6542 X14.5 Y68.6023 Z-3.897
N6484 X19.9 Y73.506 Z-0.8397	N6543 X13.3 Y67.7626 Z-3.9185
N6485 X18.7 Y72.7125 Z-0.9416	N6544 X11.8 Y67.1528 Z-3.9341
N6486 X17.5 Y71.6115 Z-1.0829	N6545 X11.2 Y67.0728 Z-3.9361
N6487 X15.4 Y69.2806 Z-1.3822	N6546 X10. Y66.9928 Z-3.9381
N6488 X14.5 Y68.4177 Z-1.493	N6547 X5.
N6489 X13.3 Y67.5846 Z-1.6	N6548 Y67. Z-4.5
N6490 X11.8 Y66.9795 Z-1.6777	N6549 X10.
N6491 X11.2 Y66.9002 Z-1.6879	N6550 X11.5 Y67.11
N6492 X10. Y66.8208 Z-1.6981	N6551 X11.8 Y67.16
N6493 X5.	N6552 X13.3 Y67.77
N6494 Y66.8853 Z-2.2563	N6553 X14.5 Y68.61
N6495 X10.	N6554 X15.7 Y69.8
N6496 X11.5 Y66.9947 Z-2.245	N6555 X17.5 Y71.83
N6497 X11.8 Y67.0444 Z-2.2399	N6556 X18.7 Y72.94
N6498 X13.3 Y67.6513 Z-2.1777	N6557 X19.9 Y73.74
N6499 X14.5 Y68.4869 Z-2.0921	N6558 X21.1 Y74.21
N6500 X15.7 Y69.6707 Z-1.9707	N6559 X22.3 Y74.39
N6501 X17.5 Y71.6901 Z-1.7637	N6560 X23. Y74.5
N6502 X18.7 Y72.7943 Z-1.6505	N6561 X28.
N6503 X19.9 Y73.5901 Z-1.5689	N6562 G00 Z27.4976
N6504 X21.1 Y74.0577 Z-1.5209	N6563 M9
N6505 X22.3 Y74.2367 Z-1.5026	N6564 G90 G00 G49 Z0 M5
N6506 X23. Y74.3462 Z-1.4914	N6565 X0 Y0
N6507 X28.	N6566 M30
N6508 Y74.4134 Z-2.2418	N6567 %
N6509 X23.	
N6510 X21.1 Y74.1243 Z-2.264	
N6511 X19.9 Y73.6557 Z-2.3	
N6512 X18.7 Y72.858 Z-2.3612	
N6513 X17.5 Y71.7513 Z-2.4462	
N6514 X15.4 Y69.4082 Z-2.6261	
N6515 X14.5 Y68.5407 Z-2.6927	
N6516 X13.3 Y67.7032 Z-2.757	
N6517 X11.8 Y67.095 Z-2.8037	
N6518 X11.2 Y67.0152 Z-2.8098	
N6519 X10. Y66.9354 Z-2.8159	
N6520 X5.	
N6521 Y66.9713 Z-3.3767	
N6522 X10.	
N6523 X11.5 Y67.0812 Z-3.371	
N6524 X11.8 Y67.1311 Z-3.3685	
N6525 X13.3 Y67.7403 Z-3.3373	
N6526 X14.5 Y68.5792 Z-3.2945	
N6527 X15.7 Y69.7676 Z-3.2337	
N6528 X17.5 Y71.795 Z-3.13	
N6529 X18.7 Y72.9036 Z-3.0734	
N6530 X19.9 Y73.7025 Z-3.0325	
N6531 X21.1 Y74.1719 Z-3.0085	
N6532 X22.3 Y74.3517 Z-2.9993	
N6533 X23. Y74.4615 Z-2.9937	
N6534 X28.	
N6535 Y74.4904 Z-3.7466	
N6536 X23.	
N6537 X21.1 Y74.2005 Z-3.754	
N6538 X19.9 Y73.7306 Z-3.766	

APPENDIX (F)

