A

THESIS REPORT

SIMULATED TOPOGRAPHIC ERROR PREDICTION FOR 3-AXIS MILLING

Submitted in partial fulfillment of the requirements for the award of degree of

MASTER OF ENGINEERING
IN
CAD/CAM & ROBOTICS

Submitted by

BALRAM KALRA
ROLL NO: 800981006

Under the guidance of

Mr. A.S.JAWANDA
ASSISTANT PROFESSOR

Mr. RAVINDER.K.DUVEDI
ASSISTANT PROFESSOR

MECHANICAL ENGINEERING DEPARTMENT
THAPAR UNIVERSITY
PATIALA-147004, INDIA
2011

CERTIFICATE

This is to certify that the Thesis titled, **"SIMULATED TOPOGRAPHIC ERROR PREDICTION FOR 3-AXIS MILLING"** being submitted by **Mr. BALRAM KALRA"**, in partial fulfillment of the requirements for the award of degree of MASTER OF ENGINEERING (CAD CAM & ROBOTICS) at THAPAR UNIVERSITY (DEEMED UNIVERSITY), PATIALA is a bonafide work carried out by him under our guidance and supervision and that no part of this thesis has been submitted before for the award of any degree.

4/7/2014 04/07/2014

MR. A. S. JAWANDA
ASSISTANT PROFESSOR

MR. RAVINDER K. DUVEDI
ASSISTANT PROFESSOR

COUNTER SIGNED

Dr AJAY BATISH
Professor & Head
Mechanical Engineering Department

COUNTER SIGNED

Dr S. K. MOHAPATRA
Dean of Academic Affairs

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(BALRAM KALRA)

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CHAPTER-1

INTRODUCTION

In the present days of technology advancement and competition in the machining industries every industry is opting for the implementation of CNC machining and machining simulators all over the world. As present machining scenario demands for high accuracy and reduced machining losses, NC machining is a fundamental and important controlled machining process for the production of mechanical parts. An NC machine would be running in automatic mode. The use of NC simulation and verification is essential if programs are to be run with confidence during an unmanned operation. Therefore, it is of vital importance to verification of NC paths before execution. The machining simulators are the solution for all such problem.

Since it is impossible to avoid surface topography errors completely during machining process, while calibration of surface topography errors can be done and can be further used to refine the tool path in order to reduce the surface topography errors . There are various techniques available for surface topography error measurement of the machined component but every technique requires the machining of the workpiece for comparing against the requirement.

Thus tool path simulators are developed in which simulation of NC program containing the tool path data is carried out. The simulation of the tool path can be done and the physical shape is verified on the simulator but no prediction of the surface topography error can be done. The present machining requirements demands for the calibration of the surface topography errors by the simulators itself.

1.1. SIMULATOR USE AND DESIGNS

Simulation is the imitation of some real thing, state of affairs, or process. The act of simulating something generally entails representing certain key characteristics or behaviors of a selected physical or abstract system. Traditionally the formal modeling of systems has been via a mathematical model, which attempts to find analytical solutions enabling the prediction of the behavior of the system from a set of parameters and initial conditions. Computer simulation is often used as an adjunct to, or substitution for, modeling systems for which simple closed form analytic solutions are not possible.

A computer based simulation is an attempt to model a real-life or hypothetical situation on a computer so that it can be studied to see how the system works. By changing variables, predictions may be made about the behavior of the system .Computer simulation has become a useful part of modeling many natural systems in physics, chemistry and biology, and human systems in economics and social science (the computational sociology) as well as in engineering to gain insight into the operation of those systems. There are many different types of computer simulation. The common feature they all share is the attempt to generate a sample of representative scenarios for a model in which a complete enumeration of all possible states would be prohibitive or impossible. As an example the in flight navigator simulators receiver that may for example be used on an aircraft, can be tested under dynamic conditions without the need to take it on a real flight. The test conditions can be repeated exactly, and there is full control over all the test parameters. This is not possible in the 'real-world' using the actual signals

The machining simulation is a 3D representation of the workpiece , cutting tools and verify the tool path by comparing the designed geometry and the simulated geometry. The main idea of simulating the milling process is to imitate the behavior of the real process with all relevant input values as accurately as possible to be able to transfer conclusions from the simulation to the real-world process. It should allow to identify all relevant problems of the actual process in advance of the real production. Simulation provides the geometry error occurs during the machining, possibility to save time and material costs without any risk of damaging the machining center or tools by collisions. The production of lightweight structures is especially challenging for the three-axis milling process. To avoid a bending of the workpiece , special chucks are necessary. Thus, the probability of collisions is even higher than during the production of other types of structures, like more massive dies or moulds. The collision detection can be accomplished by using the simulation as a regular in-process tool to verify and optimize NC paths generated by CAM systems .An in-process simulation has to fulfill various needs. In order to provide maximum of flexibility, the duration of a simulation run should be short. Additionally, the results of the simulation must be reliable as it replaces other types of verification and will be the only step that prevents damage of the semi-finished product, the tools, and the milling machine.

1.1.1. TYPES OF SIMULATION

Continuous-state simulation is applicable to systems where the notion of state is continuous and typically involves solving (numerically) systems of differential equations. Circuit-level simulators are an example of continuous-state simulation.

Discrete-event simulation is applicable to systems in which the state of the system changes at discrete instants of time, with a finite number of changes occurring in any finite interval of time. The simulation in CNC is Continuous state simulation for checking of the tool path and for the machining of the geometry. Manufacturing represents one of the most important applications of Simulation. This technique represents a valuable tool used by engineers when evaluating the effect of capital investment in equipment and physical facilities like factory plants, warehouses, and distribution centers.

1.1.2. SIMULATION USE :

The machining simulation is used to simulate the tool path for machining process for verifying it against the actual shape requirement. Machining Simulation thus verify and analyze the tool path without any physical machining requirement of the workpiece. As an example Fig.1.1[26]shows a process fragment of rough machining simulation of complex human’s face which is generated from a box.

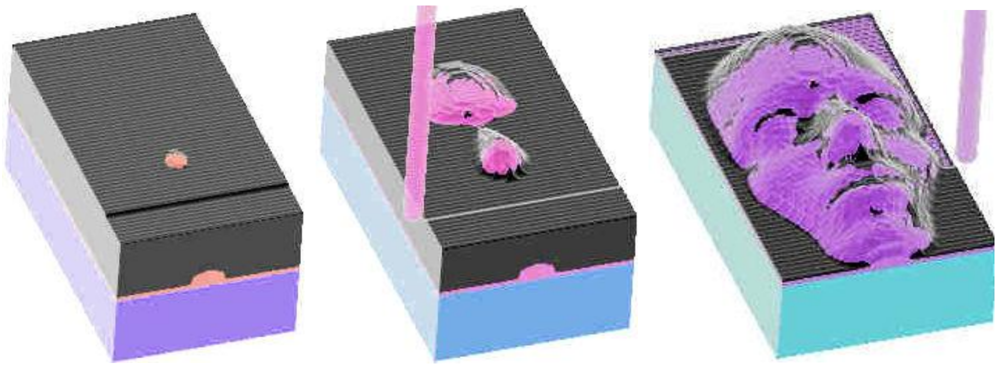

Fig.1.1Simulated processes of rough machining [26]

Fig.1.2 [26] shows machining process simulation of material removal during finish process that results into the generation of the complex human face geometry machined surface.

Fig.1.2 Simulated processes of finish machining [26]

As seen from the above figures that even complex human face geometry can be easily simulated and can be verified against the designed geometry. Thus any deviation from the required geometry can be visualizes and if there is any error in tool path data then it can be corrected by running simulation again before performing the physical machining of the workpiece in real environment.

1.1.3. ADVANTAGES ASSOCIATED WITH GRAPHICAL SIMULATION IN CNC MACHINING

A. **Evaluate changes before you make the investment:** As with the implementation of simulation before the actual machining will help in taking better decisions of tolling , changes in the tool path if , required , tooling selection, better decision etc and hence all required changes can be done before the actual machining is implemented **.**

B. **Better Decisions :**As with the implementation of machining simulators better visualization of the process is possible then its imagination so better decisions regarding the selection of the tooling, machining centers etc. can be done**.**

C. **Compare different scenarios to consider all possible angles:** With the use of machining simulators all different alternatives e.g. cutter type in milling , cutter diameter ,different machining parameters can be compared against achieving the required objectives .Thus help in achieving optimization**.**

D. **Fewer Risks:** With the use of machining simulators risks of implementing the wrong selection regarding the machining center , tool or cutter type, cutter diameter can be reduced and thus help in reducing the indirect losses that can be occurred without the actual comparing of data and hen its replacement **.**

E. **Test ideas for improvement in a completely risk free environment**: With the use of machining simulator all new ideas can be test without the requirement of implementing it in the actual machining environment and thus avoid all the risks involved in losses of purchasing the tooling and then to do the trials on the machine**.**

F. **Product cycle time reduced:** With the implementation of the machining simulators overall product cycle of bringing product into the actual machining environment is reduces to a great extent because the testing stage is completed by the simulator only without requiring the actual machining of the component and thus speed up the process of implementing the product into the regular production schedule**.**

G. **Forecast years ahead in seconds:** with the implementation of simulators machining of complex shape is possible even though if tooling and machine required to generate that shape is not available and thus help in predicting the future scope and thus forecast the future ahead**.**

H. **Lower Costs :** Machining simulators also contribute to lower the cost because losses going to occur due to the wrong tooling purchase ; trials over the workpiece is totally eliminated and also as the product life cycle is shortened thus lowers the cost**.**

I. **Prevent accident:** with the implementation of the machining many accidents due to wrong tool path during machining, wrong tooling selection etc. can be avoided as can be seen in Fig.1.3[22] there is collision of the tool holder and the job thus simulation can prevent these type of accidents , also with the selection of the wrong tooling that can cause an accident can be visualized and thus accidents and the losses that can occur due to it can be projected. Sometimes even a small accident like one shown in Fig.1.3[22] can cause the life time injury to a worker operating on the machine and thus projecting such accidents during the simulation stage can prevent the injury to the worker**.**

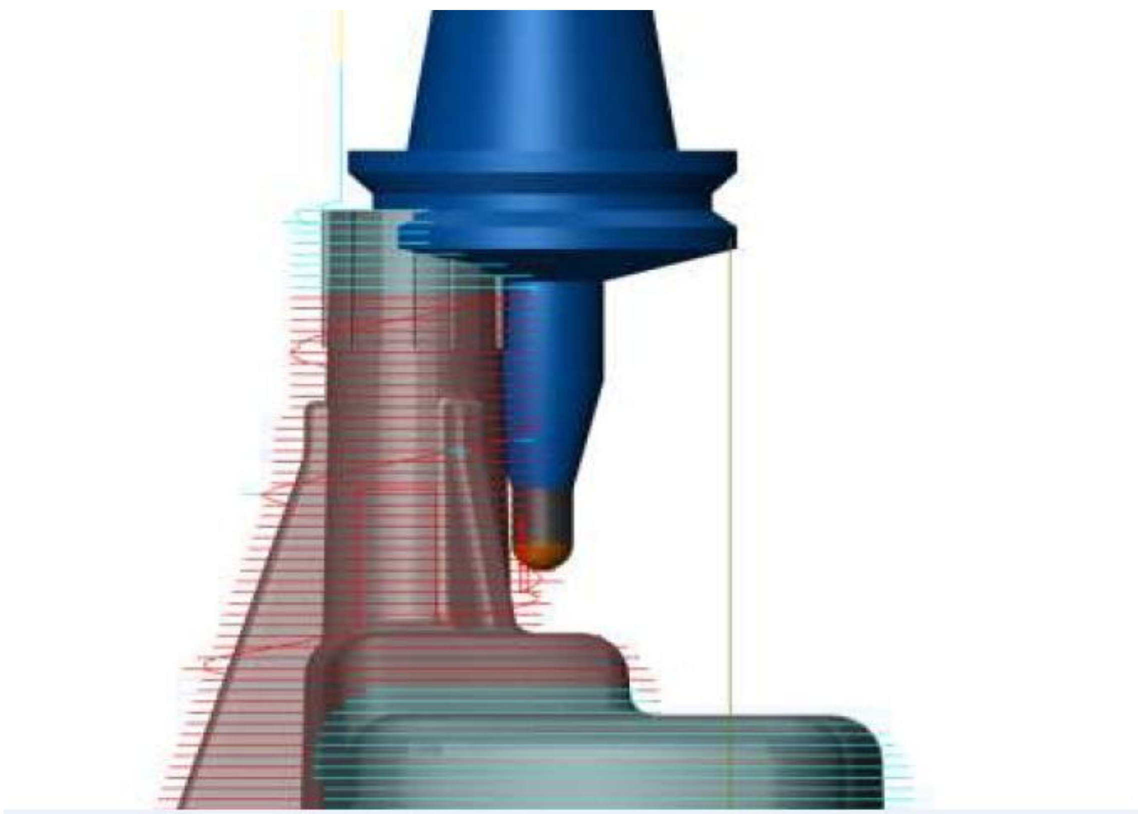

Fig.1.3 Collision of tool and job in simulation process [22]

1.2. THREE AXIS MILLING SIMULATION

Milling is a machining operation in which a workpiece is fed past a rotating cylindrical tool with multiple cutting edges. The axis of rotation of the tool is perpendicular to the feed direction. The tool is called the milling cutter and the cutting edges are called teeth. Mostly plane surfaces are created through milling. It's an interrupted cutting operation; the teeth of milling cutter enter and exit workpiece during each revolution. So, the tool material and cutter geometry must be chosen carefully to withstand cycles of impact forces and thermal shock. Fig.1.4 [30] shows the general arrangement of a three axis NC milling machine and Fig.1.5[30] shows the 3 axis machining.

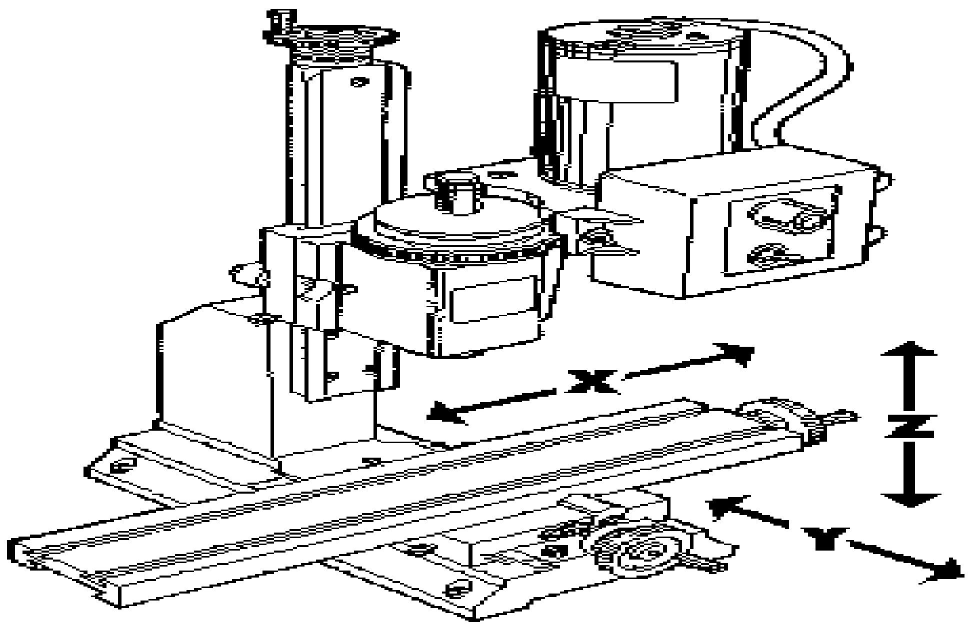

Fig.1.4 Three axis NC milling machine[30]

Fig.1.5 Three axis NC milling machining[30]

The major processes that contribute to the generation of the complex shapes are described below in Fig.1.6 [31]. In which (a) represents the face milling operation, (b) is the side milling operation, (c) is the slot milling operation, (d) and (e) is the profile milling operation and very small amount of material is removed during this operation as compared with the other operations and in this feed is perpendicular to the cylindrical axis. (f) is the profile milling operation in which feed is not exactly perpendicular to the axis. A combination of all these operation is able to generate the complex geometries in three axis milling process.

