

**DETERMINATION OF TOOL DEFLECTION COMPENSATION FOR FINISH
MACHINING OF T6061 ALUMINIUM ALLOY IN 3-AXIS CNC VERTICAL
MILLING OPERATION USING BALL END MILLING TOOL**

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fulfillment*

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Masters of Engineering

in

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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled, “**Determination of Tool Deflection Compensation for Finish Machining of T6061 Aluminum Alloy in 3-axis CNC Vertical Milling Operation using Ball End Milling tool**” being submitted in partial fulfillment of award of degree of **Master of Engineering in CAD/CAM Engineering** in Mechanical Engineering Department, Thapar University, Patiala, is an authentic record of work carried out by me under the supervision and guidance of **Dr. S.K. Sharma, Assistant Professors, Mechanical Engineering Department, Thapar University, Patiala** and **Dr. R. K. Duvedi, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala**.


The study embodied in this thesis has not been submitted in part or full to any other university or institute for the award of any degree.

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This is to certify that above declaration made by the student concerned is correct to the best of my knowledge and belief.

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ABSTRACT

In end-milling operations, especially for machining of sculptured surfaces when the ball-end milling cutter has very high length to diameter ratio, the tool has got the tendency to deflect sideways even when nominal cutting force is acting on the tool. This deflection of tool should be calculated and compensated before performing actual machining operation.

Various methodologies have been discussed in this whole work regarding tool deflection calculation and compensation. Out of all those methodologies, any suitable methodology can be selected where tool shape can be studied in more realistic form. Using Kim et al. [2] methodology, tool deflection has been calculated. The approach proposed by Chiang et al. [1] has been used for cutting force determination in case of ball-end milling cutter. Then *mirror method* has been used for tool deflection compensation. Machining of slots has also been done using ball-end milling cutter to compare both compensated and non-compensated toolpaths. Ball-end milling cutters are mostly used for finish machining operation of complex sculptured surfaces because they provide better surface finish along feed direction and also produce minimum number of feed-marks. Moreover, it has also been observed that toolpath applied with compensation using *mirror method* is very close to the ideal one. The Literature review and results and discussions portion related to tool deflection and compensation has also been discussed in the subsequent chapters.

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NOMENCLATURE

Symbols	Parameters represented	Units
A_{ij}	: Projected area of cutting edge of ball-end mill engaged with the workpiece material being cut.	mm ²
δ_X, δ_Y	: Deflection of ball-end milling cutter in X and Y directions	mm
δ_{Ci}	: Clamping system deflection in X, Y and Z directions	mm
δ_{Ti}	: Cutter bending deflection in X, Y and Z directions	mm
δ_{CX} and δ_{CY}	: Compensated deflection value in X and Y directions	mm
δ_s	: Deflection of shank or non-fluted portion of ball-end mill	mm
δ_f	: Deflection of flute	mm
ϕ_s	: Deflection angle of shank	radians
L_f	: Length of fluted portion of tool	mm
n_f	: Number of flutes of ball-end milling cutter	Dimensionless
N	: Spindle speed	rpm
z	: Position of considered deflection	mm
L	: Length of overhang portion	mm
E	: Young modulus of elasticity	N/mm ²
I	: Moment of inertia of overhang portion	mm ⁴
I_s	: Moment of inertia of shank or non-fluted portion	mm ⁴
B	: Tool base diameter	mm
D	: Depth of non-fluted portion outside collet	mm
I_f	: Moment of inertia of fluted portion	mm ⁴
Z_F	: Z – direction position of applied force	mm
L_c	: Contact length of tool	mm
c	: Contact compliance coefficient	Dimensionless
F_{rep}	: Force representation	N
δ_{ed}	: Elastic displacement in connection	mm
m	: Clamping stiffness material coefficient	Dimensionless
n	: Compensatory contact length coefficient	Dimensionless
CL	: Cutter location vector (Cutter location center representing the center of spherical part of ball-end mill)	mm

CL_X and CL_Y	: Compensated new cutter location coordinates in X and Y directions	mm
\hat{i}	: Normal vector	mm
CC_X, CC_Y, CC_Z	: Cutter contact points X, Y and Z coordinates	mm
R	: Distance of cutting edge element from origin and Arc radius	mm
\emptyset	: Rotation angle of cutting edge element	radians
r_{rd}	: Radial runout	mm
f_t	: Feed per tooth	mm/tooth
f_r	: Feed per revolution	mm/rev
K_c	: Cutter clamping stiffness	N/mm
a_d	: Axial depth of Cut	mm
r_d	: Radial depth of cut	mm
F	: Feed rate	mm/min
h_c	: Cusp height	mm
δA_d	: Variation in axial depth of cut	mm
Z	: Number of teeth	Dimensionless
D	: Tool diameter	mm
R	: Tool radius	mm
t_{cij}	: Instantaneous chip thickness	mm
R_θ	: Equivalent radius	mm
a	: Position of centre of arc	mm
j	: Number of cutting edge segments used to approximate the total cutting edge	Dimensionless
γ_j	: Cutting edge element engagement angle	radians
η_j	: Projection of helix angle on vertical plane	radians
$\Delta\eta$: Variation in projection of helix angle	radians
h_d	: Workpiece hardness	HRB
K_n, K_r and K_t	: Specific cutting forces in normal, radial and tangential directions respectively	N/mm ²
$\Delta f_{n_{ij}}, \Delta f_{r_{ij}}$ and $\Delta f_{t_{ij}}$: Local Normal, Radial and Tangential Forces respectively	N
$c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8, c_9$ and c_{10}	: Constant parameters used for calculation of specific cutting forces K_n, K_r and K_t	Dimensionless
$[T_1], [T_2]$ and $[T_3]$: Transfer matrices between local coordinates and global coordinates of cutting forces	Dimensionless

$\Delta f_{Xij}, \Delta f_{Yij}$ and Δf_{Zij}	: Infinitesimal global cutting forces in X, Y and Z directions	N
F	: Resultant force vector	N
F_{Xi}, F_{Yi} and F_{Zi}	: Force Vector Components	N
I_{XX} and I_{YY}	: Moment of Inertia of two-flute ball end mill about X- and Y-axis respectively	mm ⁴
I	: Total moment of inertia of fluted portion	mm ⁴
f_d	: Flute depth	mm
R_θ	: Equivalent radius	mm
CL_{Ci}	: Compensated cutter location points	mm
CL_{CX}, CL_{CY} and CL_{CZ}	: Components of compensated cutter location points	mm
N_e	: Number of infinitesimal cutting edge elements	Dimensionless

ACRONYMS

CNC	Computer Numerical Control
ISO	International Organization for Standardization
NC	Numerical Control
VMC	Vertical Machining Centre
BLU	Basic Length Unit
CMM	Coordinate Measuring Machine
CAM	Computer Aided Manufacturing
CL	Cutter Location
CC	Cutter Contact
CNC	Computer Numerical Control

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CHAPTER: 1

INTRODUCTION

In recent years, freeform or sculptured surfaces have gained a significant importance in various engineering and creative operations in automotive, die/ mould and aerospace sectors. Machining of these surfaces is usually done using Computer Numeric Control (CNC) machining centers for achieving required good surface finish and higher productivity. For such surfaces machining, time consumption is more, thereby increasing the machining cost. Due to increased competition in the manufacturing market nowadays, it becomes very important to reduce production time and cost without compromising with the part quality. The productivity of CNC machining of any complex surface can be improved further by selection of optimized cutting speeds and the feed rates. The machining process consists of number of steps comprising of several roughing operation, semi-finishing and then finish machining operations. Out of these, the finishing operation is the most time consuming operation. Though a good amount of work related to finish machining of complex surfaces has been reported in the literature but still there is scope of investigation of effect of tool deflection and the machining parameters for accurate finish machining using CNC systems.

For most of the finish machining operations of complex surfaces, the 3-axis CNC milling centers are used. At the same time, the preferred tool shapes used for complex surface milling is the ball-nose end mill [1]. Surface quality provided by ball-end milling cutters is relatively better for sculptured surface machining. Moreover, the computation of gouge free CNC toolpath data for complex sculptured surfaces is relatively easy in case of a ball end milling tool.

The 3-axis surface milling operation is basically a metal cutting operation where the metal removal is in the form of chips sheared from the metallic workpiece. The cutting forces encountered during this machining operation are directly experienced at the tool-workpiece contact in the cutting zone. The cutting forces magnitude encountered at the cutting interface depends upon the choice of the machining parameters like: feed, speed, cutter geometry and material, axial and radial depths of cut and workpiece material hardness [2]. The cutting force tends to cause the deflection in the ball-end milling cutter thereby deflecting it away from the required cutter location position. At the same time, a part of the reaction of the cutting forces also tries to deflect the spindle of the vertical milling centers. These deflections experienced by the cutting tool as well as the machine spindle cause the inaccuracies in the machining operation, which can adversely affect the surface quality of the machined part.

Thus in the present work, the aim is to examine the cutting forces effect on tool deflection experienced by a ball-end milling cutter. Further the aim of the study is to determine the magnitude of the tool deflection and effect of tool deflection compensation applied on the cutter location data for CNC machining of T-6061 Aluminum alloy.

1.1 CNC Machining of Complex Sculptured Surfaces

The accurate machining of complex sculptured surfaces can be accomplished efficiently using CNC machining centers. The 3-axis roughing operation for sculptured surface machining is generally accomplished using a larger diameter flat end milling cutter for bulk material removal and the effect of the cutting forces on tool deflection is not severe whereas the excessive cutting forces during roughing machining can cause significant spindle deflection. A reasonable estimate of the cutting forces in roughing operation can help in safe working of the machining center as well as help in avoiding the deflection in the machined workpiece. The roughing operations does not significantly affect the final surface properties required after finish machining operation because the left over stock material after finishing operation that is to be removed in finishing operation is sufficient to accommodate any deflections or deformations that may have happened during roughing operation. Thus the key concern is the finish machining operation which directly and significantly affects the properties of the machined sculptured surface.

The most of the finishing operations for sculptured surface machining are executed using ball end milling tools. A few application areas include the machining of dies for dental applications, machining of dies for ornamental jewelry or artifacts, machining of orthopedic implants etc. In some of these applications, the cutting length to diameter ratio of the spherical cutter is quite large. In such cases, the tool deflection becomes a significant contributor for machining errors.



(a)



(b)



(c)

Figure 1.1: Types of ball-end milling cutters, (a) Helical fluted solid ball end mill [3], (b) Straight flute solid ball end mill [3] and (c) Insert based ball end mill [3]

1.2 Types of Ball-End Milling Cutters

There are basically three types of spherical milling cutters which are most commonly used for surface machining operations. The main classification is the full solid cutter and the insert based cutter. The full solid ball end milling cutters are further classified as helical fluted and the straight fluted cutters as shown in figure 1.1(a) and 1.1(b). The helical fluted solid ball end milling tools are generally used for metal machining whereas the straight fluted cutters are used especially for wood machining applications. The insert based ball end milling cutters are also becoming famous these days owing to the higher rigidity of the insert holder as well as replaceable inserts which makes the machining operation cost effective. A typical insert based ball-end milling cutter is displayed in figure 1.1(c).