FOR COMPOUND-CRHS PROFILE DIE

Appendix F

Curvatures for Compound-CRHS profile die:

[illegible]

Appendix F

Radiuses of Curvatures for Compound-CRHS Profile Die:

[illegible]

Appendix F

%	N0060 X14. Y72.6734
N0001 00	N0061 X13. Y73.3375
N0002 (Surfware, Inc.)	N0062 X12. Y73.9035
N0003 (5703 Corsa Ave)	N0063 X11. Y74.3856
N0004 (Westlake, Ca. 91311)	N0064 X5.
N0005 G17 G40 G80 G90	N0065 Y74.2968
N0006 T10 M6	N0066 X11.
N0007 M3 S1492	N0067 X12. Y73.8161
N0008 G00 G54 X5. Y74.5	N0068 X13. Y73.2518
N0009 G43 Z50. H10	N0069 X14. Y72.5897
N0010 M8	N0070 X15. Y71.814
N0011 G00 Z27.4968	N0071 X17. Y70.5419
N0012 G01 Z24.9968 F354.4	N0072 X19. Y69.3312
N0013 X11. F708.7	N0073 X20. Y68.5619
N0014 X12. Y74.016	N0074 X21. Y67.967
N0015 X13. Y73.4478	N0075 X22. Y67.5019
N0016 X14. Y72.7811	N0076 X23. Y67.1375
N0017 X15. Y72.	N0077 X24. Y66.8485
N0018 X17. Y70.7191	N0078 X30.
N0019 X19. Y69.5	N0079 Y66.7634
N0020 X20. Y68.7253	N0080 X24.
N0021 X21. Y68.1263	N0081 X23. Y67.0512
N0022 X22. Y67.658	N0082 X22. Y67.4143
N0023 X23. Y67.291	N0083 X21. Y67.8775
N0024 X24. Y67.	N0084 X20. Y68.4701
N0025 X30. Y66.9905	N0085 X19. Y69.2365
N0026 X24.	N0086 X15. Y71.7096
N0027 X23. Y67.2814	N0087 X14. Y72.4823
N0028 X22. Y67.6482	N0088 X13. Y73.1418
N0029 X21. Y68.1163	N0089 X12. Y73.7039
N0030 X20. Y68.7151	N0090 X11. Y74.1827
N0031 X19. Y69.4894	N0091 X5.
N0032 X15. Y71.9884	N0092 Y74.0434
N0033 X14. Y72.7691	N0093 X11.
N0034 X13. Y73.4355	N0094 X12. Y73.5669
N0035 X12. Y74.0035	N0095 X13. Y73.0075
N0036 X11. Y74.4873	N0096 X14. Y72.3511
N0037 X5.	N0097 X15. Y71.5821
N0038 Y74.4492	N0098 X17. Y70.3211
N0039 X11.	N0099 X19. Y69.1208
N0040 X12. Y73.966	N0100 X20. Y68.3581
N0041 X13. Y73.3988	N0101 X21. Y67.7684
N0042 X14. Y72.7332	N0102 X22. Y67.3073
N0043 X15. Y71.9535	N0103 X23. Y66.946
N0044 X17. Y70.6748	N0104 X24. Y66.6595
N0045 X19. Y69.4578	N0105 X30.
N0046 X20. Y68.6844	N0106 Y66.537
N0047 X21. Y68.0864	N0107 X24.
N0048 X22. Y67.6189	N0108 X23. Y66.8219
N0049 X23. Y67.2526	N0109 X22. Y67.1811
N0050 X24. Y66.9621	N0110 X21. Y67.6396
N0051 X30.	N0111 X20. Y68.226
N0052 Y66.9147	N0112 X19. Y68.9844
N0053 X24.	N0113 X15. Y71.4318
N0054 X23. Y67.2046	N0114 X14. Y72.1964
N0055 X22. Y67.5702	N0115 X13. Y72.8491
N0056 X21. Y68.0366	N0116 X12. Y73.4053
N0057 X20. Y68.6333	N0117 X11. Y73.8791
	N0118 X5.