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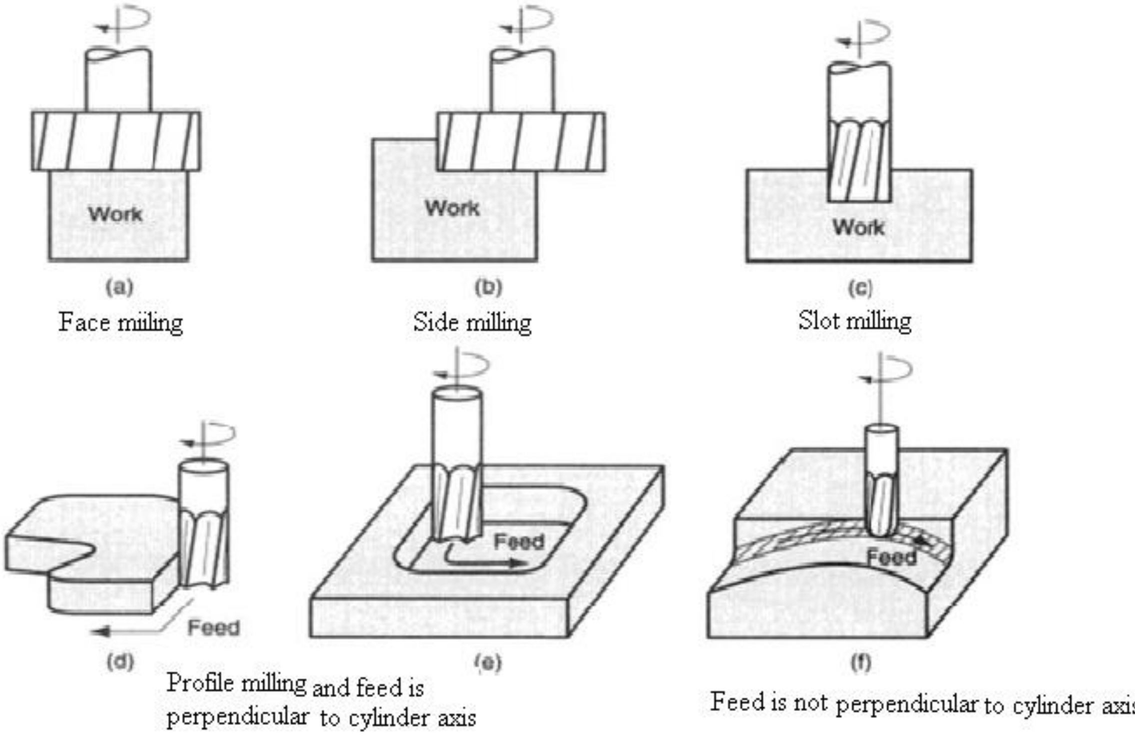


Fig.1.6 Different types of milling operations[31]

The three axes used in the milling process are described as by X, Y and Z axis where ‘Z’ axis is always the axis of the cutter and perpendicular to the feed direction as shown in Fig.1.7[31]; where axis marked in Red color is the ‘X’ -axis and marked in Green color is the ’Y’ axis and the one marked in Blue color is the ‘Z’ axis and it is the cutter axis.

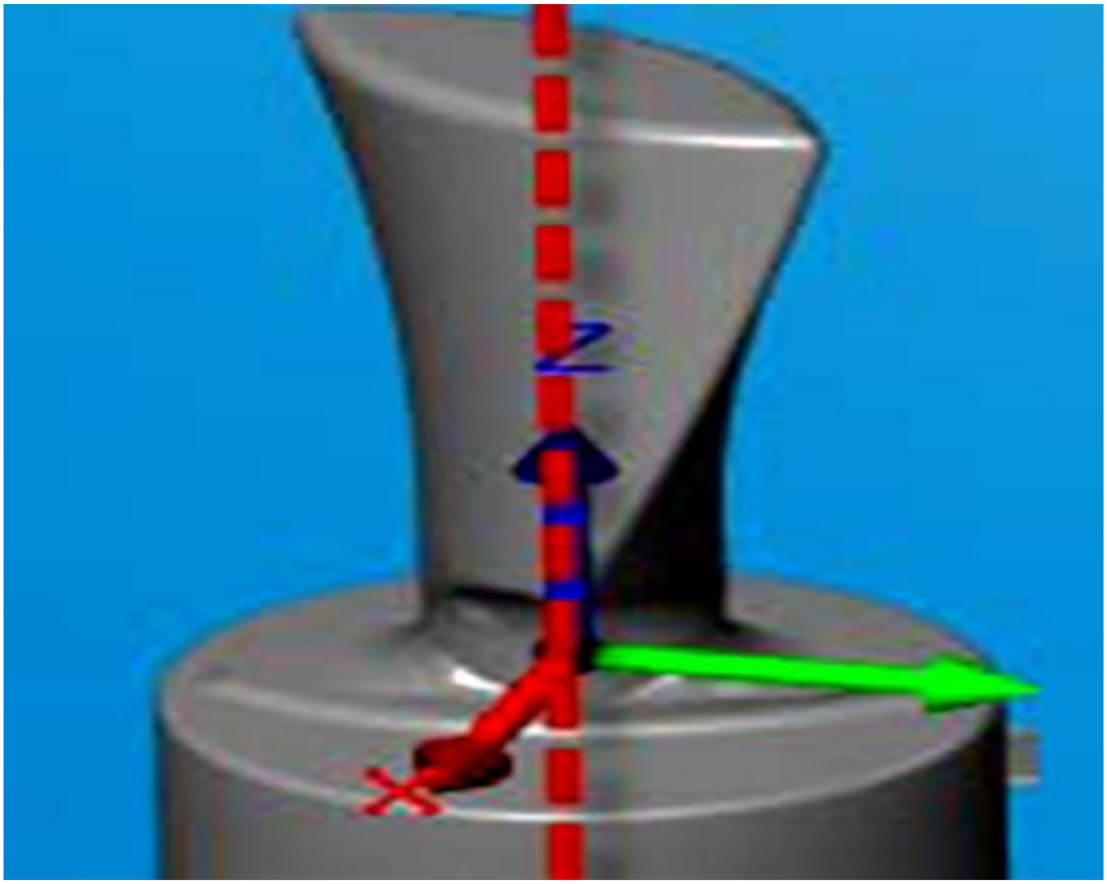


Fig.1.7 Axes direction for three axis milling machine[31]

With the use of simulation technology, machining visualization of the tool path become possible a tool path planner can visualize the tool path simulation and can decide the changes in the tool path and then the trial machining is done on the workpiece for evaluating the amount of the surface topography error. The present CNC machining simulation paradigm used is described below in Fig. 1.8.

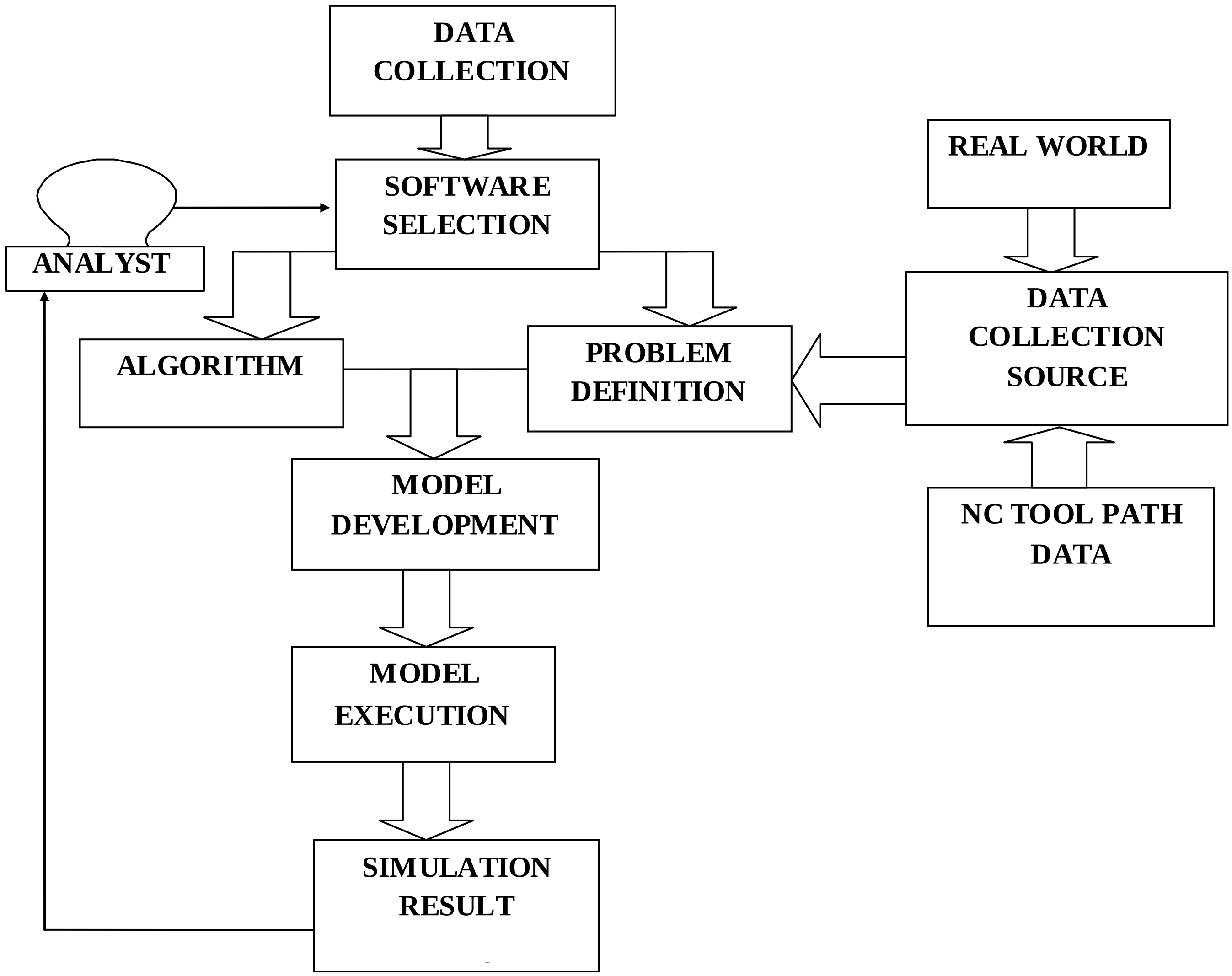


Fig 1.8 Present CNC simulation Paradigm

It is clear from the above paradigm of present day simulation that after the simulation the analyst only visualize the surface and tool path, but the surface topography error measurement and the tool path refinement is not performed by the simulator. For measuring the surface topography error a trial machining is required on the workpiece to get the final result for comparing against the requirement.

1.2.1. TYPES OF SURFACE TOPOGRAPHY ERROR AND THEIR MEASURING TECHNIQUES

Geometric errors are those errors that are extant in a machine on account of its basic design, the inaccuracies built-in during assembly and as a result of the components used on the machine. As such, they form one of the biggest sources of inaccuracy. Geometric errors can be smooth and continuous or they could exhibit hysteresis or random behavior. Geometric errors have various components like linear displacement error (positioning accuracy), straightness and flatness of movement of the axis, spindle inclination angle, squareness error, backlash error etc. Such errors occur during the execution of linear, circular or other types of interpolation algorithms and are more pronounced during actual machining. The three types of surface topographic errors are given below in Fig.1.9[26].

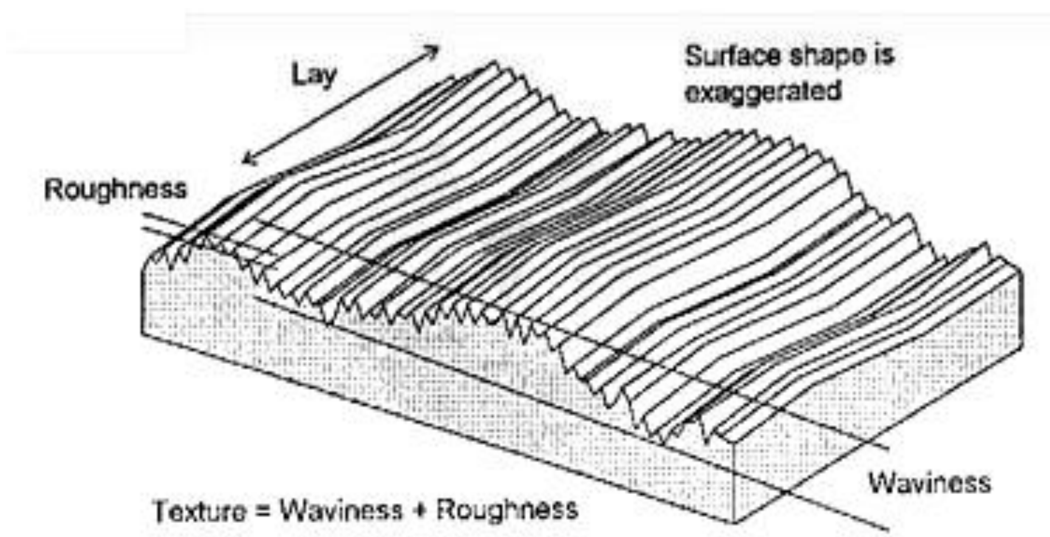


Fig.1.9 Surface topography errors[26]

WAVINESS: Arithmetic average of peaks and Valleys widely spaced, regular profiles and is shown in Fig. 1.10[26]

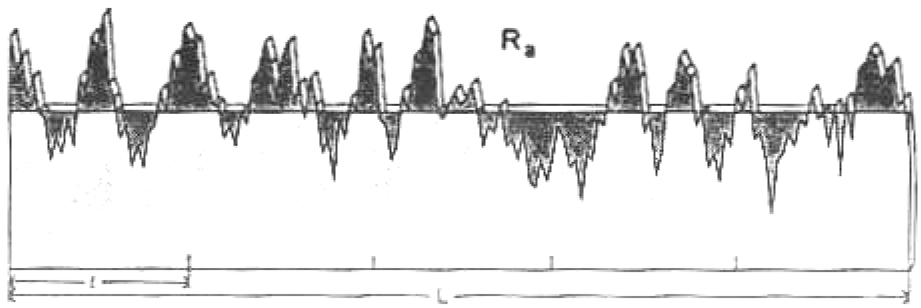


Fig.1.10 Surface topology for waviness[26]

SURFACE ROUGHNESS: Arithmetic average of peaks and valleys closely spaced irregular profiles and is shown in Fig. 1.11 below[26].

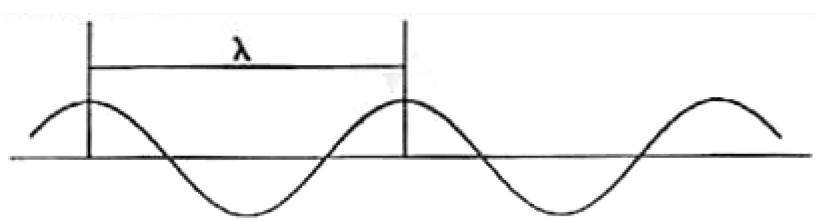


Fig.1.11 Surface roughness profiles[26]

FLATNESS: Tolerance zone defined by 2 planes in which surface lies.

1.2.2 PRESENT ART OF MEASURING THE TOPOGRAPHY ERROR

Now the present technique of machining simulation is focused only upon simulating the tool path fed and is not used for the prediction of the surface topography error. Thus for the measurement of the surface topography error actual machining of the component is required and is as shown in Fig.1.12[32] below in which the machining is carried out and the measured deflection of the surface is used for calculating the surface topography errors.

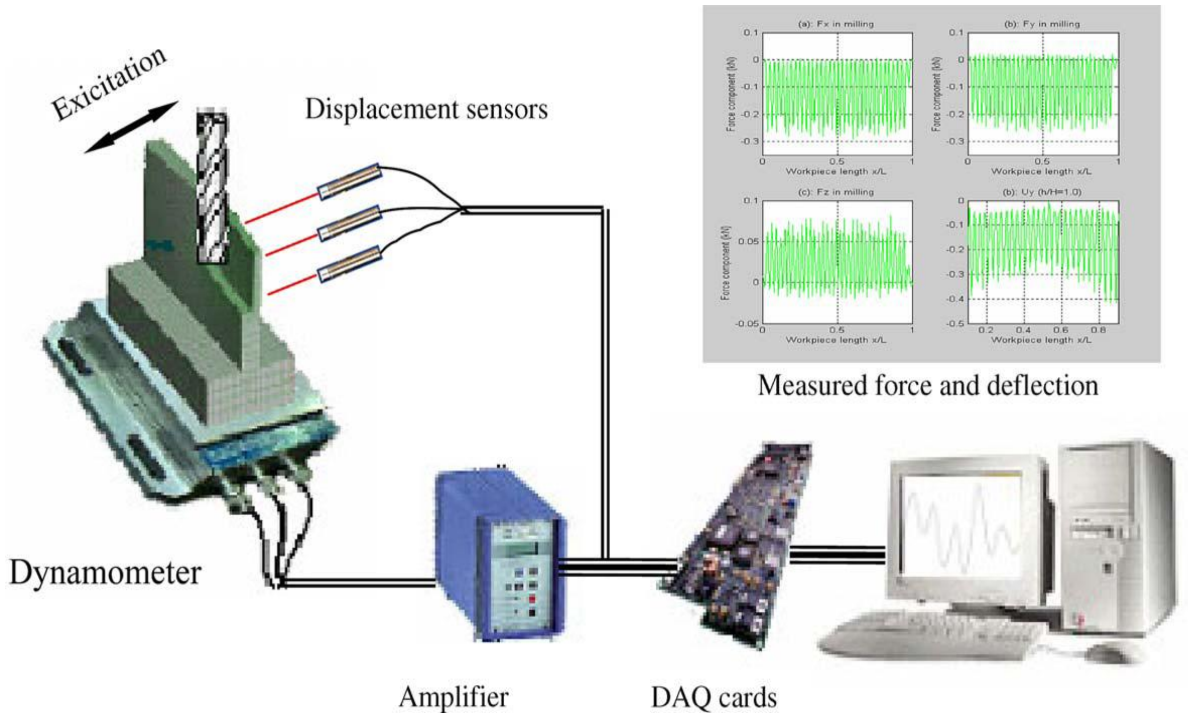


Fig.1.12 Measurement of surface topography errors during machining [32]

As it is clear from the above technique of error measurement that a large capital is also involved in purchase of the instruments for measurement of the surface topography error .As each instrument has its own calibrating error value. Thus the output obtained from the above calibration is itself containing some amount of calibration error. Thus it is also clear thus the measurement error will be definitely their due to the imperfectness of the calibrating instruments.

The output value of the error obtained from the above physical measurement is compared with the standard designed requirement and the various checks are made for the shape testing, error calibration .Thus if the trial component is as per the requirement then the tool path , tooling, fixture etc. are documented for that product but in actual a minimum of the two-three trials are necessary for getting the final required product and for every time a large amount of labor, time, cost is involved and thus overall losses are increased and thus product cost is also increased due to these indirect losses .