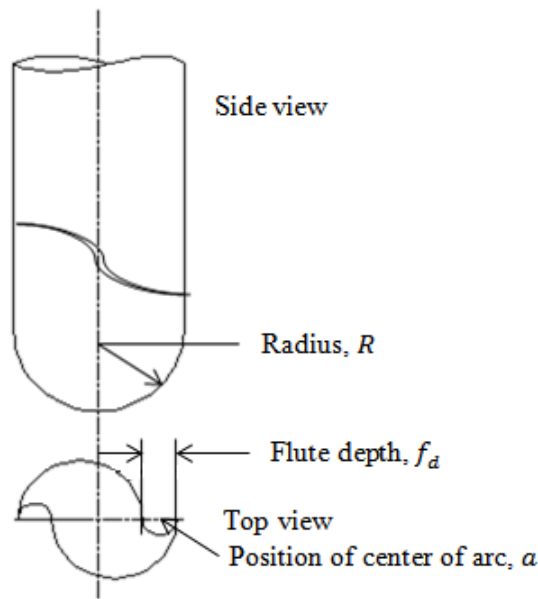


Figure 1.2: Geometry of a fluted ball-end milling tool [4]

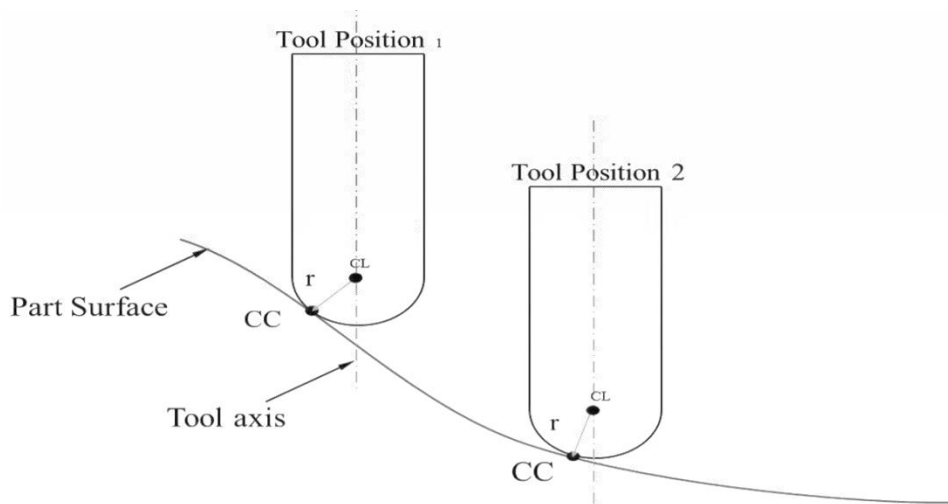


Figure 1.3: Concept of cutter contact and cutter location data [5]

The geometry of a rotating spherical end mill cutter is defined by the radius, R of the spherical bottom of the tool as shown in figure 1.2. The motion of the ball/spherical end mill cutter is controlled using the position of the center of the spherical bottom of tool called cutter location (CL), while for computation of the CL data for machining of a particular surface shape the first step is the determination of the cutter contact point (CC). The figure 1.3 shows the concept of cutter contact (CC) and cutter location (CL) for a ball end milling cutter.

1.3 Components of CNC Machines System

There are three main ingredients in a CNC machining system which includes: machine tool, CNC controller and the toolpath data. The machine tool is the physical mechanical structure used to move the cutting tool relative to the workpiece by virtue of motion of machine slides actuated using axis drive actuators. The drive motions available on a 3-axis vertical CNC machine tool are X, Y, Z -axes, which are actuated by the motion commands issued by the CNC control unit. The CNC controller unit is also responsible for accurate position control and feedback control for precise working of the CNC system. The third component of the CNC system is the toolpath data which is the sequential information of the positions of the control point on the cutting tool which is used for positioning the cutting tool relative to the workpiece for accurate machining. This information corresponds to the centre position of spherical bottom of the ball nose cutter which is also known as cutter location (CL) information. The toolpath data is the path that the cutting tool follows while passing through a series of cutter location points that approximates the part surface to be machined.

1.4 Toolpath Data for Ball-End Milling Cutter

3-axis sculptured surface machining operations are required to be carried out on various parts like dies or moulds, aerospace components, toys, artifacts and for dental or orthopedic implants. The machining operations are carried out in two phases namely roughing operation and the finishing operation as discussed earlier [1]. The need for roughing and finishing operations has been discussed below:

1.4.1 Roughing machining operation

For ball-end milling cutter, roughing operation is the first stage of material removal procedure during which it is preferred to remove most of the volume of raw material, so that the resulted surface of the product can be approximated. Roughing operation is regarded as the most significant operation which is very important for the accomplishment of the succeeding finishing operation. So, roughing operation should be properly optimized in order to achieve the desired surface finish in future and to reduce the manufacturing time also, thereby increasing the productivity. Thus, roughing process decides the total time of machining. In roughing operation of sculptured surfaces in ball-end milling operation, most of the material is removed with the help of a large diameter cutter. For this operation, flat end milling cutters are mostly used because they exhibit good cutting properties over the entire cutting edge engagement region. In case of roughing operation, the values of side step distance, feed-forward distance, feed and depth of cut are more.

1.4.2 Finishing operation

For ball-end milling cutter, finishing operation is done after roughing operation by using less feed amount and depth of cut and more cutting speed. In case of finishing operation, main emphasis is given

on generating cutter location points that will remain under tolerance limits so as to maintain the required surface finish. In this operation, if tool path interval will be a lengthy one, rough surface will be generated while a small one can increase the machining time, so the productivity will be reduced. Moreover due to the complex surface geometry, both the tool body and tool holder will intervene with the surface, thereby obstructing the generation of tool path. In the case of 3-axis CNC machining, smaller tool lengths and the vertical motion of the tool might not be able to reach some unapproachable areas of the sculptured surface. In case of finishing operation for ball-end milling, the values of side step distance, feed-forward distance, feed and depth of cut are taken less than the roughing operations.

1.5 Issues in Finishing Operation for Ball-End Milling

The main issues encountered while machining with the ball end milling cutter are: tool gouging, scallop height and deflection of ball-end milling cutter. These are discussed below:

1.5.1 Tool gouging

Gouging is basically the overcutting of the workpiece when the tool dips beyond the required machined surface while performing machining operation. In other words, gouging occurs when the tool penetrates inside the machined surface and exceeds the lower limit of tolerance of machined surface. Tool gouging occurs mainly when the spherical cutter used for end-milling operation is of radius larger than the smallest radius of curvature of the boundary curve. It can cause reduction of accuracy and tool life, increase in machining time and production cost. So, thereby, tool gouging can be avoided [6].

1.5.2 Scallop height

Scallop Height is basically the uncut material between two passes while machining with ball-end milling cutter. This is also known as Cusp Height. The relationship between ball-end milling cutter radius and scallop height can be described in the following figure 1.4

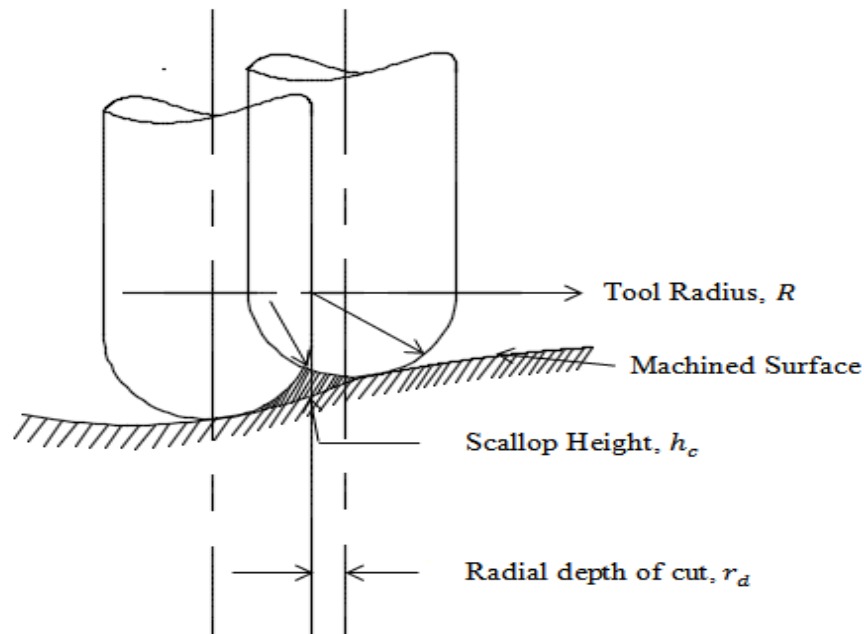


Figure 1.4: Relationship between the Tool radius, R and the Scallop height, h_c for a ball end mill.

1.5.3 Deflection of ball-end milling cutter

Tool deflection of spherical milling cutter is an important parameter which needs to be considered while performing any machining operation. This deflection occurs mainly due to the deflection of the clamping system as well as the deflection of the tool itself due to the bending action. The deflection of the cutting tool while performing machining operation together places the end position into some other location rather than the desired ideal cutter location thereby causing deviation in the required surface finish of the machined part. So for achieving the better surface texture, we need to consider these deflections before machining. In this case, machining has to be done again and again in order to come closer to the required value, which will increase the production time and also the cost.

All these deflections occur basically due to cutting forces encountered by the ball-end milling cutter while performing machining operation. These forces are encountered excessively, whenever the feed rate is increased, thereby resulting in more deflection. As a result, the surface finish of the machined workpiece is also reduced. So, it becomes very important to apply suitable compensation for the tool deflection value in the cutter location data beforehand. Thus, by applying suitable compensations before only, machining has to be done only once and that even by compensated tool path, thereby reducing the machining time and cost and increasing the overall productivity and above all, the surface finish of the machined surface.

1.6 Present Work

As discussed earlier, the tool deflection can be a major contributing factor for errors encountered in surface machining operations. The reason for overall deflection encountered at the tool cutting edge is mainly because of elastic bending of the cutter as well as the deflection of the tool clamping mechanism which includes the spindle. In this work, the mathematical model formulated by Kim et. al [7] and Chiang et. al. [8] has been used to determine the magnitude of the cutting forces experienced by the fluted helical solid ball end milling cutter and the corresponding total deflection occurring at the spherical bottom center of the ball end mill. The tool deflection thus found out can be used to apply the compensation to the cutter location data using a well-known method called “*mirror method*” [4, 7]. In this work a systematic approach is used to determine the tool compensation required to counter the tool deflections has been elaborated in chapter 3.

This dissertation work is devoted to minimization of errors while machining sculptured surfaces with ball nose milling cutter by compensation of tool deflection arising because of cutting forces. Tool deflection has been calculated for the same spherical milling cutter by determination of cutting forces.

CHAPTER: 2

LITERATURE REVIEW

The accuracy of machined sculptured surface is influenced by a large number of error sources such as: inaccuracies in 3D solid model used to compute the tool path data, the inaccuracies in the computation of the cutter location data/NC tool path data, the deflection of the tool, deviations in geometry of moving machine drive axes, thermal distortions and vibration in the high speed spindle drives of the CNC machine tools. In this thesis work the main focus is on the determination of cutter location (CL) data considering the effect of the tool deflections so as to get the best possible surface finish close to the theoretical surface finish that could be ideally achievable. As stated in Section 1.1 of Chapter 1, the present work is focused on study of improving the surface finish during finishing stage while machining sculptured surfaces on Aluminum 6061 alloy using ball-end milling cutter. For the purpose of present thesis work, the various concepts published in the literature has been explored and are summarized under the following headings in this chapter:

1. Computation of cutter location data for ball-end mill
2. 3D CAD formats of the part models used for computation of cutter path
3. Ball-end milling cutter deflection determination methods
4. Cutting forces magnitude and point of action determination techniques
5. Tool deflection compensation methods
6. Cutting forces and surface finish inter-relationship in CNC machining

2.1 Computation of Cutter Location Data for Ball-End Mill

Milfelner and Cus [11] presented a unique method of simulation system of cutting process (SCP) for determining cutting forces when end milling is done with spherical cutter by optimizing both cutting process and tool shapes and using mathematical relationship between tool and workpiece in relation with various cutting parameters like cutting speed of tool, feed rates and depth of cut. Zeroudi et al. [12] identified a new geometrical approach for modeling of cutting forces in 3-axes CNC sculptured surfaces milling considering for the first time radial run out by using various position points of cutting tool coming from CAM data thus improving surface finish, tool life and machining efficiency by optimizing cutting parameters, thereby reducing tool wear.