Appendix F

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.....
.....
N5883 X23. Y22.9488 Z-1.2393
N5884 X24. Y23.2366 Z-1.2819
N5885 X30.
N5886 Y23.1515 Z-1.9222
N5887 X24.
N5888 X23. Y22.8626 Z-1.8881
N5889 X22. Y22.4981 Z-1.8451
N5890 X21. Y22.033 Z-1.7902
N5891 X20. Y21.4381 Z-1.72
N5892 X19. Y20.6688 Z-1.6293
N5893 X16. Y18.8313 Z-1.4125
N5894 X15. Y18.186 Z-1.3363
N5895 X14. Y17.4103 Z-1.2448
N5896 X13. Y16.7482 Z-1.1667
N5897 X12. Y16.1839 Z-1.1001
N5898 X11. Y15.7032 Z-1.0434
N5899 X5.
N5900 Y15.6144 Z-1.9049
N5901 X11.
N5902 X12. Y16.0965 Z-1.9475
N5903 X13. Y16.6625 Z-1.9975
N5904 X14. Y17.3266 Z-2.0561
N5905 X15. Y18.1047 Z-2.1249
N5906 X17. Y19.3806 Z-2.2375
N5907 X19. Y20.595 Z-2.3448
N5908 X20. Y21.3667 Z-2.4129
N5909 X21. Y21.9634 Z-2.4656
N5910 X22. Y22.4298 Z-2.5068
N5911 X23. Y22.7954 Z-2.5391
N5912 X24. Y23.0853 Z-2.5647
N5913 X30.
N5914 Y23.0379 Z-3.2089
N5915 X24.
N5916 X23. Y22.7474 Z-3.1918
N5917 X22. Y22.3811 Z-3.1703
N5918 X21. Y21.9136 Z-3.1428
N5919 X20. Y21.3156 Z-3.1076
N5920 X19. Y20.5422 Z-3.0622
N5921 X16. Y18.6952 Z-2.9536
N5922 X15. Y18.0465 Z-2.9154
N5923 X14. Y17.2668 Z-2.8696
N5924 X13. Y16.6012 Z-2.8305
N5925 X12. Y16.034 Z-2.7971
N5926 X11. Y15.5508 Z-2.7687
N5927 X5.
N5928 Y15.5127 Z-3.634
N5929 X11.
N5930 X12. Y15.9965 Z-3.6482
N5931 X13. Y16.5645 Z-3.6649
N5932 X14. Y17.2309 Z-3.6844
N5933 X15. Y18.0116 Z-3.7074
N5934 X17. Y19.292 Z-3.745
N5935 X19. Y20.5106 Z-3.7808
N5936 X20. Y21.2849 Z-3.8035
N5937 X21. Y21.8837 Z-3.8211
N5938 X22. Y22.3518 Z-3.8348
N5939 X23. Y22.7186 Z-3.8456

N5940 X24. Y23.0095 Z-3.8542
N5941 X30.
N5942 Y23. Z-4.5
N5943 X24.
N5944 X23. Y22.709
N5945 X22. Y22.342
N5946 X21. Y21.8737
N5947 X20. Y21.2747
N5948 X19. Y20.5
N5949 X16. Y18.6498
N5950 X15. Y18.
N5951 X14. Y17.2189
N5952 X13. Y16.5522
N5953 X12. Y15.984
N5954 X11. Y15.5
N5955 X5.
N5956 G00 Z27.4968
N5957 M9
N5958 G90 G00 G49 Z0 M5
N5959 X0 Y0
N5960 M30
N5961 %