CHAPTER- 2

LITERATURE SURVEY

The literature survey has been conducted to focus on the following areas.

2.1 SIMULATOR USE AND DESIGNS

The work for the milling simulation has started in year 1995 and the previous relevant work is listed below:

Sang Hun Lee , Kang-Soo Lee [1] , has done work in the real time three axis milling simulation they propose a new mesh decimation algorithm for the workpiece which is represented by the z-map structure and whose shape is dynamically changed by the tool .In this algorithm, the z-map data for the workpiece are divided into several regions, and a triangular mesh is constructed for each region. Then, if the tool cuts any region, its mesh is regenerated and decimated again .Since the range of mesh decimation is confined to a few regions, the reduced triangles for rapid rendering can be obtained in a short time.

Hong T. Yau1, Lee S. Tsou2 and Yu C. Tong[2], has done work in the machining of a complicated surface, This paper emphasizes the use of adaptive octree to develop a reliable multi-axis simulation procedure which verifies the cutting route and the workpiece appearance during and after simulation. Voxel models with adaptive octree data structure are used to approximate the machined workpiece with specified resolution.

Chih-Hsing Chu , Jang-Ting Chen[3], This paper presents a novel approach that automatically generates interference-free tool path for five-axis flank milling of ruled surface. A boundary curve of the machined surface is subdivided into curve segments. Each segment works as a guide curve in the design method for developable Bézier surface that controls a developable patch for approximating the surface with available degrees of freedom. Geometric algorithms are proposed for calculating consecutive patches with G1 continuity across the patch boundary. A tapered tool can move along the rulings of these patches without inducing local tool interference as a result of their developability. The machining deviation is controlled by the surface approximation error.

Yizhen Lin, Yin-Lin Shen [4]**,** They developed 'enhanced virtual machining' framework that integrates machine tool error models into NC machining simulation. They discretized ideal cutter path into sub-paths. They used both the solid modeling approach and the surface modeling approach to translate machine geometric errors into part geometry errors for sculptured surface machining. The solid modeling approach obtains the final part geometry by subtracting the tool swept volume from the stock geometric model. The surface modeling approach approximates the actual cutter contact points by calculating the cutting tool motion and geometry. The simulation results show that the machine tool error model can be effectively integrated into sculptured surface machining to predict part geometry errors before the real cutting begins.

Spence, Allan Douglas[5], This thesis develops analytical solutions that to improve upon repeated sampling at many cutter rotation angles, numerical methods and calculus techniques are used to rapidly determine extreme forces, torques, and deflections. For process planning, a continuously varying feed rate is automatically scheduled to respect imposed average torque, maximum resultant force and surface error constraints. Additional simulation and cutter-part intersection geometry data is calculated to assist with online monitoring and control tasks.

Sang-Kyu Lee, Sung-Lim Ko [6], The paper discusses new approach for milling operation simulation using enhanced Z map algorithm. Super sampling method is used to enhance the efficiency of a simulation. By executing redundant Boolean operations in a grid cell and averaging down calculated data, presented algorithm can accurately represent material removal volume though tool swept volume is negligibly small. The key advantage thry got from extended Z map is that the data structure is same with conventional Z map, though it can acquire higher accuracy and reliability with same or lower computation time

Zhou Ming, Li Jianguang, Yuan Zhejun , Tan Jiubin [7], An efficient real-time simulation system for 3-axis NC milling using microcomputers is described in this paper. They represent work piece with an extended Z-map structure and is displayed on screen using isometric projection. After the NC code file was generated and interpreted by an NC instruction translator, a material removal process was simulated just like that performed on real NC milling machine tools driven by NC instructions. The whole process is real-time displayed on the screen; meanwhile alarm messages are given to the operator when interference between milling cutter and workpiece occurs. The simulation result is displayed using a visual realism technique, from which gross programming errors can be checked with ease.

Lee miong , janifer joe[8], This paper puts out a new entity modeling method called triangular grid, and establishes a data structure to describing the blank which greatly facilitates the simulation .The system can distinguish and translate the common NC codes used by milling machine ,it finally translates these NC command into effective information to drive system simulation.

Zhang Zixian , Savchenko Maria, Hagiwar Ichiro, Ren Bingyin[9], They prposed a path-planning approach that includes three stages: rough cut, semi-finish cut, and finish cut. For each stage corresponding mills (cutting tools) are applied. A flat-end mill is utilized in rough-cut and ball-end mill is used in semi-finish and finish-cut stages. Additional semi-finish cut is applied to avoid tool interference which may occur when the ball-end mill with a larger radius than the radius of curvature of the concave surface is used. As a result of this step, under-cut material volume is decreased and removed in finish cut. An offset surface is generated firstly for finish-cut. In order to increase efficiency, finish-cut stage is applied in the areas where precision of workpiece does not meet a user-specified tolerance. A simulation method is introduced to detect tool interference and evaluate precision of machined workpiece.

P.-L. Hsu , W.-T. Yang[14], The paper presents an efficient real time simulator for 3-axis milling processes. In this system, solid modeling is performed using isometric projection with a z-map structure. As a result, all the solid elements are either fully exposed or fully hidden, and they are well arranged and symmetrical. These characteristics make visible surface determination for the raster display more efficient, and they reduce the memory requirements considerably. As a result, this efficient and real time-based model can simulate NC milling processes satisfactorily even in personal computers, without the aid of extra hardware devices or coprocessors.

Ziang Mau,shining liu [15], This paper presents an adaptive triangular mesh algorithm to reduce the number of polygons while image quality remains high. Binary tree is used to represent the milling surface, and the optimization of the mesh is performed dynamically in the process of simulation. In this algorithm, the resolution of triangles is automatically updated according to local surface flatness, thus greatly reducing the number of triangles at planar regions. Full resolution model stored in memory is automatically loaded to ensure the accuracy and correctness of these inspections.

S.Q. Liu, S.K. Ong,Y.P. Chen and A.Y.C. Nee [16], They proposed an adaptive regular mesh decimation algorithm. That uses a quadtree to represent the milling surface and enabled flags are used to perform the optimization of the mesh, actual insertion and deletion operations of triangles do not exist. Their algorithm can automatically adjust the polygon density to approximate the milling surface according to its changes in real-time, and numerical inspections of any area of the machined surface can be performed with full resolution.

2.2 ERROR PREDICTION USING 3-AXIS SIMULATION

The Previous work done is listed below

B. M. Imani, M. H. Sadeghi and M. A. Elbestawi [19], A simulation system is developed in this paper, which deals with the geometry and mechanics of machining with ball-end milling cutters. The geometry of the workpiece, the cutter, and the cutter/workpiece engagement is modeled using a geometric simulation system. Their module uses a commercial solid modeler (ACIS) as a geometric engine and automatically extracts the critical geometric information required for the physical simulation system. A new mechanistic force model is also developed to calculate the instantaneous force. This force model takes into account the variations of the cutting coefficients along the cutting edge, and considers the variations of the rake angle and the chip flow direction on the rake face.

Hirohisa Narita, Keiichi Shirase, Eiji Arai, and Hideo Fujimoto[20], They designed a virtual machining simulator to verify machining accuracy by using an accuracy-prediction model and an error prediction expression for workpiece, integrating machine-tool deformation and geometric error models. They also propose calculation for copying errors to a workpiece.

M.F.F. Ab. Rashid and M.R. Abdul Lani [21], Their research work involves to develop a mathematical model using multiple regressions and artificial neural network model for artificial intelligent method. Spindle speed, feed rate, and depth of cut have been chosen as predictors in order to predict surface roughness. The experiment is executed by using full factorial design. After the predicted surface roughness has been obtained by using both methods, average percentage error is calculated. Their mathematical model developed by using multiple regression method shows the accuracy of 86.7% which is reliable to be used in surface roughness prediction. On the other hand, artificial neural network technique shows the accuracy of 93.58% which is feasible and applicable in prediction of surface roughness

P. De Fonseca, D. Vandepitte, H. Van Brussel, P. Sas[24], The present paper discusses the numerical condensation of a finite element model of a three-axis high speed milling machine to a low-order state-space model suitable for control system design. The proposed reduction method forms an essential part of a Virtual Engineering environment for the design of a large class of mechatronics systems. Substructures with known dynamic characteristics are described by their respective component modes. They are combined in the appropriate relative positions, and the system is solved through a reduced set of equations for each configuration. A well-considered selection of the types of component modes improves the quality of the reduced model.

Afzeri, A.G.E Sujtipto, R. Muhida, M. Konneh, and Darmawan[25],

They proposed integrated tools with virtual simulation, remote desktop protocol and Setup Free Attachment for remote operation of milling process. Accessing and monitoring of machining operation is performed by remote desktop interface and 3D virtual simulations. Capability of remote operation is supported by an auto setup attachment with a pin type setup free technology installed on the table of CNC milling machine to perform unattended machining process. The system is designed using a computer server and connected to a PC based controlled CNC machine for real time monitoring. A client will access the server through internet communication and virtually simulate the machine activity.

Nicola Senin, M.S.Roberto Groppetti and others[26] , Their work analyzes the advantages and disadvantages of a 3D-based approach by proposing an approach and a prototype system for firearms evidence comparison that is based on the acquisition and analysis of the 3D surface topography of specimens, with particular reference to cartridge cases. The concept of 3D virtual comparison microscope is introduced, whose purpose is not to provide fully automated identification, but to show how the availability of 3D shape information can provide a whole new set of verification means.

Dan Sunday[27], has done work in area of developing algorithms and basics of geometry solution to find the intersection between the various geometrical shape that are used in day to day geometry calculation and proposed the different algorithm for each calculation for finding out the intersection junction between any arbitrary shape and regular shape.

Tomas moller , Ben Trumbore [28], present a clean algorithm for determining whether a ray intersects a triangle. The algorithm translates the origin of the ray and then changes the base of that vector which yields a vector (t u v)t where t is the distance to the plane in which the triangle lies and (u v) represents the coordinates inside the triangle. One advantage of this method is that the plane equation need not be computed nor be stored which can amount to significant memory savings for triangle meshes.

Bedi, F. Ismail, M. J. Mahjoob and Y. Chen [29], This paper compares the surface roughness along and across the feed directions produced by toroidal, ball nose, and flat bottom end mills. The study is conducted numerically and by cutting tests of aluminum. Their results show that the toroidal cutter inherits the merits of the other two cutters; it produces small scallops across the feed direction, and low roughness along the feed direction.

CHAPTER-3

PROBLEM DEFINITION

After above literature survey and understanding present art of machining simulation, the present technique which is used to predict the surface topography errors is shown in Fig.3.1 below with basic components.

Firstly the 3D geometry of the part is made by using CAD software tools. The 3D geometry is created in any modeling software tool and then can be saved in neutral format. After that different machining process needs to be done on the part are defined and the process plan is made which explain the all necessary processes and the tooling required , machine requirements are decided.

After that CAM module integrated with the post processor is used to generate the machine executable statements that will define the tool path during actual machining on the machine. The tool path generated is simulated in standard simulators to visualize the tool path only. A very high skilled simulator operator is required for predicting any kind of accident during the simulation of tool path.

But the surface topography of the simulated surface and the designed surface is still not compared. Fixture and tool set up is done for performing the trial machining .The surface topography of the actual machined surface is measured and compared against the standard required topography.

If the actual machined surface topography is in machining tolerance region then the tool path is accepted and the part is brought to routine production. But if the deviation of two topography is not in tolerance region then refinement of the procedure and tool path is done again and the trial machining is repeated. This cycle repeats again and again till the requirements of the two topography are matched.

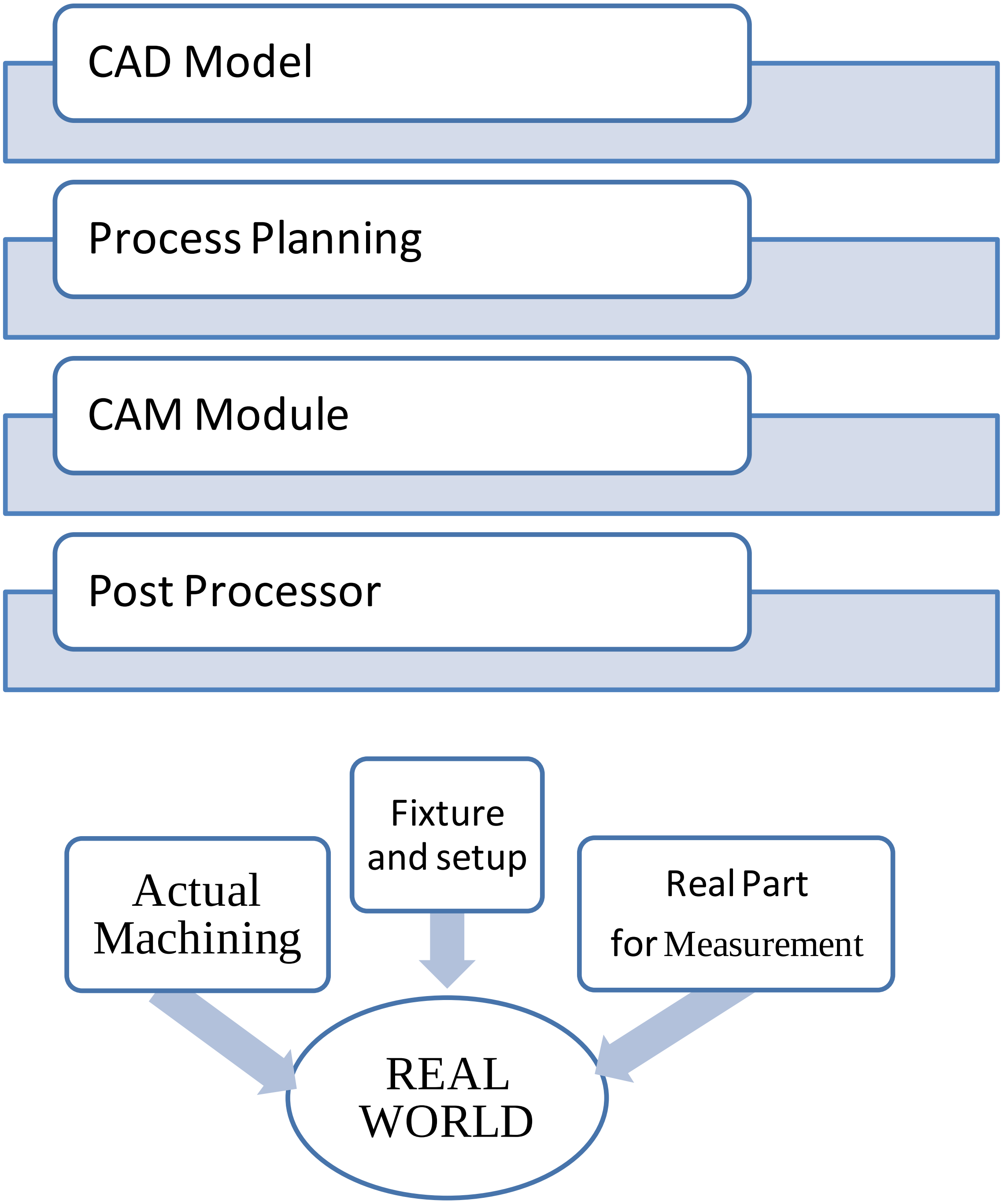


Fig.3.1 Present scope and methodology of CNC use and simulation

I t is clear from above discussion that present technique of simulating the tool path and then trial machining over a workpiece is a iterative design process and involves considerable amount of labor and cost for evaluating the surface topography error. Also as a tool path planner also not aware of the actual machining environment during the trial machining process thus the chances of getting error are increased because lack of knowledge , communication gap between the designer, tool path planner , machine operator.

After going through the above paradigm used for simulation a number of gaps has been identified in the present simulation technique and they are listed below

1. During CAM simulation there is no Comparison of surface topology of simulated surface with the Designed CAD Surface based upon STL geometry.
2. Present day Simulator's shows only machined path graphically without showing any deviation from required STL geometry.
3. Topology errors are found only from physical machined components.
4. Iterative process for achieving the required topography.
5. Losses in terms of cost involve, labor and time.

Proposed is a simulator which will show a CAD geometry required and tool along with tool geometry to plot the surface topology of machined simulated surface; also to predict the surface topology errors based upon comparison with the STL model of the required CAD geometry data will be done.

The proposed simulator takes the same input of the cutter location data but its machined surface generated using the given tool is taken and compared with the designed CAD geometry data for measuring the surface topography errors which would occurs during the simulation of the tool path for generating the geometry.

CHAPTER-4

SIMULATOR DESIGN

The simulator is designed for three axis milling machining simulation. There are three basic components of milling machining that is workpiece, cutter and cutter body. These components are integrated in the simulator to achieve the milling machining simulation. The designed simulator takes the CAD geometry STL data, tool path data as input for simulation and generates the machined top surface in visualization, surface topography error values at location with regular interval as output data.

The design of the simulator basically required algorithm that will incorporate the account of both the machining simulation as well as the measurement of the surface topography error. Also for the graphically viewing the simulation graphical tools also incorporated.

Thus the desired objectives can be met and the gaps defined above can be overcome. For the verification of the designed simulator the simulated topography must be compared against the designed topography for measuring the surface topography error and validating the simulator. Thus After designing the simulator its output is verified by doing machining over the trial workpiece which are described in detail in the literature described below.