Zeroudi and Fontaine [10] and Habibi et al. [9] and Ma et al. [13] suggested Mirror method to compensate the tool deflection which diverges any cutter from its actual position. In such a case, any resultant compensated tool path is made considering compensated Cutter location (CL) points considering the appropriate tool deflection values.

2.2 3D CAD Formats of the Part Models Used for Computation of Cutter Path

Chiang et al. [14] suggested a new reverse engineering method for creating interference free tool path in 3-axis machining by scanning data of any model by employing two procedures such as registration of scanned data and then well-organized tool-path generation of model from polygonal meshes. Yau et al. [15] presented a unique and modified approach for presentation of interference free NC tool paths that can be used for any general form of cutter with the main advantage of conversion of any parametric or implicit surface to triangulated surface. Moreover, such surface machining and tool path generation

proves to be more productive and less memory consuming than machining parametric surfaces by using the latter one.

2.3 Ball-End Milling Cutter Deflection Determination Methods

Kim et al. [7] derived a static deflection model considering various sections of ball-end mill representing different characteristics by considering the application of radial component of resultant cutting force on the tool as the fundamental reason for the deflection of the milling cutter deflection. In spite of the vertical force effecting the tool, the combined deflection of the tool and tool holder in axial direction is generally overlooked because of the comparatively high axial direction stiffness. Budak et al. [4] suggested a new method to calculate clamping stiffness of tool, which is an important parameter for accurate tool deflection calculation. It is used for determination of deflection of clamping system of machine as a function of contact length of tool, L_c , tool diameter, D and clamping coefficient, c and also radial run out, r_{rd} . Smaoui et al. [10] proposed a dynamic deflection model, thereby improving the shortcomings of the previous model by considering ball-end milling tool as a beam with cylindrical shape, whose one end is embedded while at the other end with hemispherical shape, is free. This model calculates deflection, dx from the bending moment, M equation, as function of Young modulus of elasticity, E and moment of inertia, I .

$$M = -EI\ddot{x} \quad (2.1)$$

Habibi et al. [9] suggested a new tool deflection estimation method by using three models for deflection calculation: a cutting tool geometrical model by considering tool diameter, a model of cutting force which can be either concentrated or distributed. Third model was used for deflection calculation which was basically a simple one such as a cantilever beam model or a finite element model. Zeroudi and Fontaine [12] predicted a new tool deflection prediction model for spherical milling using CAM data for describing the tool path and then modeling of the trajectory which is deflected from the interpolation done in linear manner by CAM software. Then this model estimates deflection in X, Y -axes for all reference points of the tool primarily at the CL and the CC points. This model approach for the first time considers radial deflection and does easy adjustment of integration constants.

2.4 Cutting Forces Magnitude and Point of Action Determination Techniques

S-T Chiang et al. [8] developed a cutting force model assuming that cutting force varies with specific cutting force and cutting area. Main advantage of model is that it can be used even when the cutter radius is less as compared to the axial depth of cut and it also includes the effect of helix angle and cusp-height formation on cutting force determination. Tai and Fuh [17] derived a new analytical cutting force model which stands on foundation of oblique cutting theory and ball-end milling process geometric parameters and also simplified the ball-end mill composite geometry. This force model proves to be flexible with many operation parameters, including modifications in feed rate, axial and radial depths of cut, as well as tool run out.

Kim et al. [7] suggested an innovative approach for prediction of cutting force acting on sculptured surfaces while performing end milling with spherical cutter by considering the effects of cusps and immediate change of workpiece geometry using Z-map technique and then finally evaluating cutting forces. Kim and Chu [17] proposed an accurate average cutting force assessment in complex surfaces

spherical milling operation using force determination algorithm which provides quick feedback information for regulating feed rate using force map method. Azeem et al. [18] suggested an effective ball-end milling cutting forces determination model by using the empirical force coefficients needed for a variety of cutting parameters by using geometric helical profile of the ball-end mill.

Budak et al. [4] suggested cutting forces calculation model for determining cutting forces in tangential, radial and axial directions considering, feed rates, chip thickness, milling force coefficients and immersion angle into workpiece due to the helical flutes thereby using an orthogonal data. Fontaine et al. [12] suggested an analytical force approach for spherical milling operation based on thermomechanical oblique cutting modeling and also improves tool life, surface finish, and efficiency by augmenting cutting conditions, tool path, tool-workpiece inclination and considering the radial run out of the tool. Tsai and Liao [19] predicted a unique cutting forces evaluation method known as Minimum energy method for spherical milling by inter-relating undeformed chip thickness, cutting velocity, rake angle, chip flow angle and shear plane area which can be used for all cutting tools with single or multi-flute tools.

Matsumura and Usui [20] predicted a new Minimum cutting energy method for determining cutting forces and chip flow directions while cutting with ball-end mill by compiling all the cuttings in the plane consisting chip velocities and cutting velocities. Wei et al. [21] exhibited a maiden prediction approach for determination of cutting forces in case of end milling of sculptured surfaces with spherical cutter along any random tool path by considering the effects of fluctuating feed directions and cutter engagement variations in sculptured surface machining using an improved Z-map method. Wojciechowski et al. [22] proposed a new method for analyzing cutting forces during ball nose milling process in relation with changing feed per tooth and surface inclination angles, also considering radial run out phenomenon.

Wojciechowski [10] further suggested a unique model for cutting force prediction, used for sculptured surfaces finished ball-end milling of by considering for the first time radial run out in equations used for calculation of cross-sectional area of cutting edge element and active length of cutting edge and thus provides good surface finish.

2.5 Tool Deflection Compensation Methods

Sortino et al. [24] develops a maiden feasible and simple approach as an innovation for changing the 3D STL model of the workpiece for automatic compensation of machined structures geometrical errors. Then tool trajectory is automatically regenerated using commercial CAM softwares. But, its application is limited only to correction of macroscopic errors and this can be improved by using more accurate scanning strategies. Moreover, efforts are being made now to apply compensation during tool path calculation only. Zeroudi and Fontaine [10] and Habibi et al. [9] and Ma et al. [25] suggested *mirror method* to compensate the tool deflection but without considering the tangential deflection along feed rate. Whenever tool/cutter is deflected, it is diverged from the hypothetical position given in NC Codes. In this case, any final programmed tool path consists of points diverged along the X, Y -axes by values contrary to the estimated deflection of the tool for both axes. This modification can be written as $(-dx, -dy)$ respectively and is put into application for the CL points along any tool path. Thus, finally, the compensated new coordinates will be defined as $(CL_X - dx, CL_Y - dy)$. This proposed approach

proves to be a landmark by reducing both manufacturing time and cost by elimination of repeated machining and hardware modification.

2.6 Cutting Forces and Surface Finish Inter-relationship in CNC Machining.

Kim et al. [7] and Budak et al. [4] presented a unique development of using the elastic compliance of the spherical milling cutter/ tool for evaluating the three-dimensional form error of any machined surface, by predicting cutter deflection at the contact point between cutting edge and any perfect machined surface. Lacalle et al. [9] derived tool deflection by considering tool as a cylindrical cantilever beam and also considered the dimensional errors as an outcome of deflection of tool whenever hardened steel surfaces are machined at high speed. Habibi et al. [9] suggested a new method for compensation of volumetric geometric errors by amending the nominal tool path. The main strength of this method is that this can be applied for any continuous point to point machining path, thereby improving the surface quality. Also, software establishment is done to create a tool path, which is a compensated one by copying the original tool path and doing essential compensation of geometrical deviations.

2.7 Conclusion

The literature associated with the tool deflection calculation and compensation procedures has been discussed elaborately in the previous sections. From the above literature review, it can be concluded that cutting forces play a significant role in determining the tool deflection. It becomes very important to determine the magnitude and direction of point of action of force in case of ball-end milling for tool deflection calculation. Although there are different models presented by different authors, but the cutting force model proposed by S-T Chiang et al has been preferred. For tool deflection, Kim model [7] has been preferably used and for tool deflection error compensation, Mirror method proposed by Zeroudi and Fontaine [10] has been used. All these models have been preferred because the values obtained by these models are very close to the experimental values.

CHAPTER: 3

MATHEMATICAL MODEL FOR FINDING TOOL DEFLECTION

Tool deflection is an important phenomenon which needs to be considered for accurate machining. While machining on 3-axis vertical milling machine, tool encounters the cutting forces and thus it acts as a cantilever beam. In this case, maximum forces are encountered in a plane normal to the axes of the tool. The forces acting on the ball-end milling cutters are basically tangential and radial cutting forces which cause tool deflection. These deflections are mainly due to the tool bending deflections and the deflection of the clamping mechanism of the machine. Various authors have developed various models for the determination of cutting forces [8,10,12,19]. Cutting forces depend on the composition of material to be machined, workpiece hardness and type of flutes whether straight flutes or helical flutes and also on machining parameters like axial and radial depths of cut, cutting speed and feed rates.

The deflections of the cutting tool while machining operation together place the end position into some other location rather than the desired ideal cutter location. In finishing operation, this change in the position of the spherical milling cutter causes the desired surface finish to deviate. So for achieving the better machined surface properties, we need to consider these deflections before and the suitable compensations in the cutter location data must be applied beforehand. The cutting forces encountered, can be found out from the machining parameters, workpiece material properties and the cutter/ tool material properties. Then these cutting forces are used later on to compute deflections. These deflections can be accommodated in the tool path calculation, where the effect of that compensation will place the tool at the correct place even after bending at the desired position. So the user gets the best desired surface finish.

In order to achieve the best desired surface finish while machining complex sculptured surfaces, ball-end milling cutter is mostly used [1]. Also, it generates better surface finish along feed direction or one can say produces minimum feed-marks as compared to flat end mill cutters. Moreover, it is easy to generate the gouge free cutter location data in case of ball end mill for triangulated surfaces [26-28].

3.1 Tool Deflections in End Milling Operation

In 3-axis vertical end milling operation, the main reason of the tool deflection is the horizontal component of the cutting forces encountered during machining. Though vertical force component is not absent, but its magnitude is comparatively much lesser as compared to the horizontal force components. Moreover the deflection of the tool system in axial direction is usually negligible because the comparatively high stiffness in this direction. Thus in most of the tool deflection studies, vertical force component is not considered [7]. Basically, tool deflections of a ball-end milling cutter are of two types which effect the machining operation and are listed below [7]:

- 1.) Bending deflection in the ball-end mill, δ_T
- 2.) Clamping system deflection in the machine spindle, δ_C

Thus, the total deflection of the cutting system, δ is expressed as given below [7]:

$$\delta = \delta_C + \delta_T \quad (3.1)$$

The following sub-sections detail the mathematical model used in our work to find out the expression for tool deflection δ_T and clamping system deflection δ_C for ball-end milling cutter.

3.1.1 Bending deflection of ball-end mill in 3-axis finishing operation

In this study, we have focused on cutting force identification model which considers the solid ball-end milling tool in its most realistic form and which gives better approximation of analytical results. The cutting force model given by Kim et al. [2] has been identified as the one which fulfills the requirement mentioned above and provides accurate results close to the experimental values. This section details the method proposed by Kim et al. for finding the cutter deflection for ball-end mill when the cutting forces are acting on the tool's spherical region.