الخلاصة

يركز هذا البحث على تطوير خوارزمية لحساب افضل طول قطعة المستقيم في اتجاه (u) و (w) للسطوح العقدية. تم في هذا البحث توليد مسار العدة على السطح المراد تشغيله بالاعتماد على الدقة المطلوبة، ان الجزء المشغل تم تمثيله بالاعتماد على الطرق الرياضية المختلفة لتمثيل الأقواس والسطوح وتم اختيار (Bezier technique) لتطبيق الخوارزمية لأنها سهلة الاشتقاق والتطبيق مقارنة بالطرق الأخرى. أن الخوارزمية المقترحة تتكون من نقطتين أساسيتين: الأولى هي حساب طول قطعة المستقيم الامثل في اتجاه (u) بين نقاط (cutter contact) والتي تعتمد على (tolerance) المعطى وعلى (Minimum Radius of curvature) المحسوب على السطح. أما الثانية فهي حساب طول قطعة المستقيم الامثل في اتجاه (w) بالاعتماد على نوع السطح (مستوي ، مقعر او محدب) وكذلك على نصف قطر عدة القطع (tolerance) و (height scallop) المعطى. تم تطبيق الخوارزمية المقترحة في مجال الإنتاج (تصميم قوالب البثق) بواسطة استخدام ثلاثة انواع مختلفة من الأقواس المستكملة هي (cubic Bezier, interpolator Bezier and compound-CRHS extrusion profile die).

في هذا البحث، الجزء المصنع هو بواسطة استخدام نظام ماكينة تفريز 3-axis CNC (FANUC 15MB) وذلك لغرض الحصول على لغة الماكينة (G-code) من برنامج (SURFCAM). حيث تم ايجاد طريقة تتجنب حدوث (gouging) خلال استخدام هذه الماكينة.

عملية التشغيل تم محاكاتها باستخدام برنامج يدعى (SURFCAM) لمختلف الطرق المستكملة من اجل تقييم وتخمين السطوح قبل تشغيلها. تم استخدام طريقة العناصر المحددة (FEA) للتقييم طرق الاستكمال الثلاثة من خلال استخدام برنامج (ANASYS 9.0) من اجل التعرف على الانفعالات والقوى المطلوبة لبثق المعدن خلال القوالب المستكملة الثلاثة.

ان برنامج (G-code) تم تطبيقه على ماكينة ذات خمس محاور (Okuma VH-40-HS dynamic machine)، المادة التي تم تشغيلها هي (cibatoool)، وأن التشغيل تم بدون سائل تبريد في مصنع (Oy) في فنلندا (Helsinki/Finland).

اخيرا تم المقارنة بين الطرق الثلاثة لقوالب البثق نسبة الى طول قطعة المستقيم في اتجاه (u) و (w)، (curvature)، (radius of curvature)، (number of segments)، (height scallop)، ((size store in memory in (Bytes))، (number of G-code)، (number of tool path)، (length of tool path) والانفعالات والقوى المطلوبة لبثق معدن الألمنيوم. وان الخوارزمية المقترحة (interpolator Bezier profile die) تمتلك

افضل جودة سطح بسبب (number of segment) أكثر من (cubic Bezier profile die) بحدود (٧٤%) وأكثر من (compound-CRHS profile die) بحدود (٦٦%) وأن عدد مسارات العدة يساوي (١٢٤) مسار وهي أكثر من (cubic Bezier & compound-CRHS profile die) بحدود (١٢,٩%). والخوارزمية المقترحة تحتاج قوة أعلى من (cubic Bezier profile die) بحدود (٨,٥%) وأقل من (compound-CRHS profile die) بحدود (٣,٨%) لبثق معدن الألمنيوم.



جمهورية العراق
وزارة التعليم العالي والبحث العلمي
الجامعة التكنولوجية
قسم هندسة الانتاج والمعادن

دراسة استكمال المنحني لنظام مكائن السيطرة الرقمية

أطروحة تقدم بها

عباس ميثم جابر الغنزي

الى قسم هندسة الانتاج والمعادن-الجامعة التكنولوجية
وهي جزء من متطلبات نيل درجة الماجستير
في علوم هندسة الانتاج

بإشراف

د.معن عابد توفيق الهاشمي

د.ليث عبد الله محمد

٢٠٠٨