4.1. ALGORITHM

The simulator is designed to cover the all aspects of the requirement to measure the surface topography errors. Proposed simulator will cover the highlighted steps of the advanced simulator algorithm as shown below in fig. 4.1:

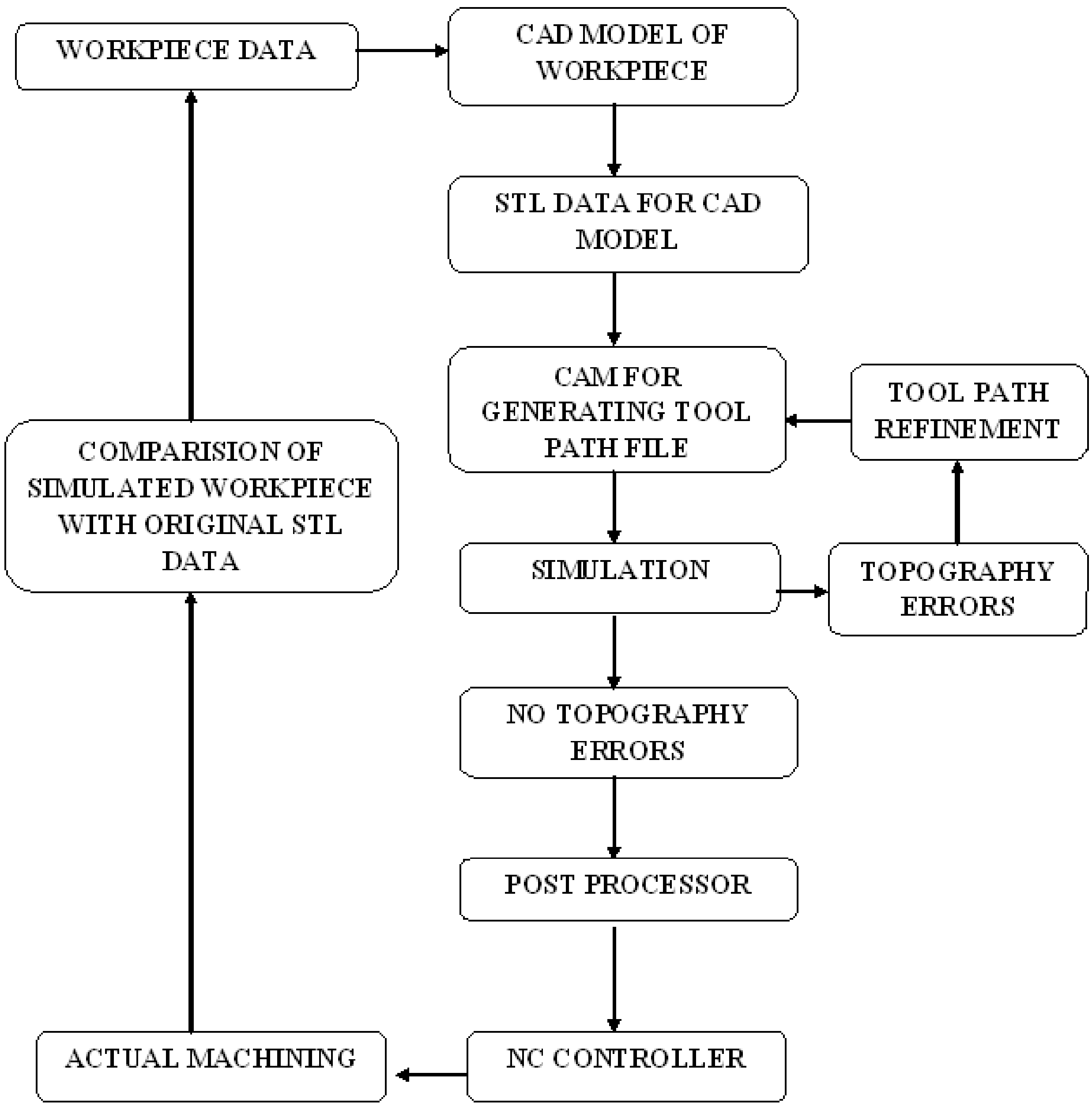


Fig. 4.1 Paradigm of proposed simulator

4.2. SIMULATOR WORKING

As discussed in the algorithm of the simulator the detailed working flowchart is shown in Fig.4.2 with various input required and the output generated with the simulator as its components.

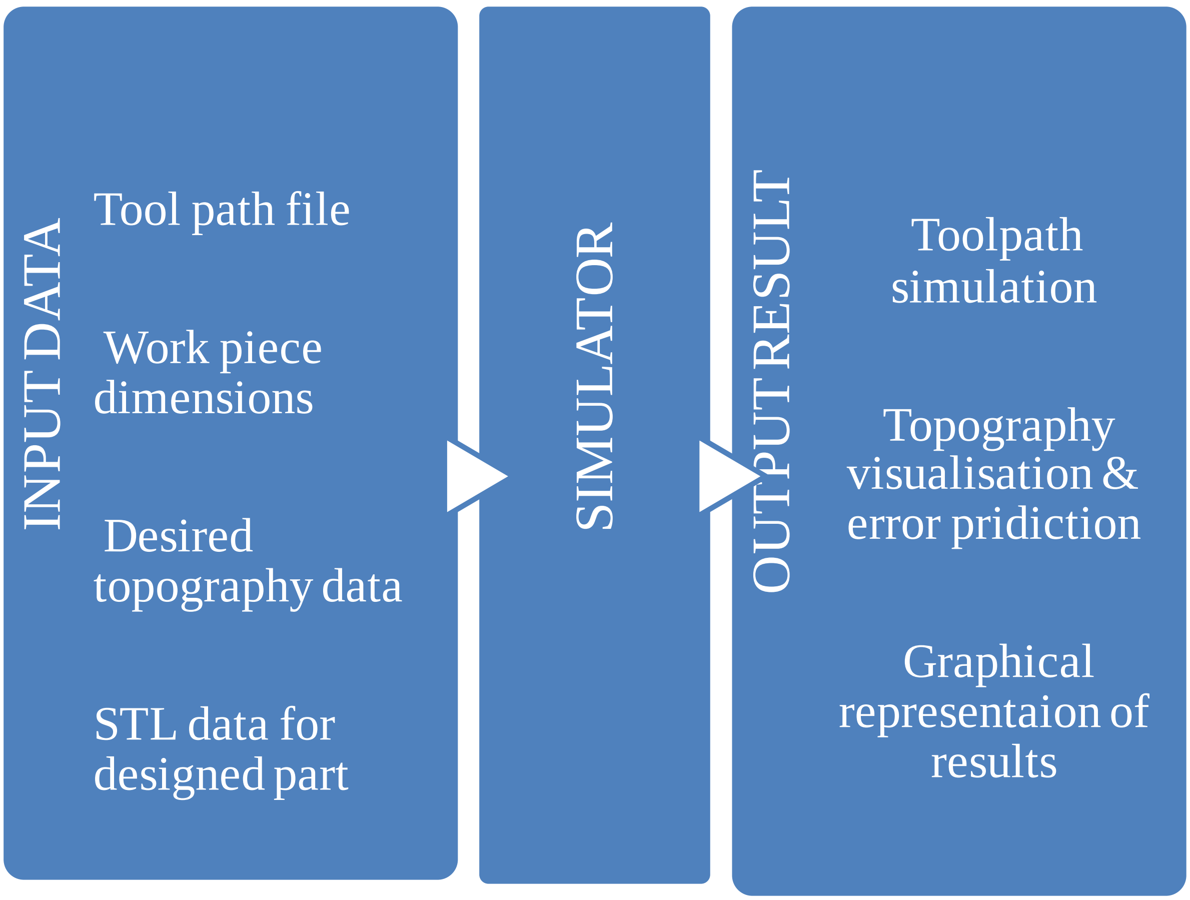


Fig.4.2 Simulator working algorithm for topography error prediction

4.2.1. Simulation algorithm: The simulation algorithm simulate the geometry and verify the tool path. The basic steps involved in the algorithm are described below:

The algorithm which is used for measuring the scallop height for measuring the surface topography error is described as below;

Step I. The workpiece is represented by projecting vertical grass from the base surface. The grasses are equally spaced by interval of 0.5 mm. Thus grass density is 0.5 considered for representing the workpiece. The top surface is represented by the triangle's in regular pattern.

Step II. Tool used for milling simulation is ball nose cutter of diameter 3.175 mm(1/8") and the various tool positions are obtained from the STL data of the designed part by considering a constant side step of 0.793 mm(1/32").

Step III. Simulation of the 3 axis milling machining is done by moving the tool through various tool position's of the tool path file and simultaneously cutting the vertical grasses for various toll positions.

Step IV. Algorithm used for calculation of cut grass height for various tool positions is obtained by calculating the intersection of line with sphere. For various tool positions the scallop's are generated and these scallops are contributing to the surface topography error.

Step V. Grass top points are stored in the output file of this simulation algorithm.

Step VI. The scallop height generated by a ball nose end mill can be obtained with the help of equation as described below also refer fig 4.3[29] for scallop height:

$$h = Rs(Rs - rc)cos\alpha - \sqrt{(rc^2 - ac^2\left(\frac{Rs-rc}{Rs}\right)2\ )} \qquad \text{----------------- (4.1)}$$

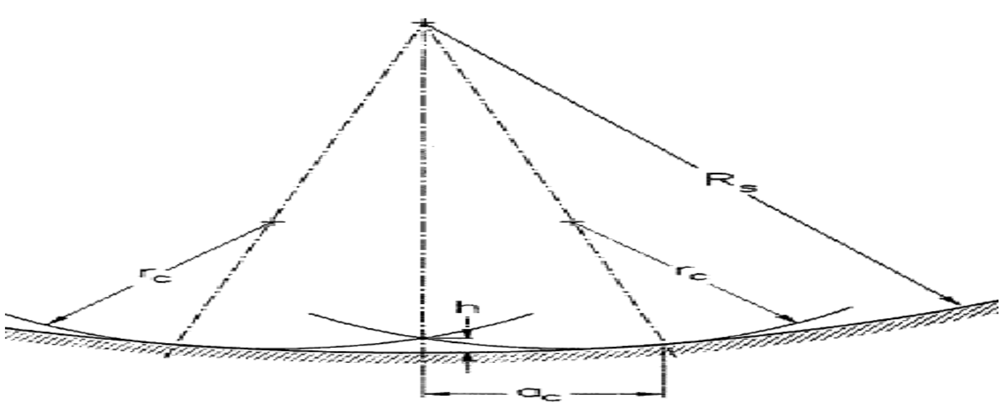


Fig 4.3 Scallop height generated on machined surface[29]

Here ;

Rs = Surface curvature radius

rc = Cutter radius

h =Scallop height

ac= half the cross feed

α= the subtended angle between the points of contact of the tool profile and the surface sin -1 (ac/Rs)

4.2.2.Surface Topography error measurement algorithm:

For the measurement of the surface topography error the STL surface data of the designed part is compared with the simulated cut grass height obtained from output file of the simulation algorithm. The various steps involved are listed below:

Step I. Surface topography error for the given grass density is measured.

Step II. For measurement of surface topography error Triangle- Ray intersection algorithm [29] is used. The simulated cut grass surface is assumed to be the Ray and its intersection with the designed STL surface is evaluated .

Step III. The cut grass height is either below the STL surface or above the STL surface or either lies in the STL surface .Thus error either Positive or negative or zero respectively. When the ray(Grass) top point is below the STL surface then error comes to be positive, if the top point is above the STL then error comes negative and if top point is inside the triangle then no error occurs .Positive error means overcutting, negative error means undercutting.

Step IV. The algorithm used for the Triangle-Ray intersection is described below:

Consider a ray R (or a segment S) from P_0 to P_1, and a triangle T with vertices V_0, V_1 and V_2. The triangle T lies in the plane π through V_0 with normal vector $n = (V_1-V_0) \times (V_2-V_0)$. To get the intersection of R (or S) and T, first determines the intersection of R (or S) and π. If they do not intersect, then the ray (or segment) also does not intersect T and are done. However, if they intersect in the point P_I=P(r1), we need to determine if this point is in the triangle T for there to be a valid intersection .There are a number of ways to test for the inclusion of a point inside a 3D planar triangle. The intent is to reduce the 3D problem to a simpler 2D problem which has an efficient solution. In this method which also uses direct

3D computations to determine inclusion, avoiding projection onto 2D coordinate plane. As a result, the code is more compact. Use the parametric equation of π relative to T, but derive a different method of solution which computes the parametric coordinates of the intersection point in the plane refer Fig.4.4[27]. The parametric plane equation is given by:

$$V(s,t) = V0 + S(V1 - V0) + t(V2 - V0) = V0 + Su + tv \qquad \text{----------------- (4.2)}$$

Where s and t are real numbers, and u = (V_1-V_0) and v = (V_2-V_0) are edge vectors of T. A point P = V(s , t) is in the triangle T when s>=0, t>=0, and s + t <=1. So, given P_I, one just has to find the (s1,t 1)-coordinate for it, and then check these inequalities to verify inclusion in T. Further, a point P = V(s , t) is on an edge of T if one of the conditions s=0, t=0, or s + t=1 is true (each condition corresponds to one edge). Also, the three vertices are given by: V_0=V(0,0), V_1=V(1,0), and V_2=V(0,1).

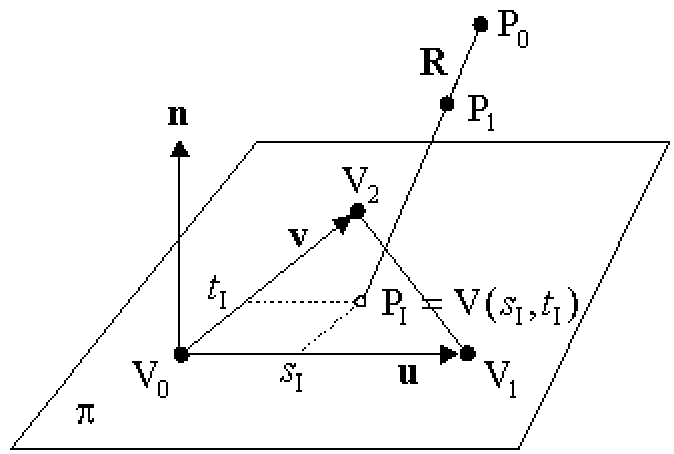


Fig. 4.4 Topography error evaluation by ray projection algorithm[27]

To solve for s_1 and t_1, a 3D generalization of "dot product" is defined. For an embedded 2D plane π with a normal vector n, and any vector a in the plane (that is, a satisfies n· a = 0), define the "generalized perpendicular operator on" by: $a^{\perp} = n \times a$. Then, $a^{\perp}$ is another vector in the plane π (since $n \cdot a^{\perp} = 0$), and it is perpendicular to a (since $a \cdot a^{\perp} = 0$). Further, this perpendicular operator is linear on vectors in π ; that is, $(Aa + Bb)^{\perp} = Aa^{\perp} + Bb^{\perp}$ where a and b are vectors in , π and A and B are scalars. Note that if π is the 2D xy-plane (z=0) with n = (0,0, 1), then this is exactly the same 2D perpendicular.

Now use the generalized perpendicular operator "dot product" to solve the plane's parametric equation for the intersection point P_I. Put w = (P_1-V_0) which is another vector in π. Now the equation: w = su + tv need to solved for s and t. Take the dot product of both sides with $v^{\perp}$ to get: $w \cdot v^{\perp} = su \cdot v^{\perp} + tv \cdot v^{\perp} = su \cdot v^{\perp}$, and solve for s1. Similarly, taking the dot product with $u^{\perp}$, we get: $w \cdot u^{\perp} = su \cdot u^{\perp} + tv \cdot u^{\perp} = tv \cdot u^{\perp}$, and solve for t1. We get:

$$s_1 = \frac{w.v^{\perp}}{u.v^{\perp}} = \frac{w.(n*v)}{u.(n*v)} \quad \text{------------------ (4.3)}$$

$$t_1 = \frac{w.u^{\perp}}{v.u^{\perp}} = \frac{w.(n*u)}{v.(n*u)} \quad \text{------------------- (4.4)}$$

The denominators are nonzero whenever the triangle T is non degenerate (that is, has a nonzero area). When T is degenerate, it is either a segment or a point, and in either case does not uniquely define a plane and the computed normal vector is (0,0,0).