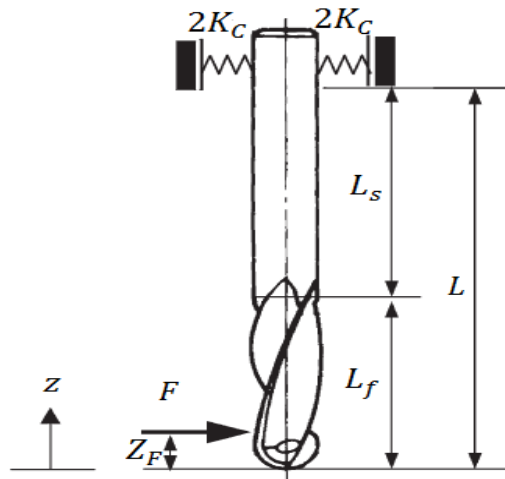


Figure 3.1: Cutter deflection model: Ball-end mill diagram showing cutter deflection system [2]

Assuming the ball-end milling tool as a cantilever, the tool bending deflection, δ_T encountered during machining is formulated as [2, 9 and 14]:

$$\delta_T = \frac{F}{6EI} [(Z_F - z)^3 - (L - z)^3 + 3(L - z)^2(L - Z_F)] \quad (3.2)$$

Where, E is Young modulus of elasticity, F is the resultant cutting force vector at the spherical part centre of ball-end mill, I represents the moment of inertia of the cutter, b denotes the tool base diameter, L represents the length of the overhanging portion, z denotes the position where the deflection is considered and Z_F represents the Z -directional position of the applied force as shown in figure 3.1.

The moment of inertia I in equation 3.2 is given by $I = \frac{bL^3}{12}$ (3.3)

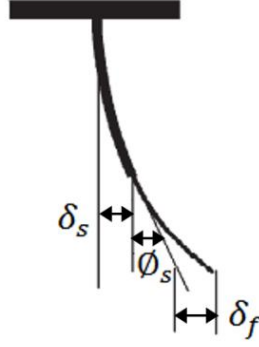


Figure 3.2: Two-step cylindrical cantilever beam representing deflection of two portions of ball-end milling cutter [7]

A typical ball-end milling tool consists of two portions, namely the fluted part and the tool shank as shown in figure 3.2. Thus equation 3.2 should be modified according to the cutter geometry variation along the Z-axis.

In the deflection model for spherical milling cutter reported by Kim et al. [7], the cutter has been assumed to be a double-step cylindrical cantilever beam as illustrated in figure 3.2. The resultant cutter bending deflection is a combination of three parts namely shank or non-fluted portion having deflection, δ_s , deflection of the fluted portion, δ_f and arc length of the deflected portion of the fluted part of ball-end mill, $[\phi_s(L_f - z)]$.

The deflection [7] of shank or non-fluted portion of the ball end mill, δ_s is given as:

$$\delta_s = \frac{F}{6EI_s} [-(L - L_f)^3 + 3(L - L_f)^2(L - Z_F)] \quad (3.4)$$

The deflection [7] of fluted portion is denoted as:

$$\delta_f = \frac{F}{6EI_f} [(Z_F - z)^3 - (L_f - z)^3 + 3(L_f - z)^2(L_f - Z_f)] \quad (3.5)$$

The arc length [7] of the deflected portion of the fluted part of ball-end mill is denoted as:

$$\phi_s(L_f - z) = \frac{F}{2EI_s} [-(L - L_f)^2 + 2(L - L_f)(L - Z_F)] (L_f - z) \quad (3.6)$$

In the equation shown above for computation of cutter bending deflection, I_s is the Moment of inertia of non-fluted or shank portion denoted by [2]: $I_s = \frac{bd^3}{12}$ (3.7)

Where b is tool base diameter and d is depth of non-fluted portion outside collet.

The ball-end milling cutter geometry is very complex along its axis, thus it is not simple to compute its moment of inertia.

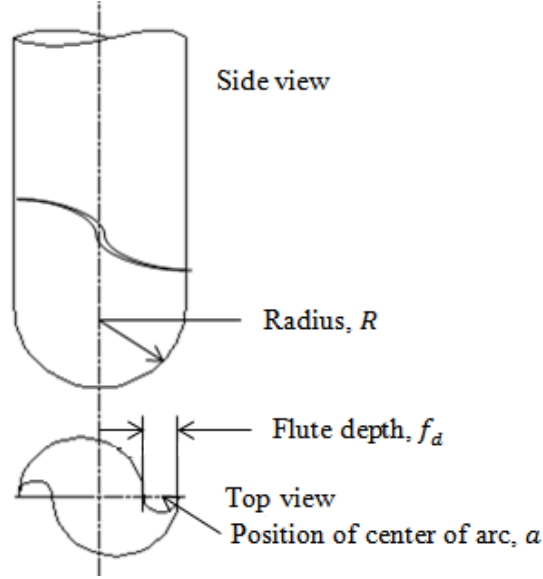


Figure 3.3: Cross-section of two flute ball-end mill [4]

The inertia of fluted portion of ball-end mill, as shown in figure 3.3 is derived by calculating equivalent radius, R_θ as a function of the arc radius, r and position of the center of the arc, a . Equivalent radius R_θ is denoted by [4] as:

$$R_\theta = -a \cos \theta + \sqrt{(r^2 - a^2) + a^2 \cos^2 \theta} \quad (3.8)$$

Where $0 < \theta \leq \pi$

Moment of Inertia of Flute, I_f is denoted by [4]:

$$I_f = 2(I_{XX} + I_{YY}) \quad (3.9)$$

Where I_{XX} and I_{YY} are Moment of Inertia of two flute ball-end mill about X- and Y-axis respectively.

$$I_{XX} = \left[\int_0^\pi \int_0^{R_\theta} \rho^3 \sin^2 \theta d\rho d\theta \right] - \left[\frac{\pi}{8} \left(\frac{f_d}{2} \right)^4 + \frac{\pi \left(\frac{f_d}{2} \right)^2}{2} \left(r + a - \frac{f_d}{2} \right)^2 \right] \quad (3.10)$$

Where, $0 < \rho \leq R_\theta$

$$I_{YY} = \left[\int_0^\pi \int_0^{R_\theta} \rho^3 \cos^2 \theta d\rho d\theta \right] - \left[\frac{\pi}{8} \left(\frac{f_d}{2} \right)^4 \right] \quad (3.11)$$

$$\delta_T = \delta_s + \delta_f + \phi_s(L_f - z) \quad (3.12)$$

Substituting the expansions of terms δ_s , δ_f and $\phi_s(L_f - z)$ from equations of 3.3 to 3.11 in equation 3.12, the resultant cutter bending deflection, δ_T for a ball end mill is given as:

$$\begin{aligned} \delta_T = & \frac{F}{6EI} \left[-(L - L_f)^3 + 3(L - L_f)^2(L - Z_F) \right] + \\ & \frac{F}{6EI_f} \left[(Z_F - z)^3 - (L_f - z)^3 + 3(L_f - z)^2(L_f - Z_f) \right] + \\ & \frac{F}{2EI} \left[-(L - L_f)^2 + 2(L - L_f)(L - Z_F) \right] (L_f - z) \end{aligned} \quad (3.13)$$

The equation 3.13 can be rewritten as

$$\text{Or, } \delta_T = \frac{F}{2E} \left[\frac{\frac{\{-(L-L_f)^3+3(L-L_f)^2(L-Z_F)\}}{3I_s} + \frac{\{(Z_F-z)^3-(L_f-z)^3+3(L_f-z)^2(L_f-Z_f)\}}{3I_f}}{I_s} + \frac{\{-(L-L_f)^2+2(L-L_f)(L-Z_F)\}(L_f-z)}{I_s} \right] \quad (3.14)$$

Where L_f is the length of the fluted portion, ϕ_s is the shank deflection angle and I_f is moment of inertia of fluted portion.

Similarly, in this way, the corresponding cutter bending deflections in X, Y, Z -directions can also be obtained by inserting values of X, Y, Z -directional components of resultant force vector F in equation 3.14.

3.1.2 Clamping system deflection

After the accurate modeling of the tool, determination of the clamping stiffness is very important for estimation of clamping part deflection of CNC Vertical milling machine. Then only finally the total deflection of the tooling system can be calculated. Relying on the fastening conditions, the impact of flexibility of the clamping system on the accumulative tool deflection can be a substantial one. Budak [4] suggested a unique method to calculate clamping stiffness of tool, which is an important parameter for accurate tool deflection calculation by calculating clamping system deflection, δ_C for ball-end milling cutter. This model proposed has been used because it considers the radial run out of 3-axes BFW CNC Vertical Milling Center. For estimating the deflection of the clamping part, δ_C for X, Y, Z -axes respectively, the clamping part stiffness, K_C is determined experimentally.

The Clamping stiffness of the tool, K_C has a significant contribution for calculation of total tool deflection. Budak model [4] is used for this stiffness measurement. According to this model, the elastic displacement of the connection, δ_{ed} can be formulated as:

$$\delta_{ed} = \frac{2cq}{\pi D} \quad (3.15)$$

In this case, δ_{ed} is the axial runout of 6 mm diameter ball-end milling cutter measured experimentally using Dial indicator to determine whether the value of radial runout measured using experimental method is equal to the value obtained from the formulation 3.17.

Where, q is cutting force, F per unit Contact length, L_c denoted by:

$$q = \frac{F}{L_c} \quad (3.16)$$

In equation 3.16 the term c is contact compliance coefficient denoted by:

$$c = \frac{L_c r_{rd} \pi d}{2F_{rep}} \quad (3.17)$$

Where, r_{rd} is radial runout of the ball-end milling cutter;

and, F_{rep} is force representation denoted by:

$$F_{rep} = \frac{2F^m}{nL_c} \quad (3.18)$$

Where, m is the clamping stiffness material coefficient, whose value is 1 for carbide tools and 0.9 for HSS tools.

So in case of tungsten carbide ball-end milling tool, being used in this study, value of m has been selected as 1. While n is Compensatory contact length coefficient, whose value is 2 for $L_c \geq 30$ and 3 for $L_c < 30$.

The clamping Stiffness, K_C is denoted by:

$$K_C = \frac{\pi L_c d}{2c} \quad (3.19)$$

The deflection of the tool clamping system, δ_C is finally determined as:

$$\delta_C = \frac{F}{K_C} \quad (3.20)$$

Where K_C is the stiffness of clamping part of the 3-axis BFW CNC Milling Machine.

By inserting values of X -axes, Y -axes and Z -axes components of resultant force vector F , namely F_X , F_Y and F_Z respectively in equation 3.20, corresponding to Cutter clamping deflections in X , Y and Z directions can be formulated.

Finally, the total deflection as suggested by the equation 3.2, like δ_T value has been explained in the section 3.2, the final expression of the total tool deflection comes out as [7]:

$$\delta_i = \delta_{Ci} + \delta_{Ti} \quad (3.21)$$

The cutting forces experienced by the tool have been discussed in the form of various analytical models in the section below.

3.2 Model Used for Finding the Cutting Forces

Thus out of all the models mentioned in the Literature review section 2.4, the model proposed by S-T Chiang et al. [8] has been selected because in this model, the results are very close to the experimental

values as well as it considers the tool in a more realistic form-cylindrical or solid part at the top and spherical part at the bottom. In our model, we have restricted ourselves to the maximum cutting forces experienced by the tool having n_f number of flutes which will help us to determine the feed per tooth and further for determination of cutting force values. These calculations are done only for side machining as the tool progresses from one side to the other and following the zigzag pattern as shown in the figure 3.4. In this case, both the radial and the axial depths of cut are taken on one side only.