Now 3 cross products which are coming in computation need to be converted into the dot product by using the mathematical identity as defined for any three vectors a ,b,c:

$$(a * b) * c = (a.c.)b - (b.c.)a \quad \text{-------------- (4.5)}$$

$$u^{\perp} = n * u = (u * v) * u = (u.u).v - (u.v).u \quad \text{-------------- (4.6)}$$

$$v^{\perp} = n * v = (v * u) * v = (v.u).u - (v.v).u \quad \text{-------------- (4.7)}$$

Now compute s1 and t1 using only dot products as:

$$s1 = \frac{(u.v)(w.v) - (v.v)(w.u)}{(u.v)(u.v) - (u.u)(v.v)} \quad \text{------------- (4.8)}$$

$$t1 = \frac{(u.v)(w.u) - (u.u)(w.v)}{(u.v)(u.v) - (u.u)(v.v)} \quad \text{------------- (4.9)}$$

The above defined algorithm will give the intersection point for the triangulated surface and the machined simulated surface which is used further for the surface topography error measurement and is applicable for any kind of geometrical shapes.Fig.4.5 shows the general picture how the simulator environment looks like

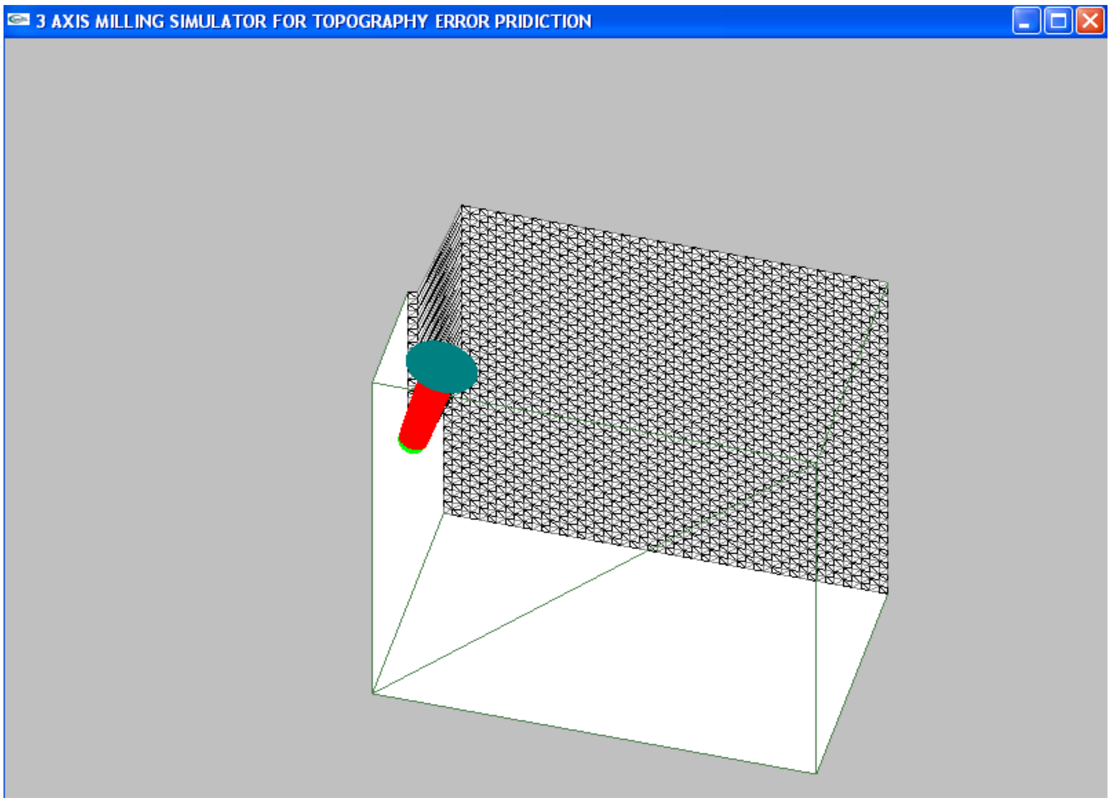


Fig.4.5 Simulator visualization during tool path simulation

4.3. SIMULATOR TESTING AND VERIFICATION

The testing is done using the Ball nose cutter of Diameter 3.175 mm(1/8") and side step of 0.793 mm(1/32"). The part for model 1 and model 2 is of dimension 25x25x15 mm and for model 3, model 4, model 5 is of dimension 50x50x30 mm. Verification of simulator is done for the finishing final cut simulation for each of the five model which will give us the direct output for the final topography generated. The parts designed for verification and testing of the simulators are as shown in Fig.4.6,Fig.4.7 Fig.4.8, Fig.4.9,Fig.4.10.The STL data of the designed parts are saved and used for generating the tool path file from CAM packages.

Then the tool path file is simulated and the surface topography error is predicted for the designed part geometry.

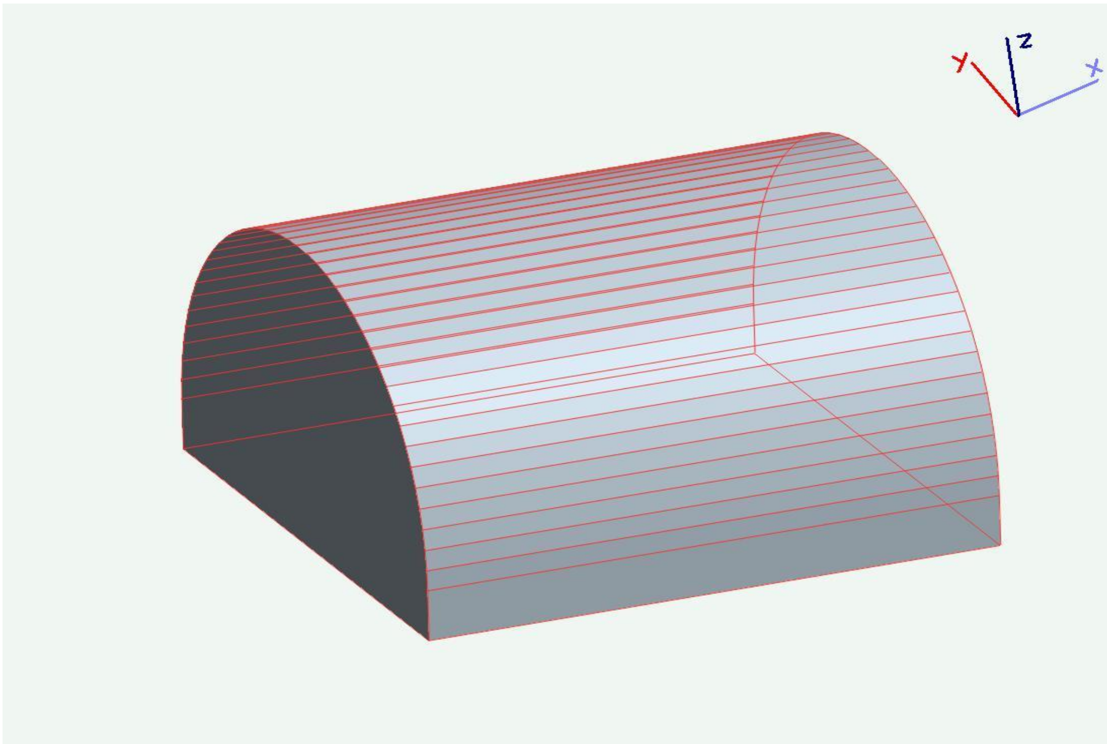


Fig.4.6 Cylindrical part along X-axis (Model 1)

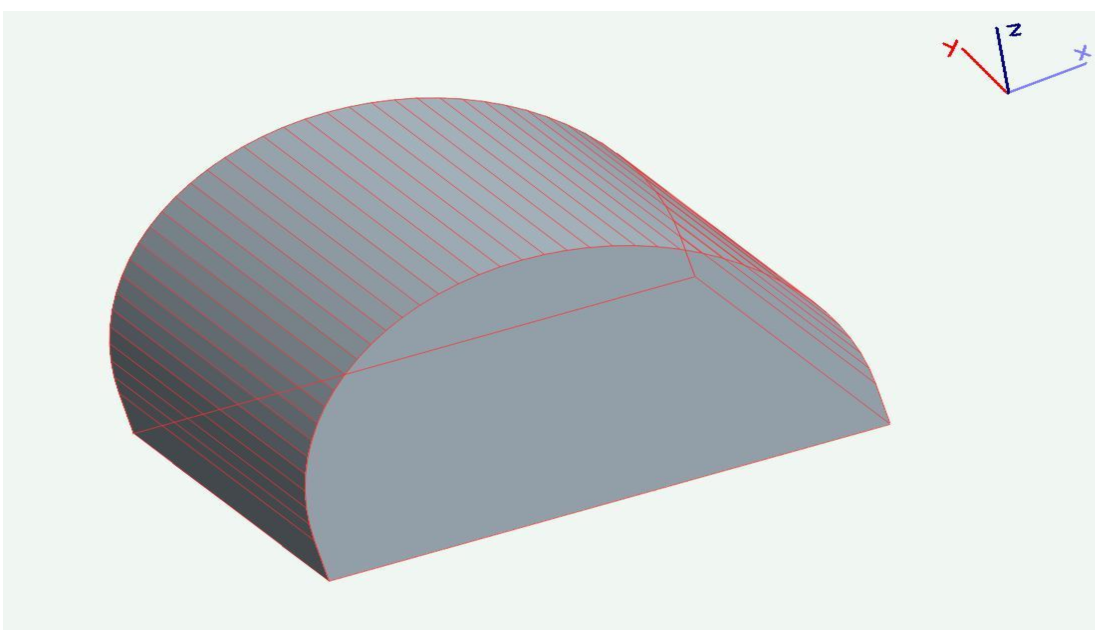


Fig.4.7 Cylindrical part along Y-axis(Model 2)

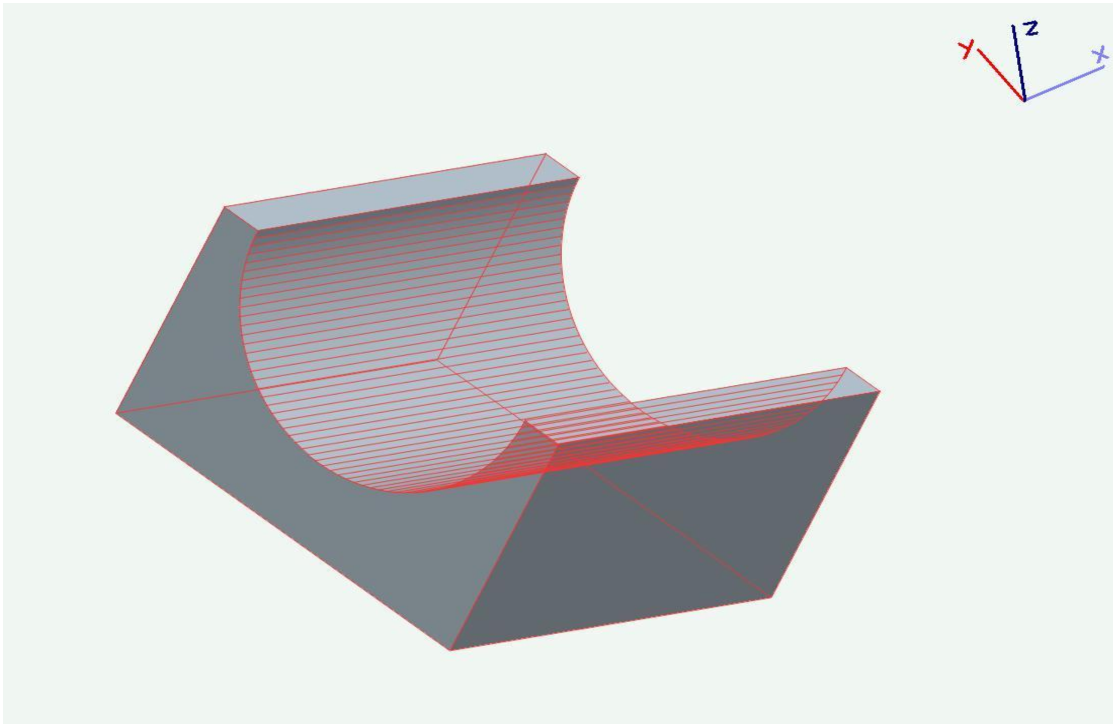


Fig.4.8 Cylindrical part cut along X-axis(Model 3

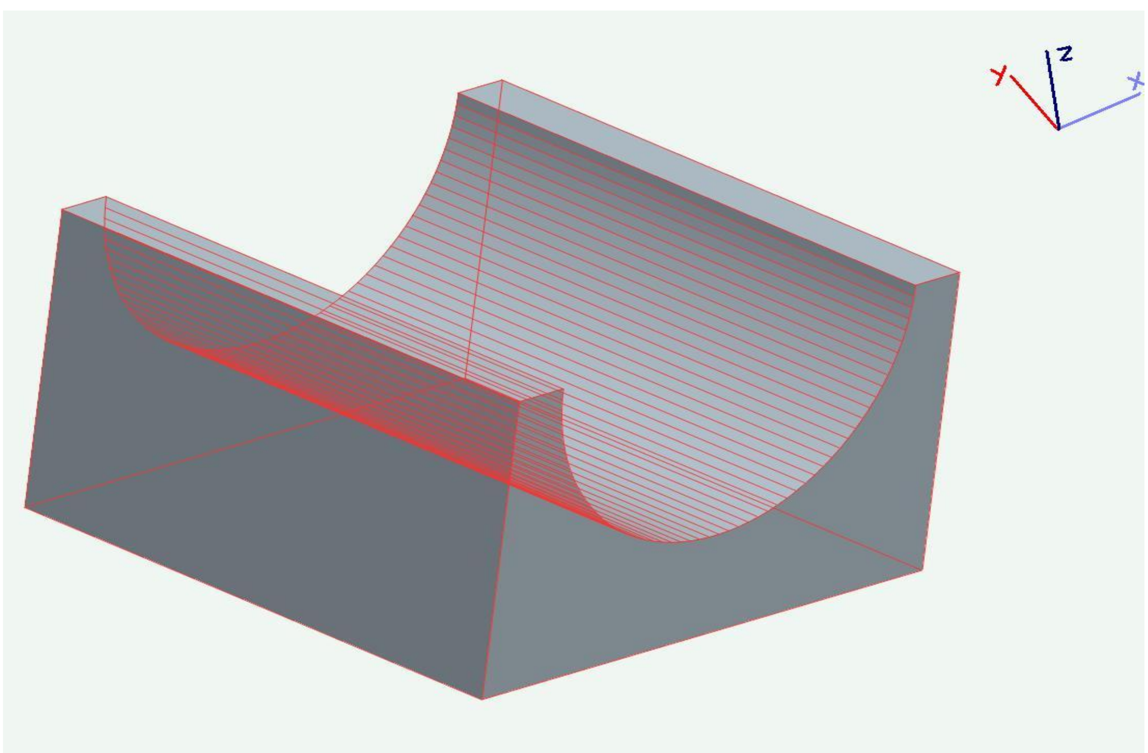


Fig.4.9 Cylindrical part cut along Y-axis(Model 4)

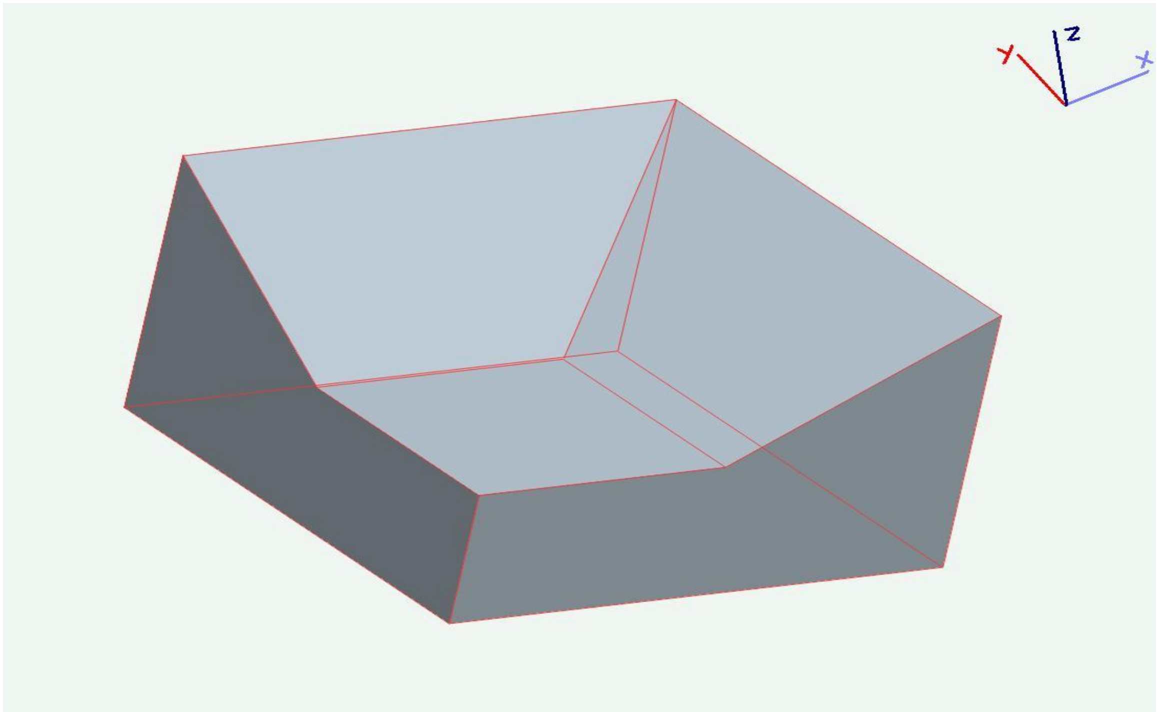
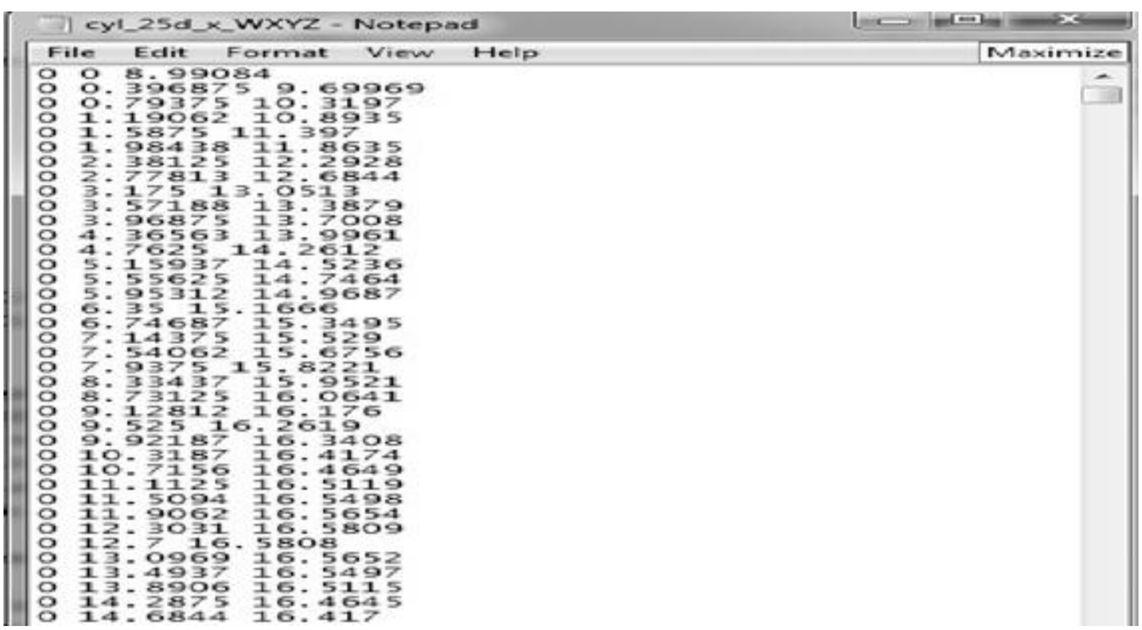