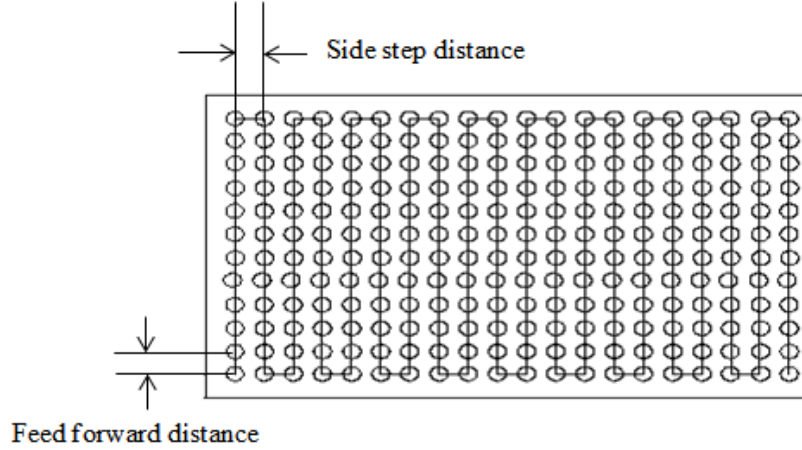


Figure 3.4: Side step and feed forward distance

As per the force model proposed by S-T Chiang et al. [8], for calculating tool deflection, cutting force determination is very important. In the present work an approximation method has been used where cutting edge is divided into infinitesimal sections or elements. For each of them, the associated chip thickness and depth of cut is determined to obtain the cutting area and then it is put into the force model to find the infinitesimal cutting force. Finally, the cutting forces obtained are summed up to obtain the accumulative force. In case of ball-end milling, instantaneous chip thickness is denoted by t_{cij} as [8]:

$$t_{cij} = f_t \sin \gamma_j \sin \eta_j \quad (3.22)$$

Where $\eta_j = j\Delta\eta$ and $\Delta\eta = \frac{\pi}{2N_e}$

The term j represents the number of cutting edge segments used to approximate the total cutting edge area.

In case of very small $\Delta\eta$ value, the infinitely small projected cutting edge element area on the vertical plane can be denoted as:

$$A_{ij} = t_{cij} R \Delta\eta \quad (3.23)$$

Thus by substituting values of t_{cij} in equation 3.23, A_{ij} can be written as:

$$A_{ij} = f_t \sin \gamma_j \sin \eta_j R \Delta\eta \quad (3.24)$$

In this case, if the helix angle, β effect is also considered, then the infinitesimal cutting area, A_{ij} is modified as:

$$A_{ij} = f_t \sin \gamma_j \sin \eta_j R \Delta\eta \sec \beta \quad (3.25)$$

Where $f_r = \frac{f}{N}$ and $f_t = \frac{f_r}{t}$

In above equations, f denotes the feed rate, N is spindle speed in rpm, f_t is feed per tooth, t is number of teeth or number of flutes, N_f . Also, $\eta_j = \eta + \Delta\eta$, where $1 \leq j \leq 10$ and $\eta = 0$ as initial value.

3.2.1 Cutting edge engagement angle, γ_j determination

For determination of Cutting edge engagement angle, γ_j , there are three cases which depend on the value of Cusp height, h_c , whose value comparison is made with the Ball-end mill radius and the value of a constant $R(1 - \cos \eta_j)$. Cusp height, h_c is denoted by 3.26:

$$h_c = R - \frac{\delta A_d}{2} - \frac{r_d}{2} \sqrt{\frac{4R^2 - r_d^2 - \delta A_d^2}{r_d^2 + \delta A_d^2}} \quad (3.26)$$

Relationship of cusp height, h_c with variation of depth of cut, δA_d for three different cases has also been shown in the figure 3.5.

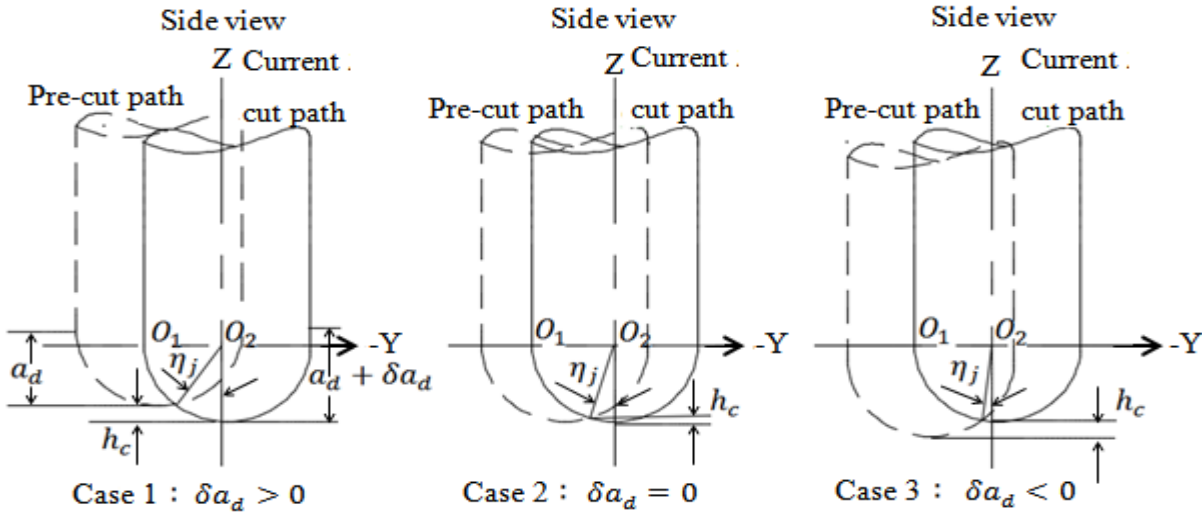


Figure 3.5: Three different cases showing relationship of cusp height, h_c with variation of axial depth of cut, δa_d . [8]

Three different cases used in the form of equation 3.26 for determination of values of angle γ_j are also shown in the figure 3.6:

Case 1: If $R(1 - \cos \eta_j) < h_c$, $\gamma_j = \pi$

Case 2: If $h_c \leq R(1 - \cos \eta_j) < R$, $\gamma_j = \cos^{-1}\left(1 - \frac{r_d}{R \sin \eta_j}\right)$

Case 3: If $R \leq R(1 - \cos \eta_j)$, $\gamma_j = \cos^{-1}\left(1 - \frac{r_d}{R}\right)$ (3.27)

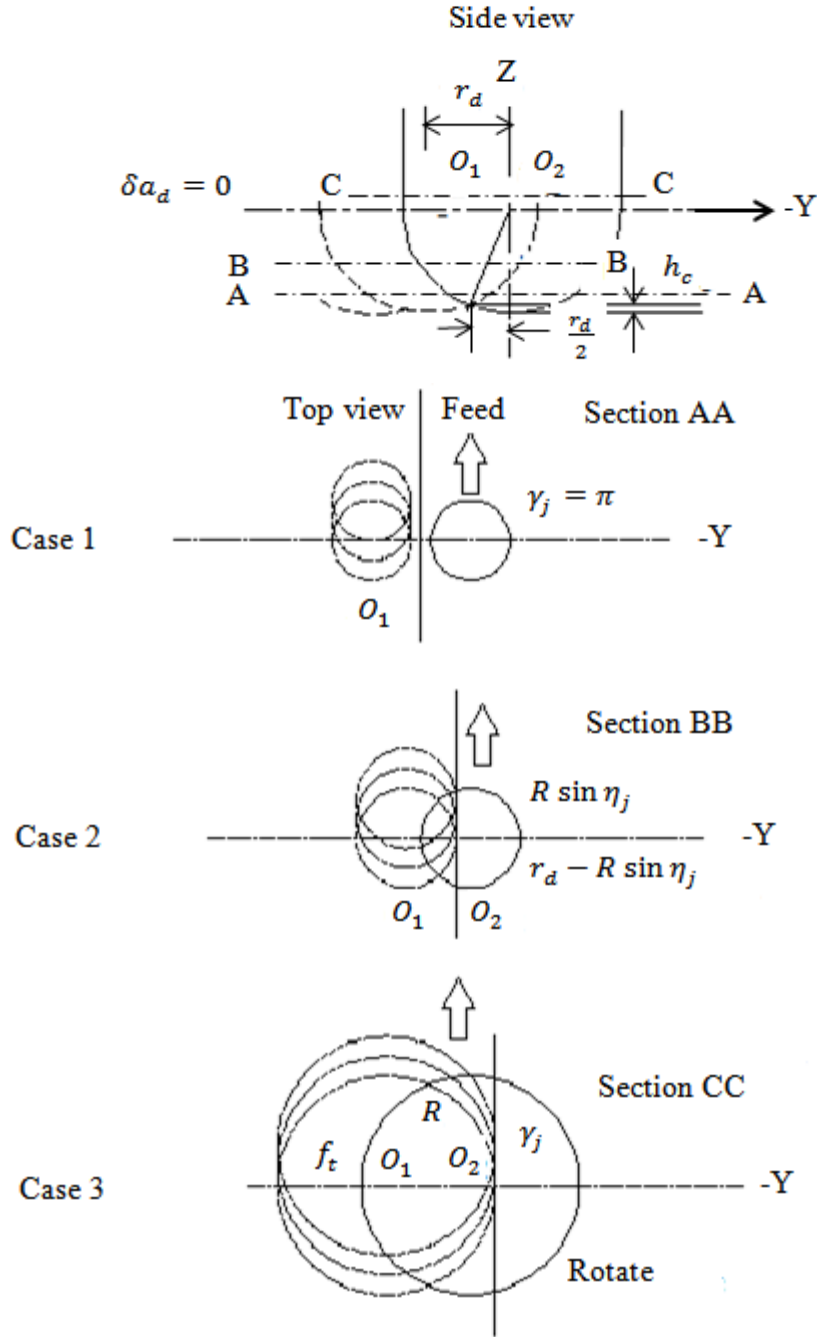


Figure 3.6: Three different cases for determination of cutting edge engagement angle, γ_j [8]

3.2.2 Cutting force model

In this section, infinitesimal cutting forces acting on the infinitely small cutting area have been calculated. These forces in normal, radial and tangential directions are formulated as a function of their respective specific cutting forces K_n , K_r and K_t .

$$\Delta f_{n_{ij}} = K_n A_{ij}$$

$$\Delta f_{r_{ij}} = K_r A_{ij}$$

$$\Delta f_{t_{ij}} = K_t A_{ij}$$

(3.28)

In these three equations 3.28, $\Delta f_{n_{ij}}$ is the force acting normally towards the cutting area; $\Delta f_{r_{ij}}$ represents the force which acts radially from the center of the area A_{ij} to the origin of the frame OXYZ, and $\Delta f_{t_{ij}}$ is the force acting tangentially along the cutting edge. Here, K_n, K_r and K_t are the specific cutting forces in normal, radial and tangential directions. Values of K_n, K_r and K_t are denoted by the below given formula 3.29 which includes different values of coefficients $c_1 - c_{10}$.

$$K_n, K_r, K_t = c_1 + c_2 f_t + c_3 h_d + c_4 f_t^2 + c_5 f_t h_d + c_6 h_d^2 + c_7 f_t^3 + c_8 f_t^2 h_d + c_9 f_t h_d^2 + c_{10} h_d^3 \quad (3.29)$$

Table 3.1: Coefficients of K_n, K_r, K_t [1]

Coefficients	K_n	K_r	K_t
c_1	-1.14×10^{-3}	-1.800×10^{-3}	-5.10×10^{-4}
c_2	-1.685×10^4	-2.850×10^4	-1.053×10^4
c_3	1.087×10^2	1.507×10^2	7.204×10^1
c_4	1.399×10^4	2.059×10^4	7.189×10^3
c_5	3.977×10^2	7.069×10^2	2.669×10^2
c_6	-2.59×10^0	-4.03×10^0	-1.958×10^0
c_7	-2.955×10^4	-4.292×10^4	-1.667×10^4
c_8	2.023×10^2	2.861×10^2	1.219×10^2
c_9	-3.902×10^0	-6.552×10^0	-2.535×10^0
c_{10}	1.885×10^{-2}	3.059×10^{-2}	1.467×10^{-2}

The cutting forces defined in equation above have to be renovated to the global rectangular coordinates in X, Y, Z -directions. Figure 3.7 shows three dimensional coordinate rotations of infinitesimal cutting forces $\Delta f_{n_{ij}}, \Delta f_{r_{ij}}$ and $\Delta f_{t_{ij}}$.