Fig.4.10 Flat 30 degree inclined surface(Model 5)

The format of the .tp file used as input for simulating the cutter positions and machining is shown in Fig.4.11 as below.




```
0 0 8.99084
0 0.396875 9.69969
0 0.79375 10.3197
0 1.19062 10.8935
0 1.5875 11.397
0 1.98438 11.8635
0 2.38125 12.2928
0 2.77813 12.6844
0 3.175 13.0513
0 3.57188 13.3879
0 3.96875 13.7008
0 4.36563 13.9961
0 4.7625 14.2612
0 5.15937 14.5236
0 5.55625 14.7464
0 5.95312 14.9687
0 6.35 15.1666
0 6.74687 15.3495
0 7.14375 15.529
0 7.54062 15.6756
0 7.9375 15.8221
0 8.33437 15.9521
0 8.73125 16.0641
0 9.12812 16.176
0 9.525 16.2619
0 9.92187 16.3408
0 10.3187 16.4174
0 10.7156 16.4649
0 11.1125 16.5119
0 11.5094 16.5498
0 11.9062 16.5654
0 12.3031 16.5809
0 12.7 16.5808
0 13.0969 16.5652
0 13.4937 16.5497
0 13.8906 16.5115
0 14.2875 16.4645
0 14.6844 16.417
```

Fig.4.11 Tool path (TP)file for simulating the part geometry

4.3.1. EXPERIMENTAL VALIDATION ON MODEL 1:

The various stages during machining simulation for model 1 is shown in Fig.4.12 , Fig.4.13, Fig.4.14 below;

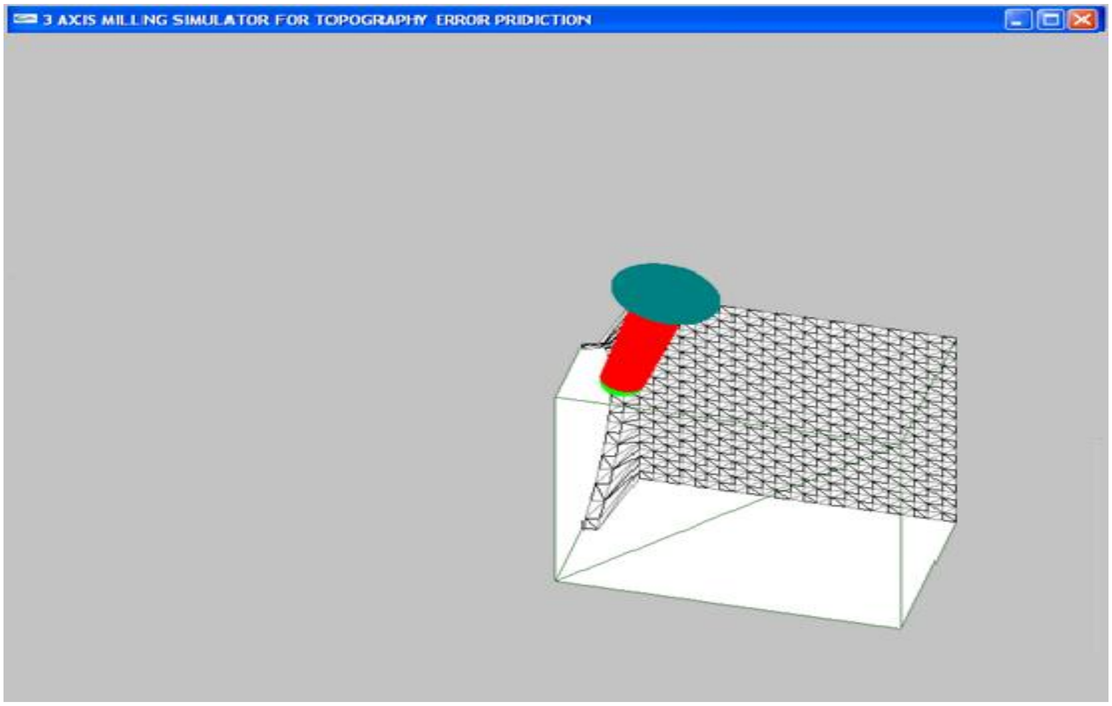


Fig.4.12 Simulation of the finishing TP(Tool path) file

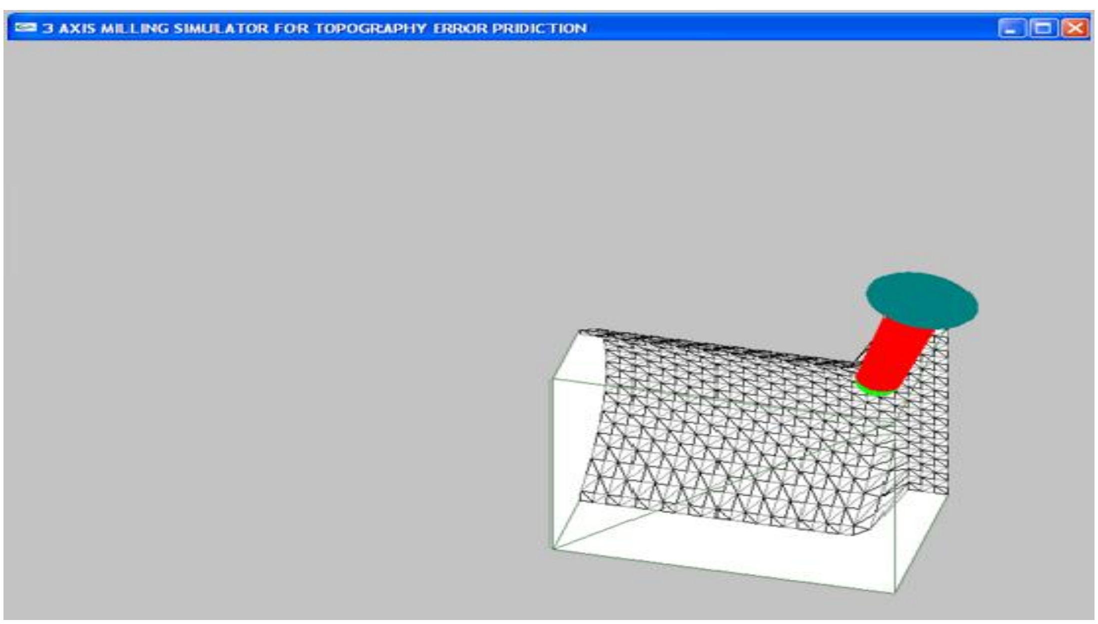


Fig.4.13 Simulation with Triangulated surface at different stage

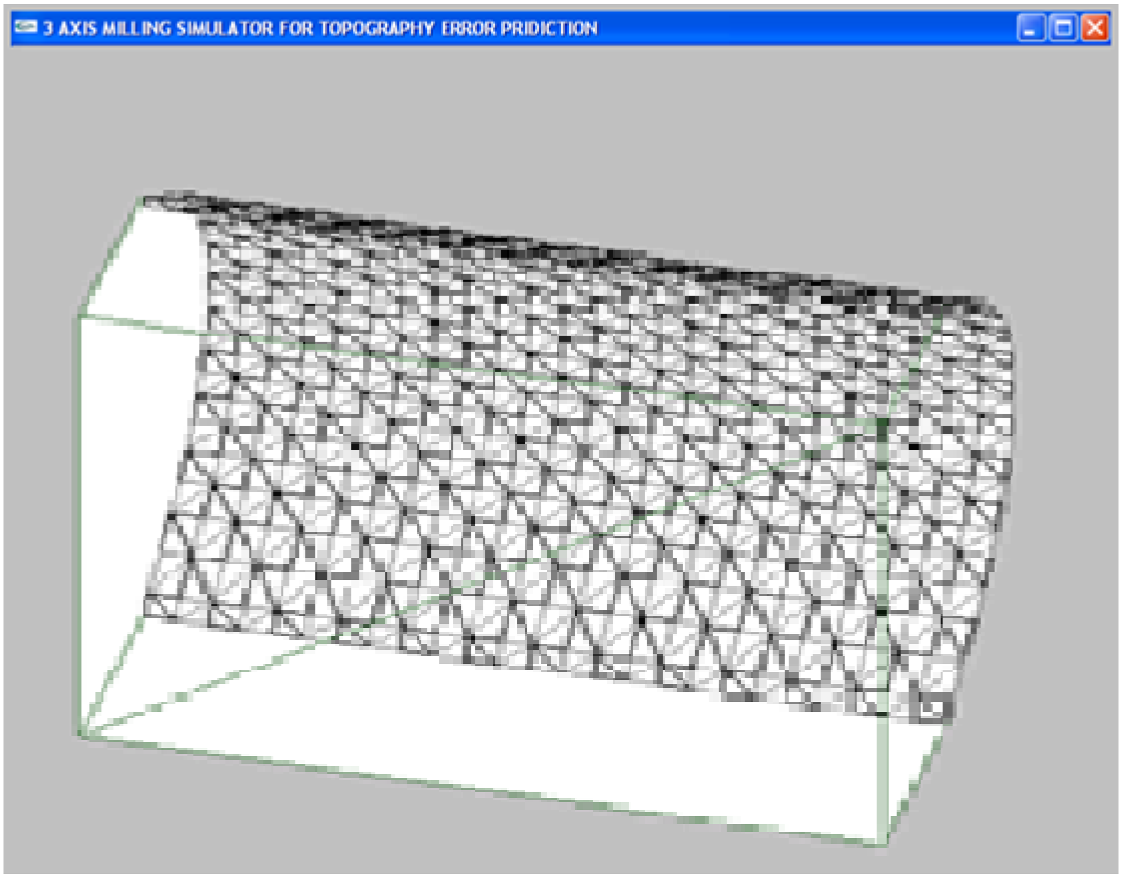


Fig.4.14 Final Simulated surface generated of model 1

As the simulation is carried out simultaneously the top triangulated surface points location are getting stored into a file .The format of file is x y z coordinates values respectively. This generated top triangulated surface is compared with the STL surface for the part.

After the machining simulation the generated output file having the top surface coordinates need to be compared against the designed surface in order to evaluate the surface topography errors. For this comparison is done between the output file and the STL file (as shown in Fig.4.15) which contain the triangulated surface data of the full geometry.

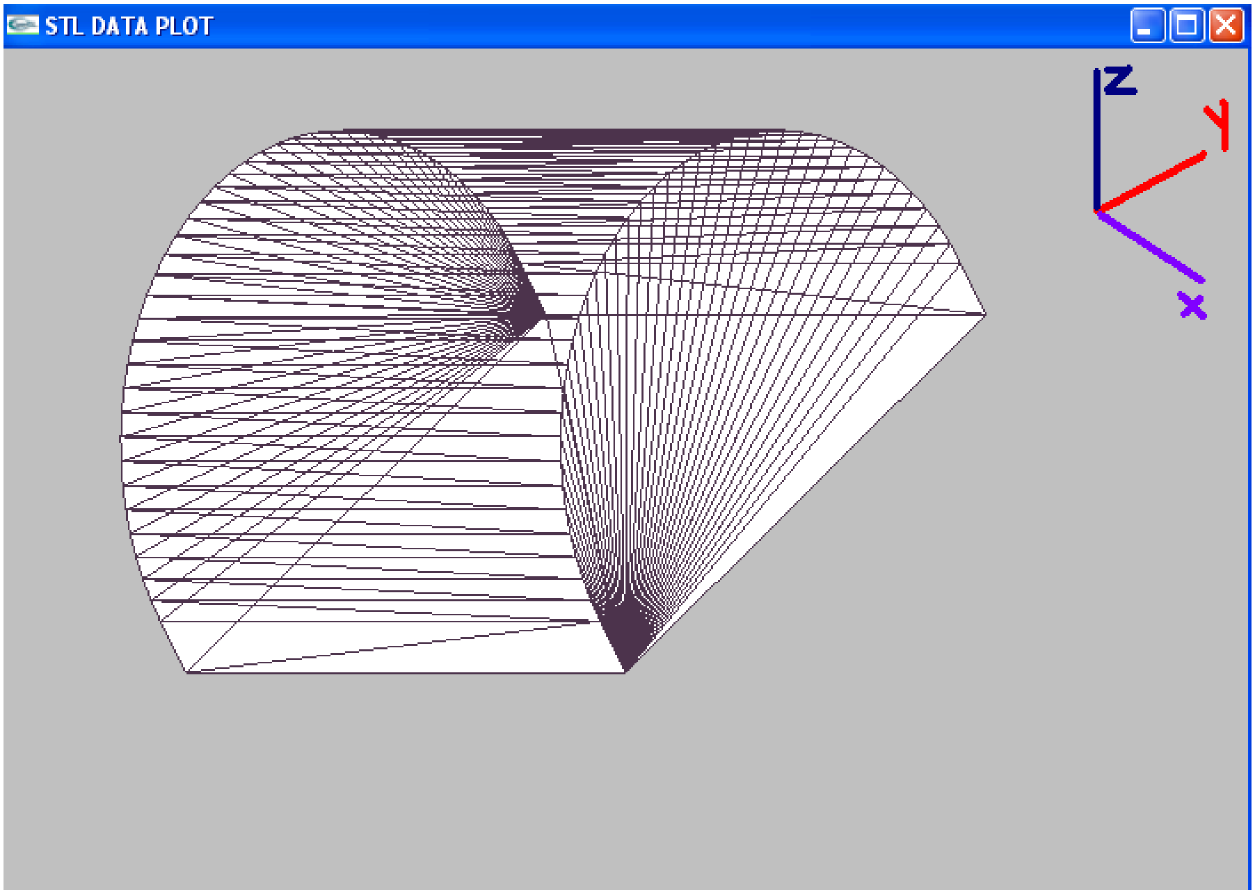


Fig.4.15 STL surface view of model 1

The Simulated surface ‘Z’ values and the STL surface ‘Z’ values are compared for the surface topography error prediction as defined below.

Topography error = (z coordinate value of STL) – (simulated surface z value)

Thus positive value of the error means the simulated surface lies below the STL surface, where as negative value of the error means the simulated surface lies above the STL surface.

Fig.4.16 shows a plot between the simulated surface Z values and the STL surface Z values along axis of the cylindrical for the model 1. It is clear from the figure that the simulated top surface is always above the STL surface thus the value of error is always negative for all coordinates value of the designed surface.

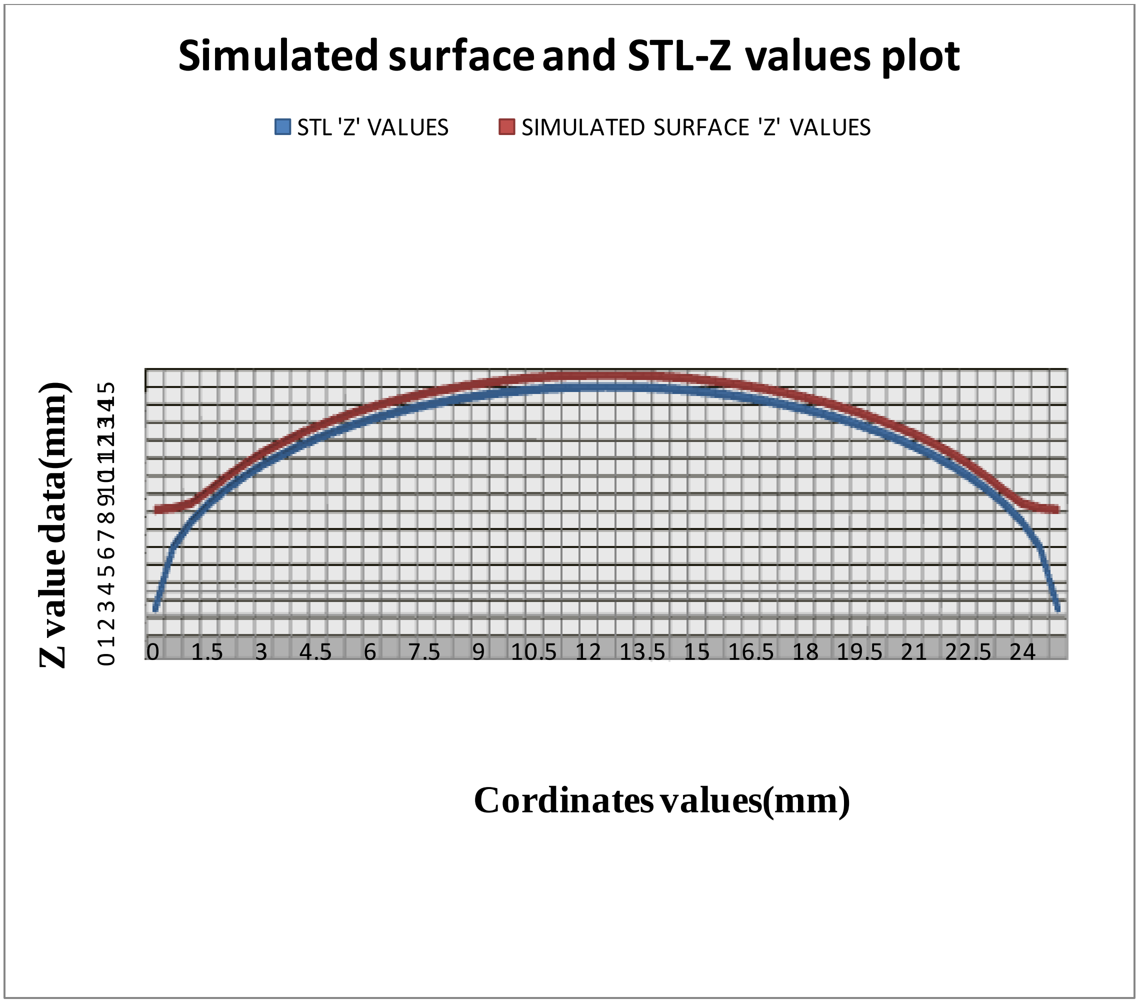


Fig.4.16 Top surface topography comparison plot

The plot for the variation of surface topography error between designed surface and the simulated surface for the model 1 is described in Fig.4.17. The topography error plot is done along the cylindrical axis and perpendicular to the cylindrical axis from the center.

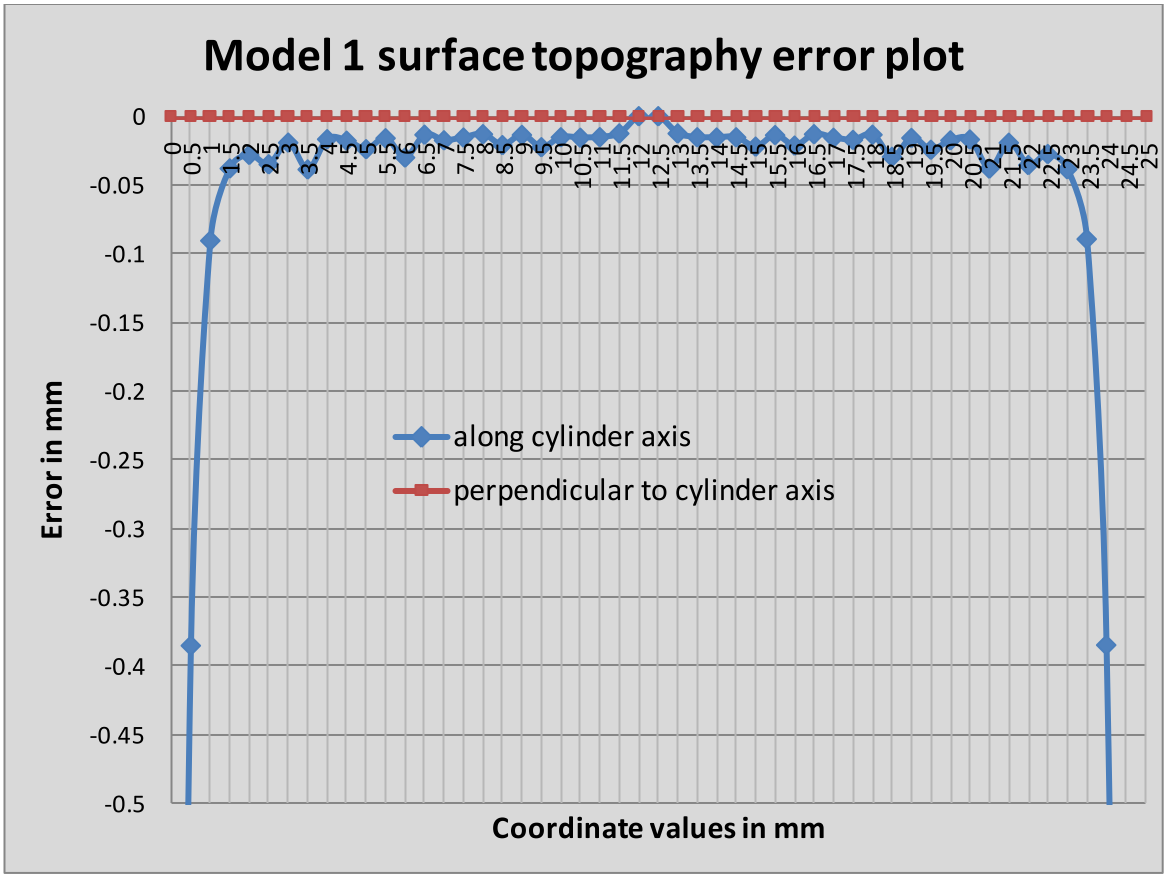


Fig.4.17 Topography error plot along and perpendicular to cylindrical axis

It is concluded from the Fig.4.17 that the value of error is comparatively high at corner points is because the tool is entering the workpiece for machining at certain minimum height also a constant side step of 0.793(1/32") is used ") is used for generating the tool path file thus error at corner points goes comparatively high.

The value of the surface topography error perpendicular to the cylindrical axis comes out to be constant and equals to 0.5 microns.

Thus it is concluded from the above simulation verification that the value of surface topography error perpendicular to the cylindrical axis is negligible and along the cylindrical axis surface topography error average value (Ra value) is 18 microns. It is concluded from the model 1 experimental validation that simulator is able to predict the surface topography error efficiently with high accuracy. It is concluded from the simulator pictures of model 1 machining simulation that graphical machining simulation is also done very efficiently.

4.3.2. EXPERIMENTAL VALIDATION ON MODEL 2:

The machining simulation on model 2 is also done by simulating the final finishing file by using the ball nose cutter of 3.175 mm (1/8") diameter .Various stages during machining simulation can be seen below in Fig.4.18, Fig.4.19, Fig.4.20, Fig.4.21.

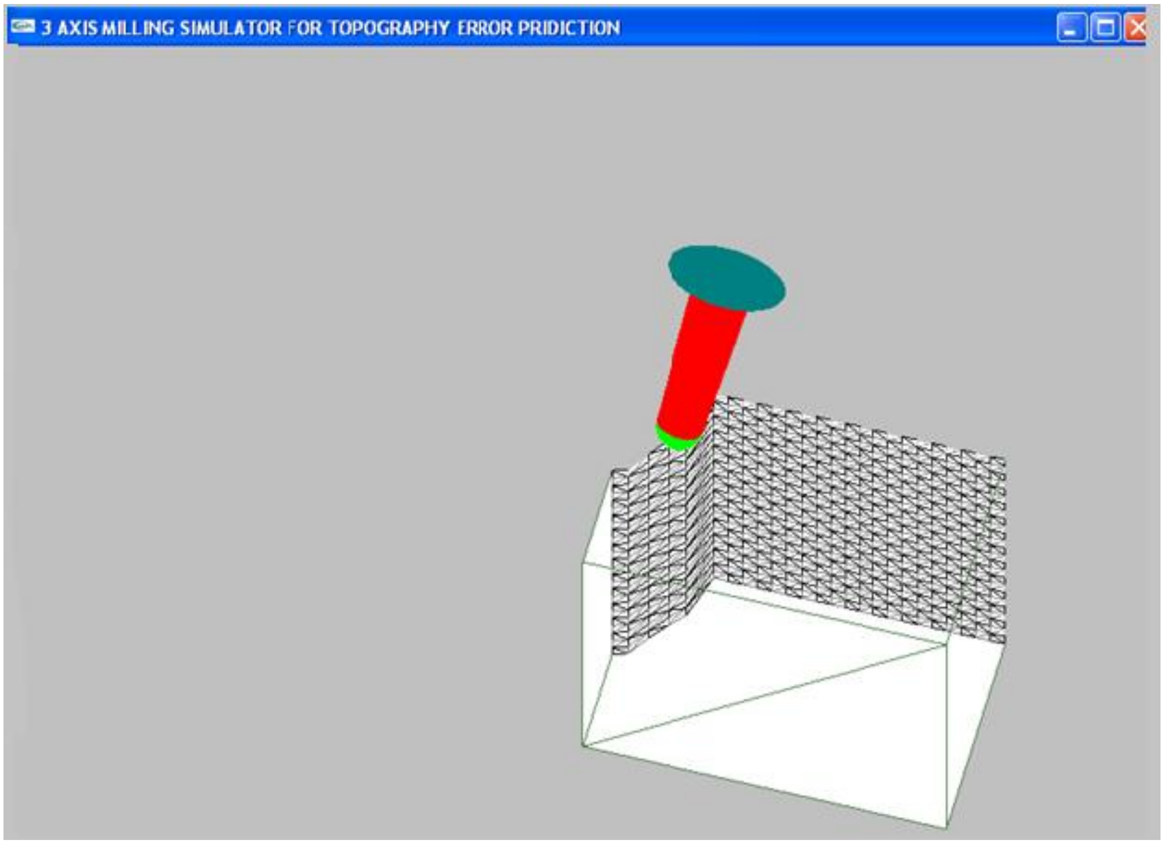


Fig.4.18 Start of machining simulation with finishing tool path file

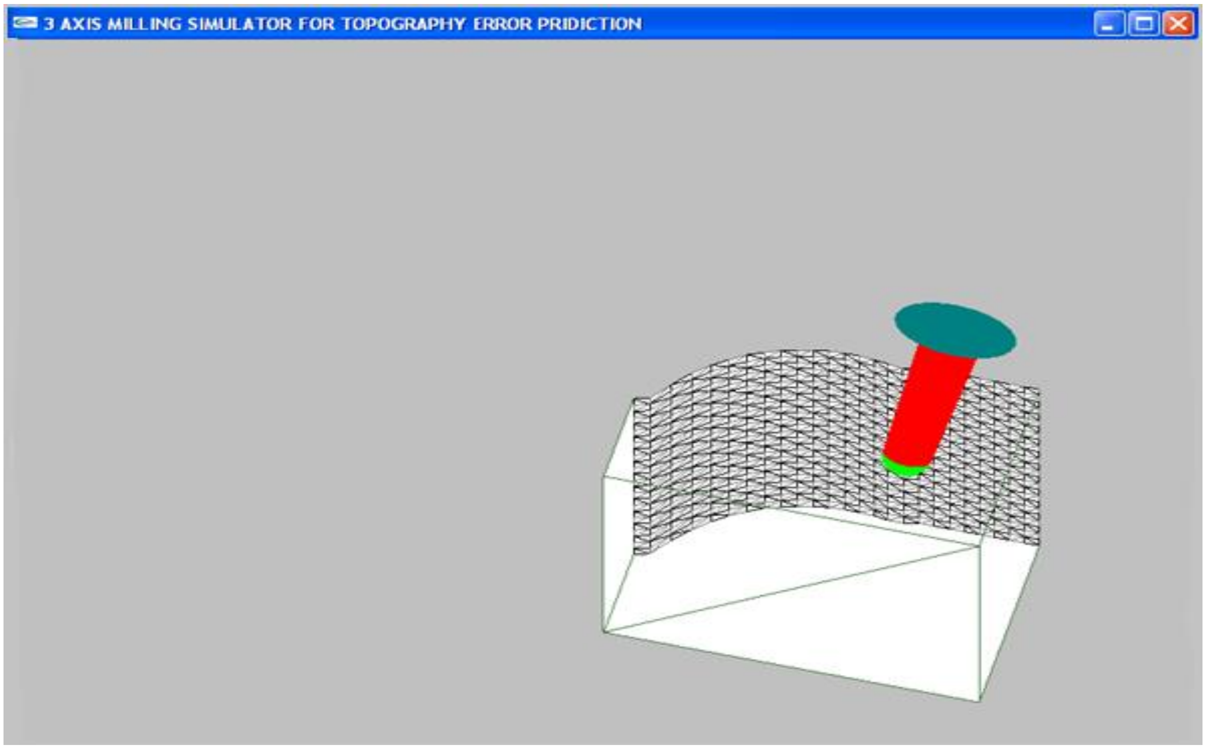


Fig.4.19 Simulation at different stage

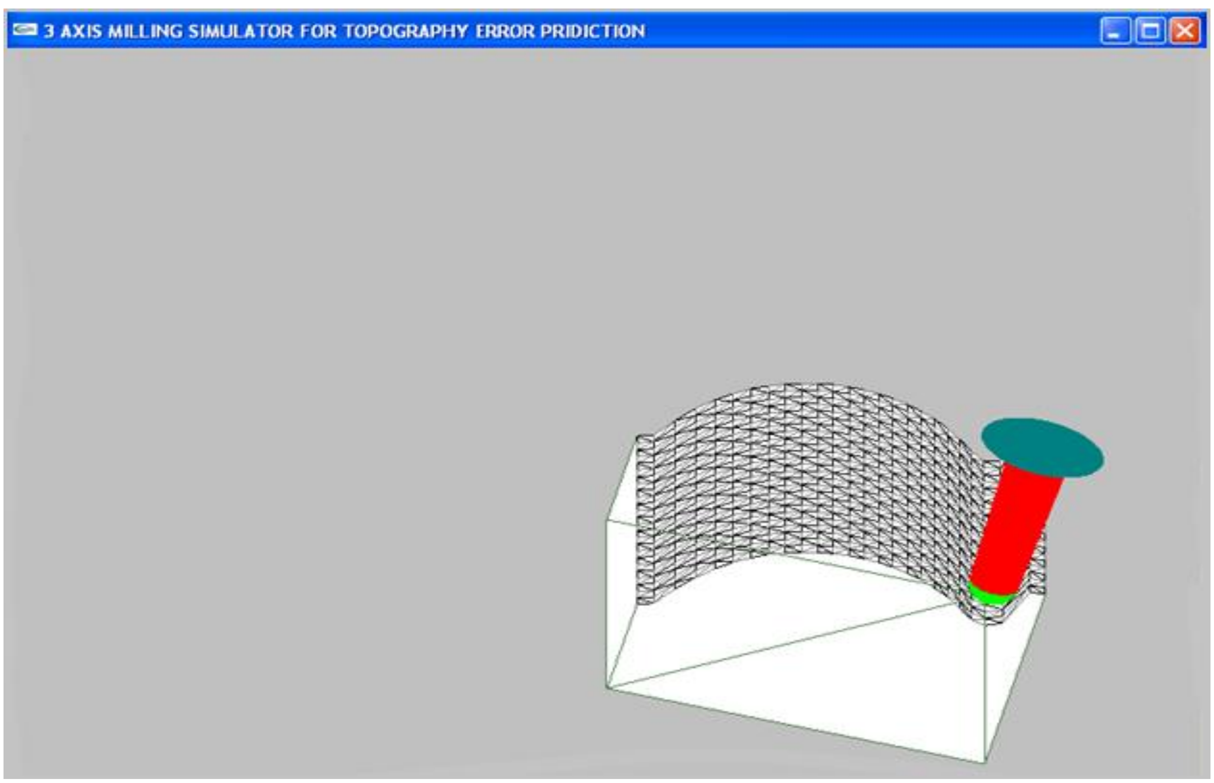


Fig.4.20 Top surface generation at different stage

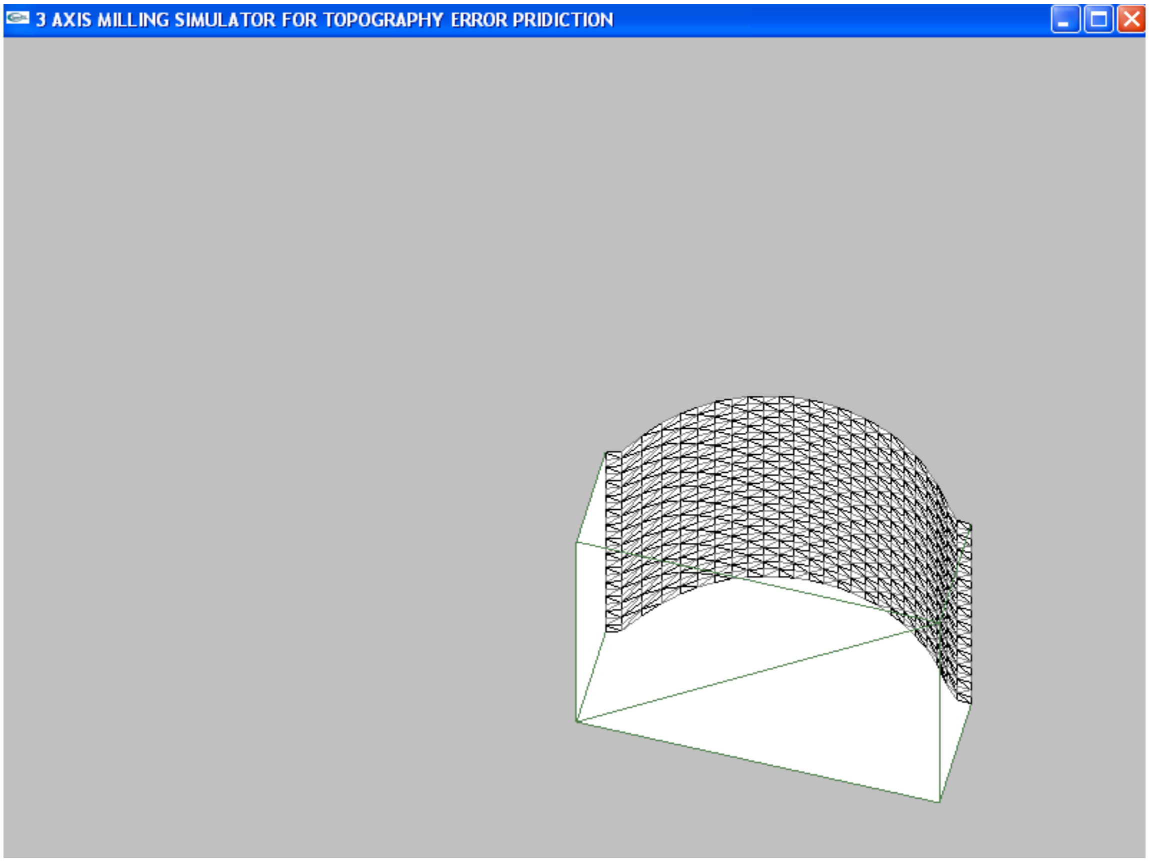


Fig.4.21 Final simulated surface of model 2

In order to evaluate the surface topography errors for model 2 comparison is done between the output file and the STL file (as shown in Fig.4.22) which contain the triangulated surface data of the full geometry.