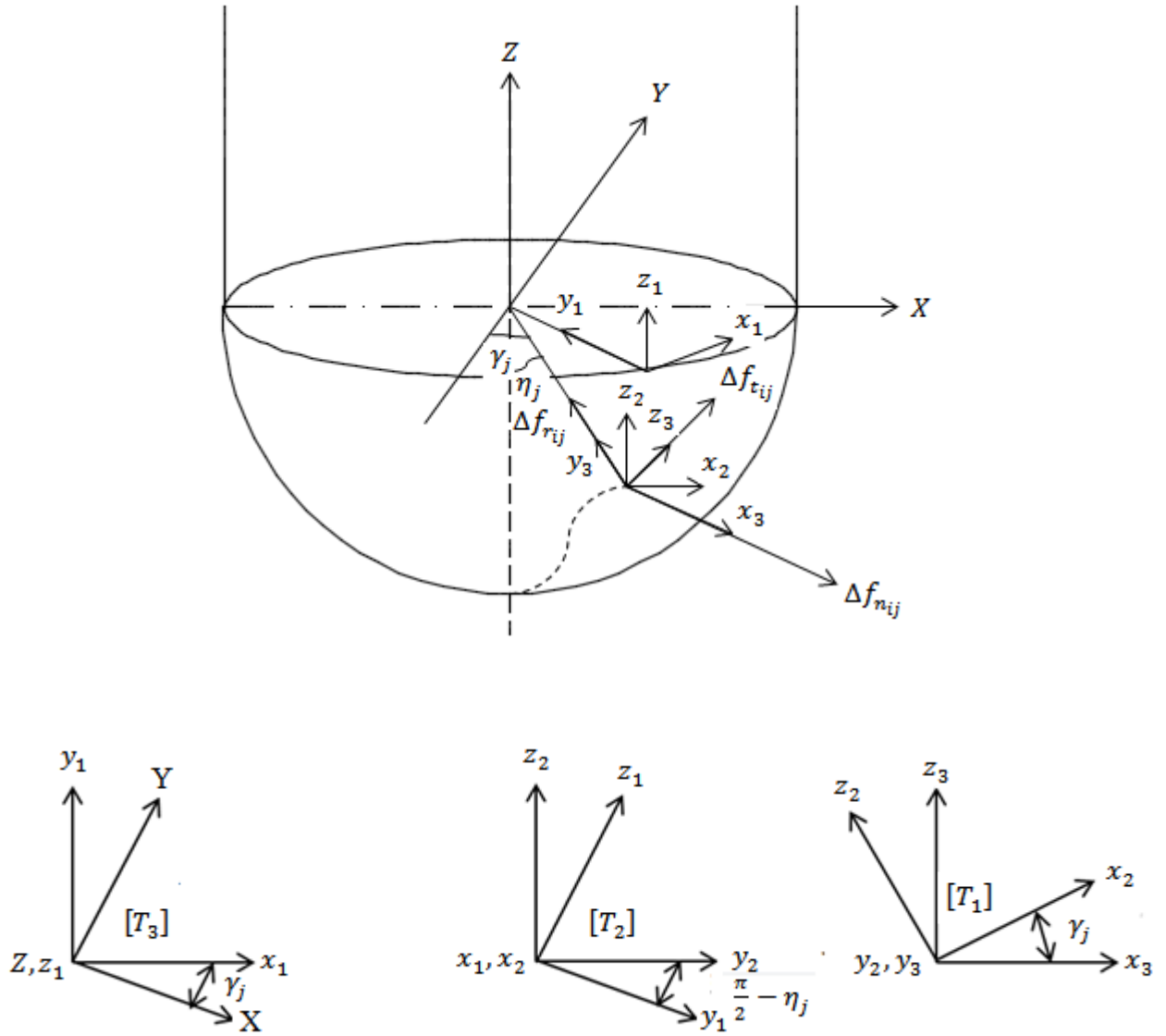


Figure 3.7: Demonstration of three dimensional coordinate rotations of infinitesimal cutting forces Δf_{nij} , Δf_{rij} and Δf_{tij} . [8]

The transformation matrices relating the local and global coordinates are $[T_1]$, $[T_2]$ and $[T_3]$, Where,

$$[T_1] = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}, [T_2] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\eta_j & -\cos\eta_j \\ 0 & \cos\eta_j & \sin\eta_j \end{bmatrix} \text{ and } [T_3] = \begin{bmatrix} \cos\gamma_j & -\sin\gamma_j & 0 \\ \sin\gamma_j & \cos\gamma_j & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3.30)$$

$$\begin{bmatrix} \Delta f_{Xij} \\ \Delta f_{Yij} \\ \Delta f_{Zij} \end{bmatrix} = [T_3][T_2][T_1] \begin{bmatrix} \Delta f_{nij} \\ \Delta f_{rij} \\ \Delta f_{tij} \end{bmatrix} \quad (3.31)$$

The aggregate cutting forces in X, Y, Z -directions are derived by summing infinitesimal cutting forces:

$$\begin{aligned} F_{X_i} &= \sum_i \sum_j \Delta f_{X_{ij}} , \\ F_{Y_i} &= \sum_i \sum_j \Delta f_{Y_{ij}} , \\ F_{Z_i} &= \sum_i \sum_j \Delta f_{Z_{ij}} \end{aligned} \tag{3.32}$$

So for computing the cutting forces, it is very important to know about the maximum shearing region or area of the cutting edge of the tool. So in this model, we have simplified the procedure considering only the maximum cutting forces experienced by the tool. Though it gives generally at the start of the tool but the tool will be immediately under the impact of the cutting forces and it will be dragged backwards but at the same time, it is being carried to a location where the maximum engagement of the cutter is there. Because we have selected the helical cutting tool with Helix Angle of 19° and only finishing operation is being considered, so the expression for the forces is only for the region lying below the ball-end milling cutter center.

The compensation procedures applied for tool deflection as a consequence of the cutting forces experienced by the tool have been discussed in the form of various analytical models in the section below.

3.3 Model Used for Compensation of Tool Deflection

Various authors have developed various models for applying compensation for tool deflection caused by the cutting forces. So, because of cutting forces in radial and tangential directions, all the deflections caused by them together place the end position of the ball-end milling cutter into some deviated location rather than the required desired ideal location. In finishing operation, this change in the ball end-mill position causes deviation in the desired surface finish. So for achieving the better properties of the machined surface, it becomes very important to consider these deflections before and thereby applying the suitable compensations before machining process in the tool path only.

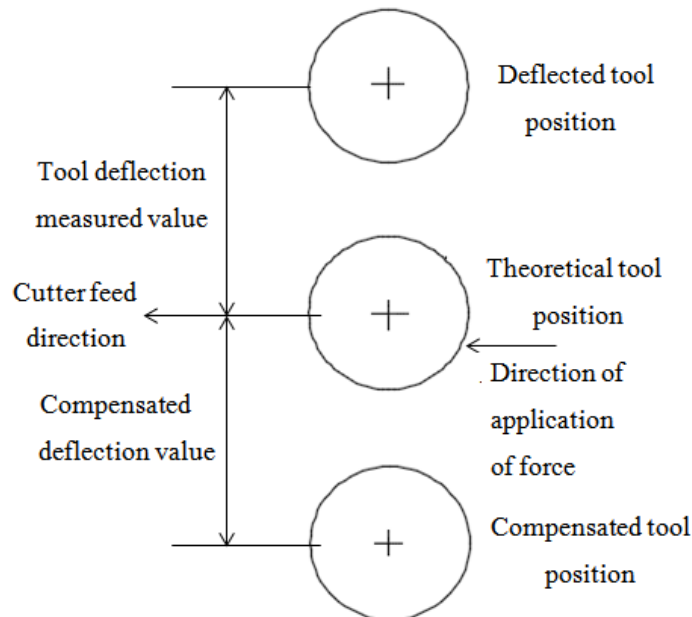


Figure 3.8: Application of Mirror method [9]

Thus, the model proposed by Zeroudi and Fontaine [10] named as *mirror method* shown in figure 3.8 has been selected for applying suitable tool deflection compensation because this compensation can be applied directly in tool path only and implementation is also easy.

Whenever tool/cutter is deflected, it is diverged from the hypothetical position given in NC Codes. In this case, any final programmed tool path consists of points diverged along the X, Y -axes by values opposite to the estimated deflection of the tool for both axes. This modification can be written as $(-dx, -dy)$ respectively and is put into application for the CL points along any tool path.

So finally, the resultant deflection of ball-end milling cutter is evaluated by using the formula:

$$\delta = \sqrt{\delta_x^2 + \delta_y^2} \quad (3.33)$$

Where δ is the resultant deflection of spherical milling cutter and δ_x and δ_y are the deflections of the same cutter in X, Y -directions respectively obtained from the equation 3.20.

Now resolving the vector components of ball-end milling cutter in X, Y -directions by using the formula:

$$\delta_x = \hat{i}\delta = \delta \sin \phi \quad (3.34)$$

In equation 3.34, \hat{i} is the normal vector denoted by $\sin \phi$.

Where ϕ is cutting edge element rotation angle denoted by formula :

$$\phi = \cos^{-1} \frac{(r-a_d)}{r} \quad (3.35)$$

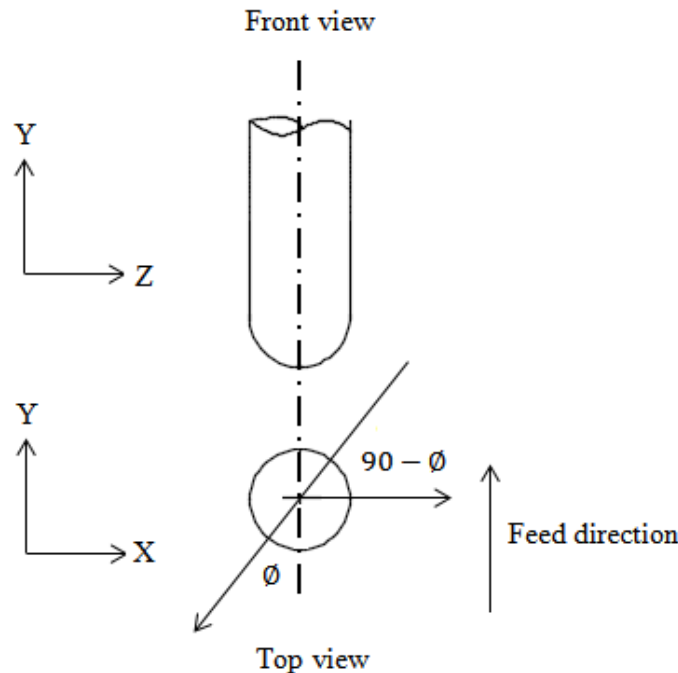


Figure 3.9: Demonstration of cutting edge element rotation angle, ϕ with proper feed direction

In equation 3.35 the parameter r is the distance of cutting edge element of ball-end milling cutter from the origin and is given by:

$$r = \sqrt{R^2 - (R - a_d)^2} \quad (3.36)$$

Thus we have, $\delta_Y = \hat{i}\delta = -\delta \cos \phi$ (3.37)

In equation 3.37, \hat{i} is the normal vector denoted by $-\cos \phi$.

After determining the vector components of ball-end milling cutter, compensated deflection values δ_{CX} and δ_{CY} are calculated by using the formula:

$$\delta_{CX} = -\delta_X \quad (3.38)$$

$$\delta_{CY} = \delta_Y \quad (3.39)$$

Thus, finally, the compensated new coordinates considering the deflections of the spherical milling cutter in X, Y -directions are defined by the formula:

$$CL_X = X + \delta_{CX} \quad (3.40)$$

$$CL_Y = Y + \delta_{CY} \quad (3.41)$$

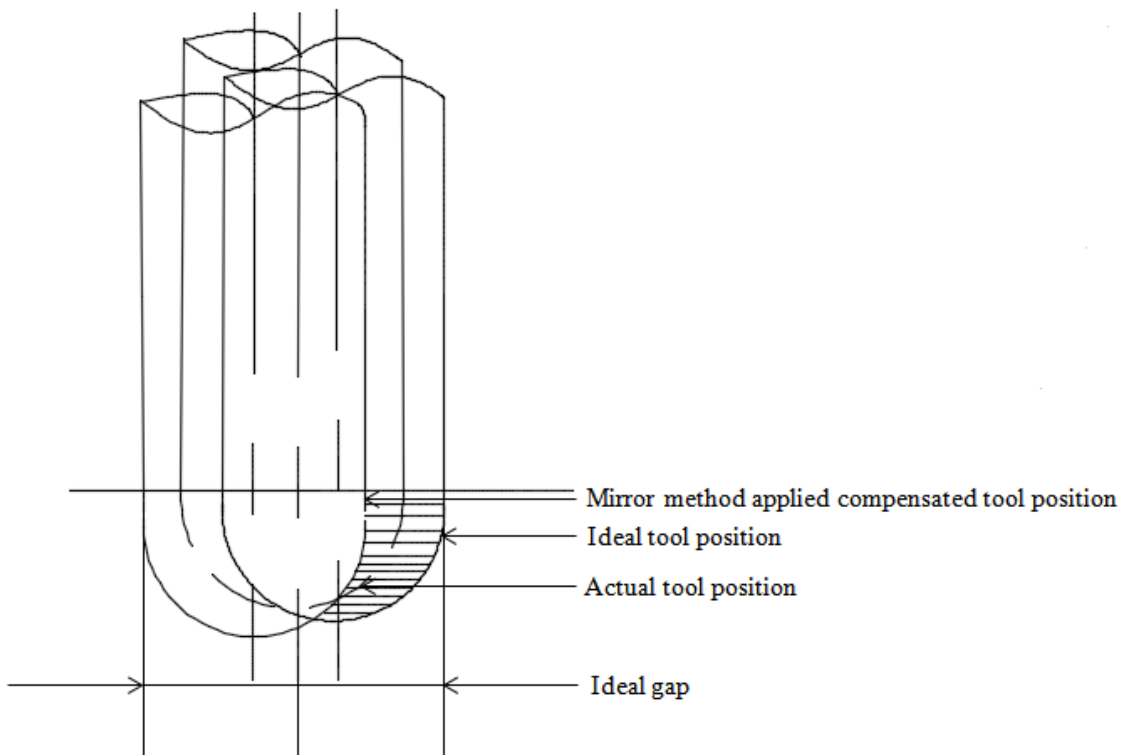


Figure 3.10: Demonstration of ideal gap in case of ball-end milling cutter with compensated toolpath

Thus finally, the whole methodology for tool deflection calculation and compensation which has been implemented in the present work is shown in the form of flowchart in Figure 3.11.

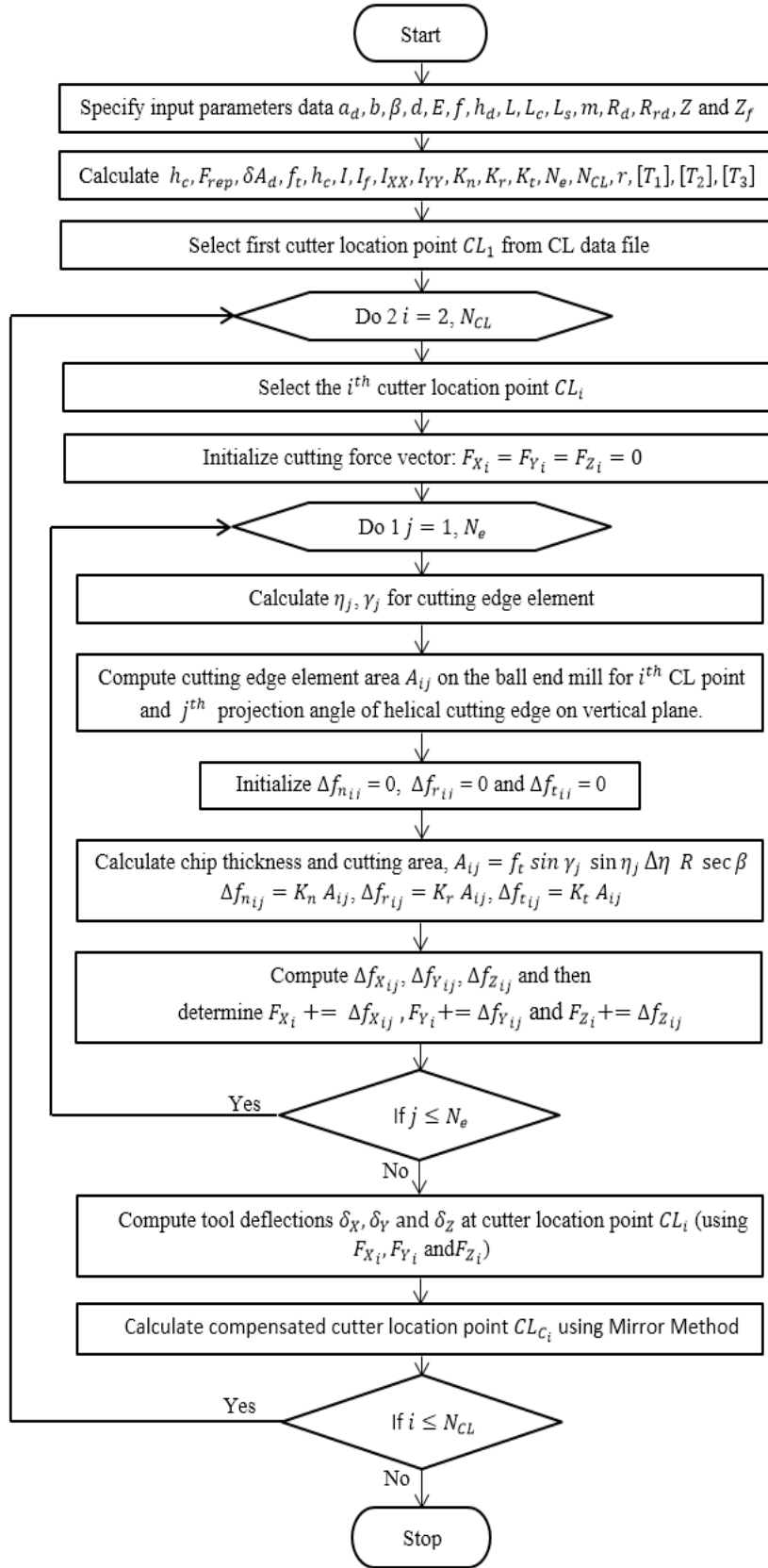


Figure 3.11: Toolpath generation algorithm for tool deflection calculation and compensation

3.4 Steps of Toolpath Generation Algorithm for Tool Deflection Calculation and Compensation

1. Firstly, all data related to input parameters required for tool deflection calculation are specified.
2. Then, various parameters like h_c , F_{rep} , transformation matrices T_1, T_2, T_3 , specific cutting force K_n , K_r , K_t are calculated using input parameter values specified before.
3. Then, first Cutter location point CL_1 is selected from CL data file prepared for performing machining operation starting from i^{th} CL point till total number of control points N_{CL} by using do loop and cutting force vectors F_{X_i} , F_{Y_i} and F_{Z_i} are initialized as zero.
4. Next, Cutting edge engagement angle, γ_j and Projection angle of helix angle on vertical plane, η_j are calculated for each engaged cutting edge.
5. Then, cutting edge element area A_{ij} is calculated.
6. Then, chip thickness is calculated and further used for calculating cutting area, A_{ij} on ball-end mill for each i^{th} CL point and j^{th} projection angle of helix angle on vertical plane for each cutting edge element by also considering the effect of Helix angle, β on cutting edge element engagement point.
7. Calculated cutting area is used for calculating instantaneous cutting forces $\Delta f_{X_{ij}}$, $\Delta f_{Y_{ij}}$ and $\Delta f_{Z_{ij}}$ using specific cutting force coefficients K_n , K_r and K_t .
8. Then, summation of instantaneous cutting forces is done to calculate global cutting forces F_{X_i} , F_{Y_i} and F_{Z_i} in X, Y and Z directions.
9. Then, tool deflections δ_X , δ_Y and δ_Z are calculated using global cutting forces F_{X_i} , F_{Y_i} and F_{Z_i} in X, Y and Z directions.
10. Finally, compensated cutter location points CL_{C_i} are calculated using *mirror method* till number of control points i become equal to N_{CL} .
11. All the data required for generating Toolpath algorithm for Tool deflection calculation and compensation has been extracted from the Excel sheet which also includes data of various Cutter Location points followed by the cutting tool while performing machining operation and various cutter and machining parameters values.

CHAPTER: 4

RESULTS AND DISCUSSIONS

In the present work, tool deflection calculation and compensation methodology has been determined and further implemented for slot milling. For experimental work, the whole methodology has been carried out on BFW CNC Vertical Milling Machine using 6 mm diameter ball-end milling cutter on Aluminum T-6061 alloy plate for both compensated as well as non-compensated tool paths. For this experimentation work, various cutter parameters and their values used are shown in the table 4.1.

Table 4.1: Cutter parameters

Sr. No.	Parameters	Values
1	Cutter diameter, or Tool base diameter, D	6 mm
2	Length of fluted portion of cutter, L_f	15 mm
3	Length of shank portion of cutter, L_s or depth of non-fluted portion outside collet, d	23 mm
4	Cutter radius, R	3 mm
5	Length of overhang portion of cutter, L	38 mm
6	Helix angle, β	19°
7	Number of teeth, Z	2
8	Contact length of cutter, L_c	12.4 mm

Also, various cutter and workpiece material properties used for current methodology along with their values are shown in table 4.2 and machining parameters values used are shown in the table 4.3.

Table 4.2: Cutter and workpiece material properties

Sr. No.	Properties	Values
1	Clamping stiffness of spindle, K_c	375.8 N/mm
2	Young Modulus of Elasticity, E	615000 N/mm ²
3	Radial runout, r_d	0.045mm
4	Moment of Inertia of fluted portion of cutter, I_f	1858.4 N/mm ⁴
5	Moment of inertia of non-fluted or shank portion of cutter, I_s	8111.3 N/mm ⁴
6	Contact compliance coefficient, c	0.31
7	Compensatory contact length coefficient, n	3
8	Clamping stiffness material coefficient, m	1
9	Number of infinitesimal cutting edge elements, N_e	10
10	Workpiece hardness, h_d	60 HRB

Table 4.3: Machining parameters

Sr. No.	Parameters	Values
1	Feed, f	158.7 mm/min
2	Properties Speed, N	2400 rpm
3	Axial depth of cut, a_d	1 mm and 2mm
4	Radial depth of cut, r_d	0.25 and 0.5 mm
5	Variation in axial depth of cut, δA_d	1 mm
6	Feed per tooth, f_t	0.033 mm/tooth

4.1 Validation Procedure Used for Results and Discussions

1. First of all, cleaning of workpiece is done using 20 mm diameter inserted Flat-end milling cutter on 3-axes CNC Vertical milling machine.
2. Then, 6mm diameter ball-end milling cutter is moved 100 mm away from one end of plate 305mm \times 305mm \times 25mm deep and is then plunged 1 mm deep as axial depth of cut, a_d into the workpiece. This cutter is then moved till the distance remains 20mm from the nearest plate end and then side feed or side step is taken as 0.25mm and 0.5mm respectively in two different cases for two different non-compensated tool paths respectively, thereby covering distance upto 100 mm again and then retracting to the initial position as shown in the figure 4.1 illustrating both compensated and non-compensated toolpaths.
3. Then compensated tool path is made for the previous two cases considering tool deflection and then machining is done again when cutter retracts to 100mm distance away from the nearest end of the plate for the second time.
4. Then again, the same procedure is followed as discussed in second step above, but in this case, the tool is plunged 2mm deep as axial depth of cut into the workpiece. Here also side feeds are taken as 0.25mm and 0.5mm for two different cases and machining is done using different non-compensated tool paths.
5. Then again, machining is done using compensated tool path considering tool deflections for 2 mm a_d .

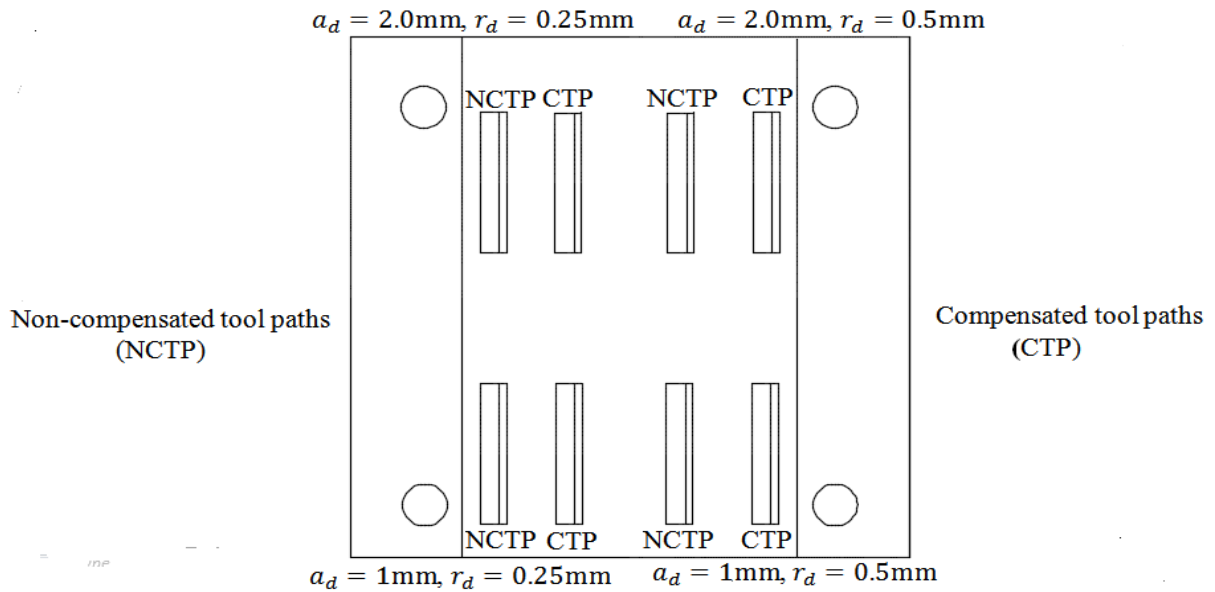


Figure 4.1: Experimental drawing of machined workpiece showing various values of axial and radial depth of cuts.

The experimental validation setup used for tool deflection compensation methodology has been shown in the figure 4.2 below. Figure 4.3 shows uncut material region of workpiece because of tool deflection.



Figure 4.2: Experimental setup of machined workpiece showing various values of axial and radial depth of cuts.

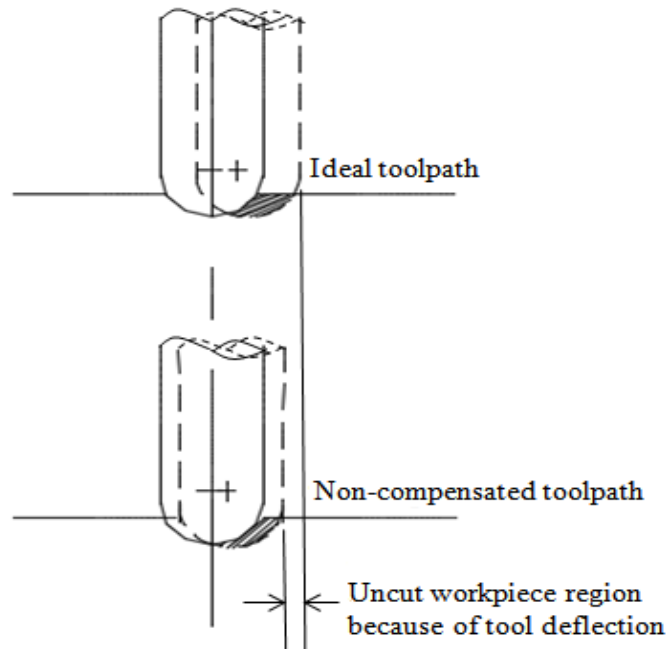


Figure 4.3: Illustration of uncut workpiece region because of tool deflection



Figure 4.4 Measurement of compensated and non-compensated slots on profile projector

All values of slots of compensated as well as non-compensated toolpaths have been measured with the help of profile projector as shown in figure 4.4. Moreover, the comparison of compensated and non-compensated cutter location data has also been shown in the form of table 4.4.

Table 4.4: Comparison of compensated and non-compensated cutter location data

Axial depth of cut, a_d (mm)	Radial depth of cut, r_d (mm)	Ideal geometric gap value (mm)	Measured value without applied compensation after machining	Percentage error measured from ideal value without applying compensation	Measured value with applied compensation after machining	Percentage error measured from ideal value with applied compensation
1.0	0.25	4.71	4.478	4.92%	4.674	0.76%
1.0	0.5	4.96	4.726	4.71%	4.915	0.92%
2.0	0.25	5.89	5.728	2.75%	5.845	0.77%
2.0	0.5	6.14	5.851	4.70%	6.107	0.54%

4.2 Inferences Drawn From the Results Obtained

So, as evident from the comparison table 4.4 showing different values of compensated and non-compensated cutter location data, it can be concluded that though the tool deflection compensation methodology employed in this work is not ensuring 100% nearness to the ideal value, but the values of the slots obtained by using the compensated toolpaths are much closer to the ideal values as compared to the non-compensated toolpaths. Moreover, in the same table, percentage error of deviations of both the compensated and non-compensated toolpaths of the machined slots from the ideal values for various axial and radial depths of cuts values has also been determined within 1% value, thereby ensuring in the form of results obtained that the procedure used is accurate enough for tool deflection compensation. Figure 4.5 shown below displays the different views of spherical milling cutter showing the direction of action of force.

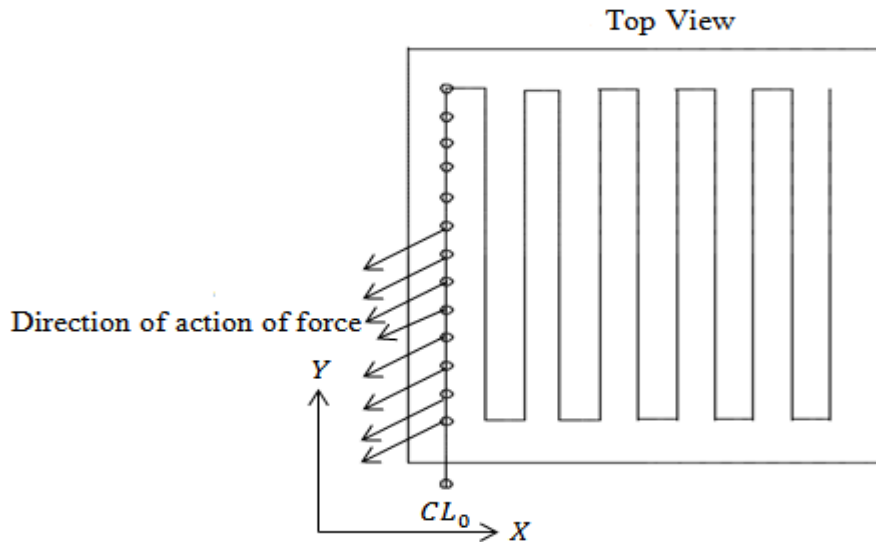


Figure 4.5: Demonstration of different views of movement of spherical milling cutter on any toolpath showing the direction of action of force

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion of Present Work

In the present work, a detailed study for the tool deflection calculation and compensation has been done. Also, this study has been verified by producing slots in Aluminium T-6061 alloy plate using compensated and non-compensated toolpaths and using ball-end milling cutter of 6mm diameter. The values of axial depths of cuts have been taken as 1mm and 2mm respectively while the values of radial depths of cuts have been taken as 0.25mm and 0.5 mm. Then measurement of slots is done using Profile Projector. Tool deflection calculation procedure in accordance with Kim et al. [2] has been used because it considers the different behaviors of different sections of ball-end milling cutter. For tool deflection determination procedure, cutting force magnitude and direction was determined by using Chiang et al. [8]. After tool deflection determination, *mirror method* was used for making compensated tool path considering deflection of ball-end milling cutter. The conclusions drawn from the present study are as follows:

1. Deflection model suggested by Kim et al. is best suitable for ball-end milling cutter deflection determination.
2. Cutting force model recommended by Chiang et al. is a better alternative for cutting force prediction.
3. Mirror method is the best suitable technique used for tool deflection compensation.
4. It was apparent from the results given in the table 4.4 of chapter 4 that values obtained from the compensated toolpaths are very close to the ideal toolpath values as the deviation of compensated toolpaths from the ideal one was very less.
5. Ball-end milling cutter is used for finishing operation of sculptured surface machining by generating CL points that will remain under tolerance limits so as to maintain the required surface finish.
6. All the values of cutting parameters required for tool deflection calculation and compensation technique have been denoted in the form of Excel Sheet where calculation has been also done for obtaining various parameters values required.

5.2 Future Scope of Work

The present work has been focused towards ball-end milling cutter deflection calculation and compensation for the finish machining of T6061 Aluminum alloy. A lot of work can be carried out for the further refinements of the work carried out in this dissertation work as listed below:

1. Tool deflection calculation and compensation procedure described above can also be extended to other materials using predetermined optimized cutting speeds, feed and depth of cuts.
2. With the help of Dynamometer, cutting forces used for tool deflection determination can also be measured before only for any predetermined material composition.
3. For accurate inspection of machined sculptured surfaces, more precise 3D scanners can be used in place of profile projector.
4. Then 3D scanned data of any machined workpiece will be compared with the original CAD model in order to determine the deviations so that suitable compensation techniques can be applied. After applying compensation, compensated toolpaths will be made.
5. 3D scanned data of compensated, non-compensated and ideal tool paths can also be compared.

6. Cleaning of workpiece can also be done using inserted ball-end milling cutters instead of end milling cutter for increasing the surface finish and improving the machining operation.
7. For cutting force determination, shear area of workpiece material can also be calculated and further used for more accurate tool deflection determination.
8. Cutting area can also be optimized considering radial runout of ball-end milling cutter in 3-axis CNC Vertical Milling Machine.
9. Ball-end milling cutters of more than 6mm diameter can also be used for finish machining operations.
10. Excel Sheet which includes the values of various cutting parameters can also be further used as an input for making C language program so that the implementation of Tool deflection calculation and compensation technique becomes easier.

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