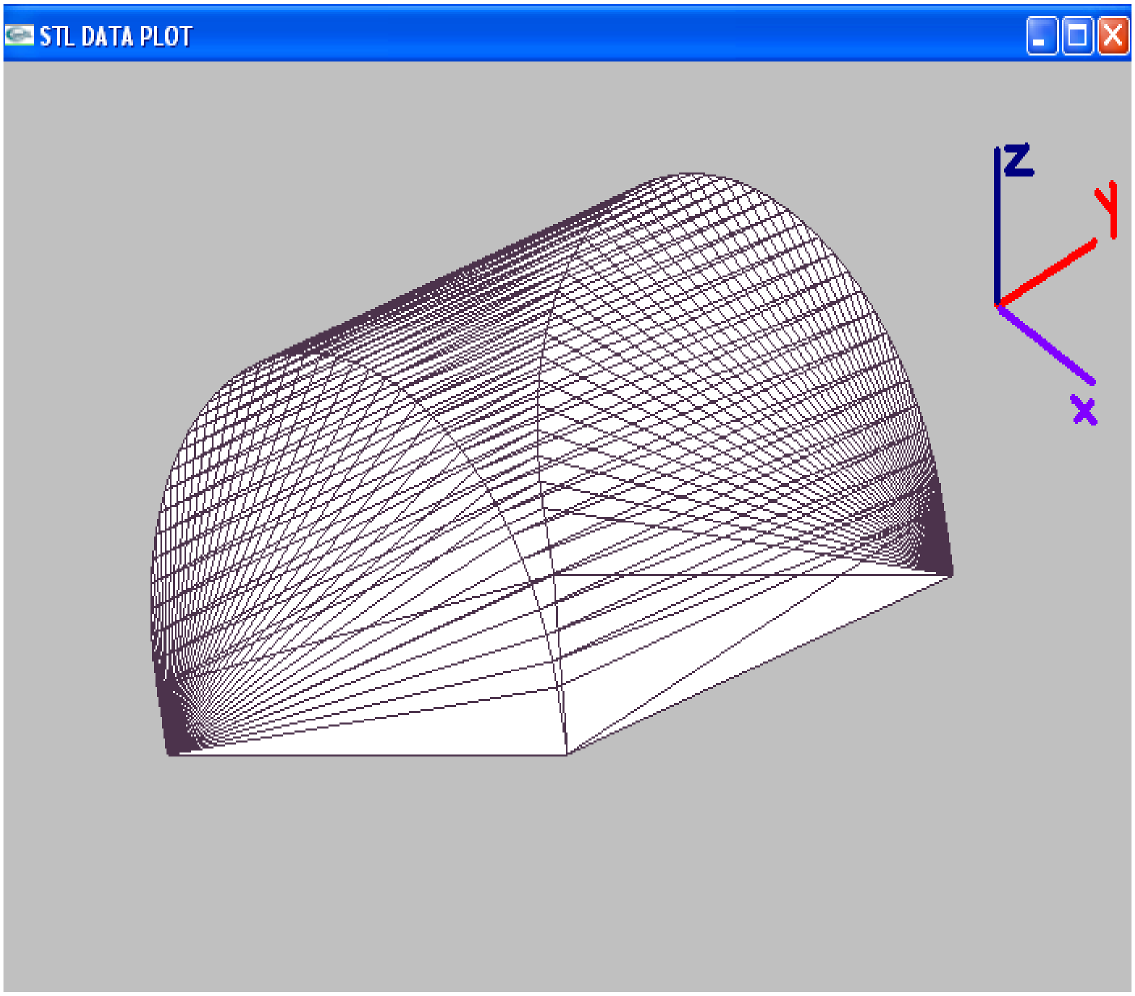


Fig.4.22 STL surface plot for model 2

The plot for the variation of the surface topography error between designed surface and the simulated surface for the model 2 is described in Fig.4.23 .The topography error plot is done along the cylindrical axis and perpendicular to the Cylindrical axis from the center.

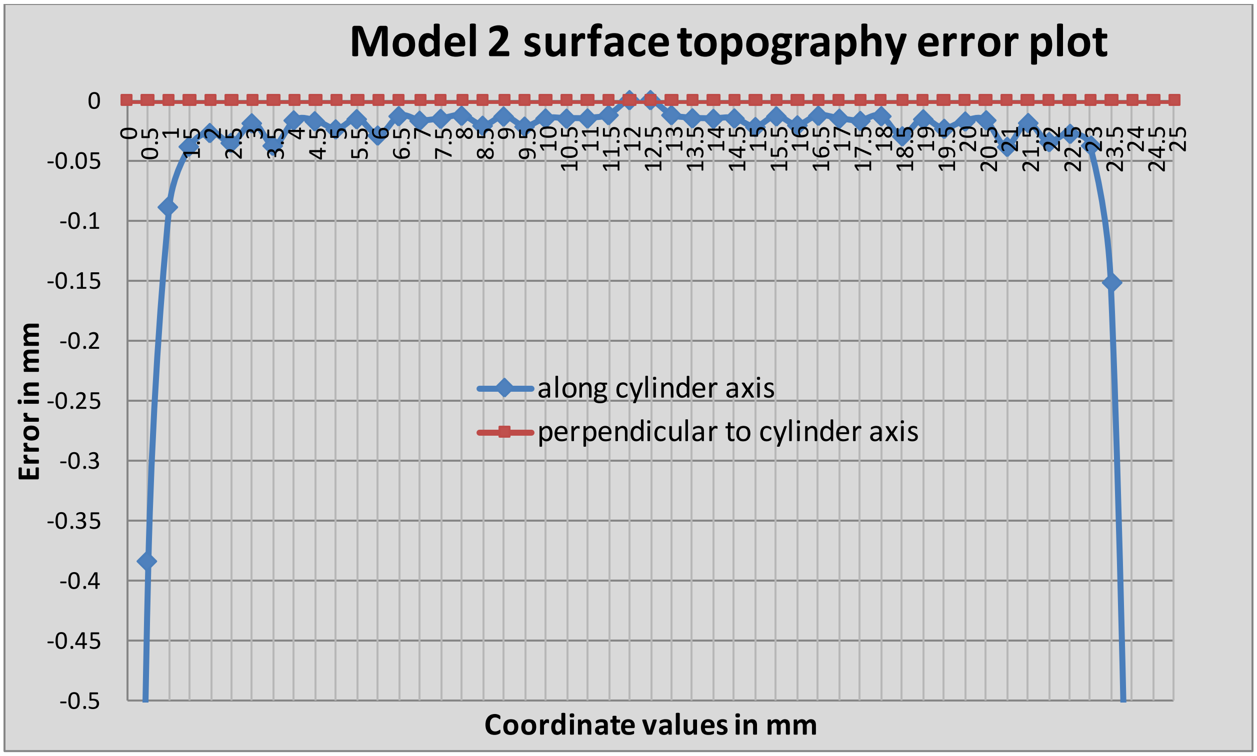


Fig.4.23 Topography error plot for model 2

It is concluded from the Fig.4.23 that the value of error is comparatively high at corner points is because the tool is entering the workpiece for machining at certain minimum height also a constant side step of 0.793(1/32") is used for generating the tool path file thus error at corner points goes comparatively high.

The value of the surface topography error perpendicular to the cylindrical axis comes out to be constant and equals to 0.6 microns.

Thus it is concluded from the above simulation verification that the value of surface topography error perpendicular to the cylindrical axis is negligible and along the cylindrical axis surface topography error average value (Ra value) is 19.5 microns.

It is concluded from the model 2 experimental validation that simulator is able to predict the surface topography error efficiently with high accuracy. The error is also measured with consistency at each point.

4.3.3. EXPERIMENTAL VALIDATION ON MODEL 3:

The machining simulation on model 3 is done by simulating the final finishing file by using the ball nose cutter of 3.175(1/8") diameter .Various stages during machining simulation can be seen below in Fig.4.24, Fig.4.25, Fig.4.26, Fig.4.27.

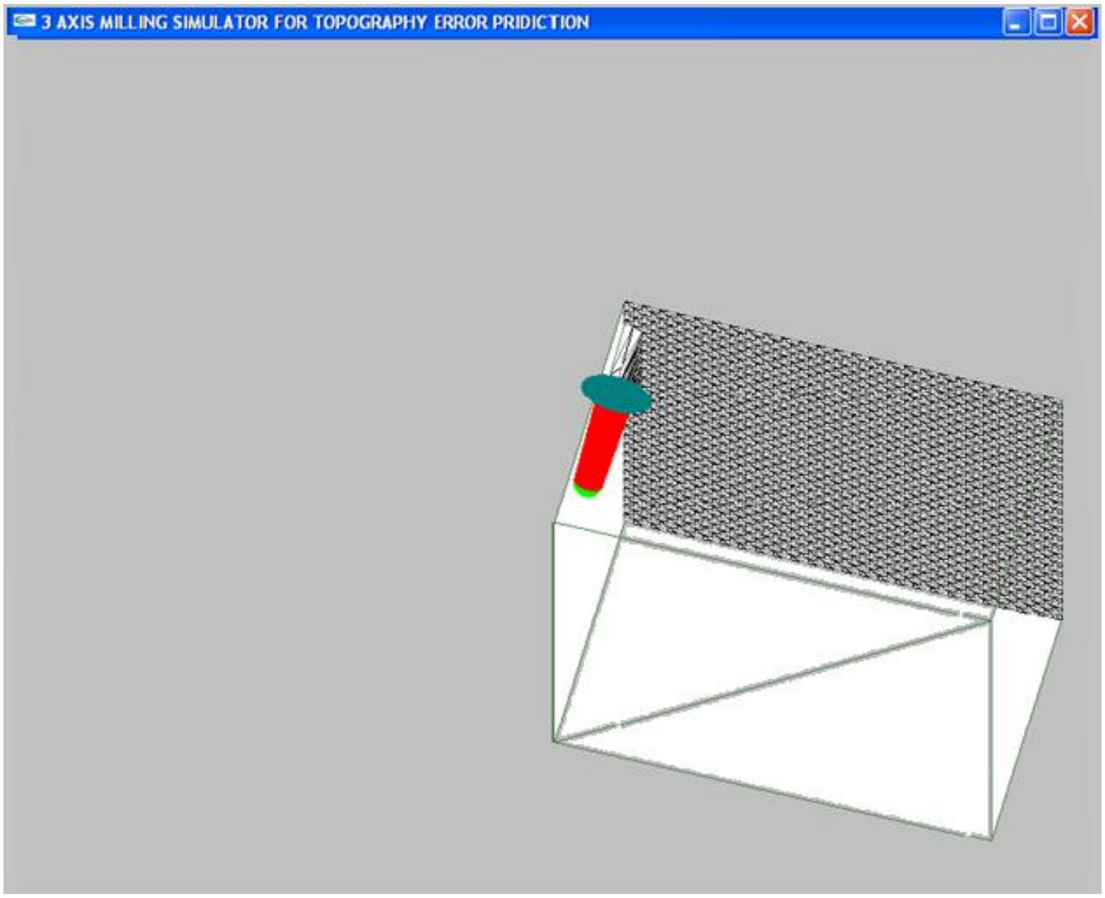


Fig.4.24 Start of machining simulation of model 3

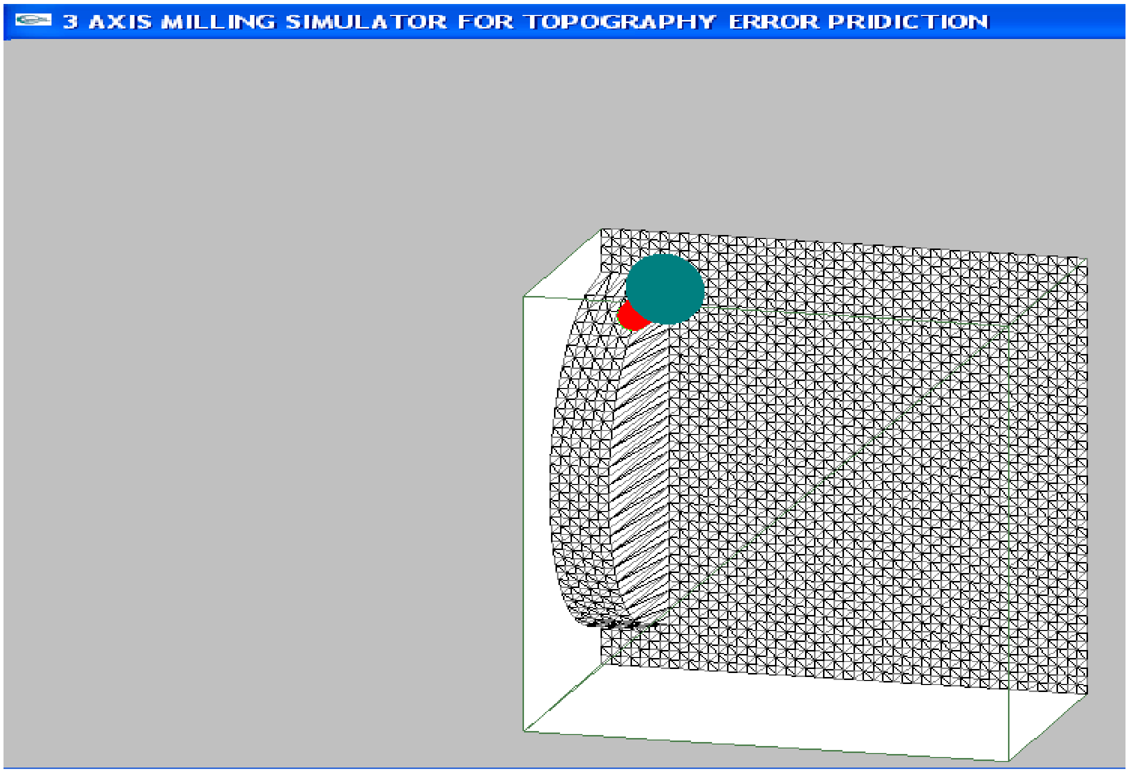


Fig.4.25 simulation shown at different stage

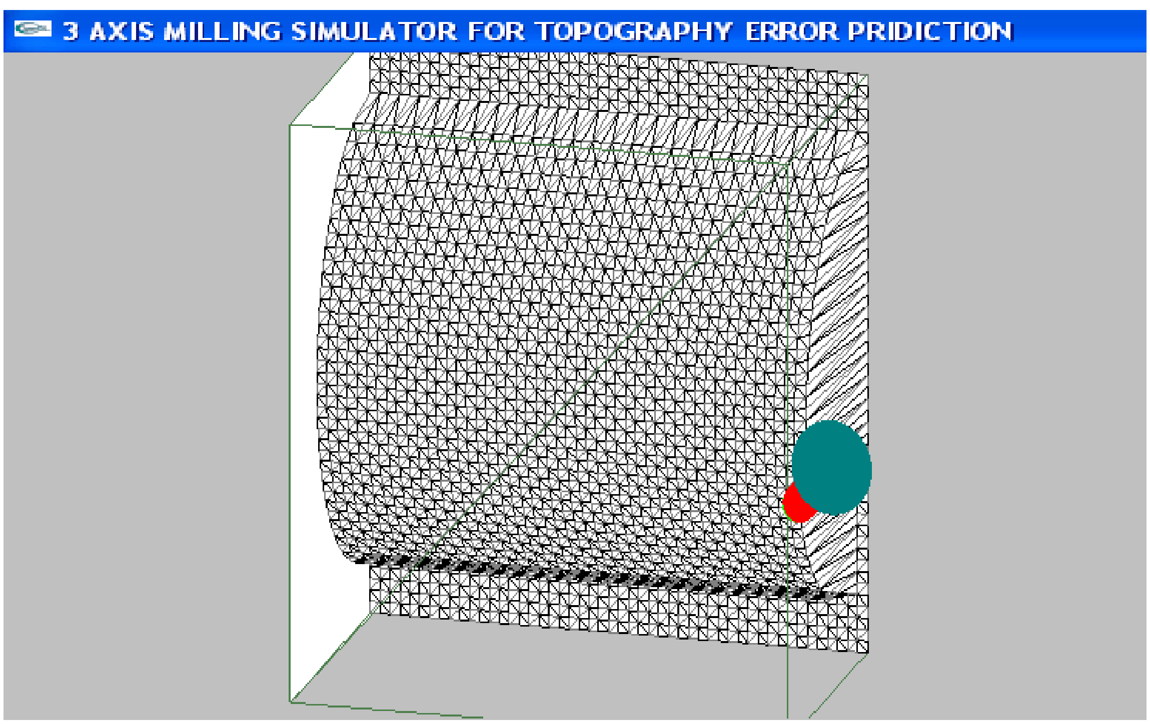


Fig.4.26 Machining simulation at different stage

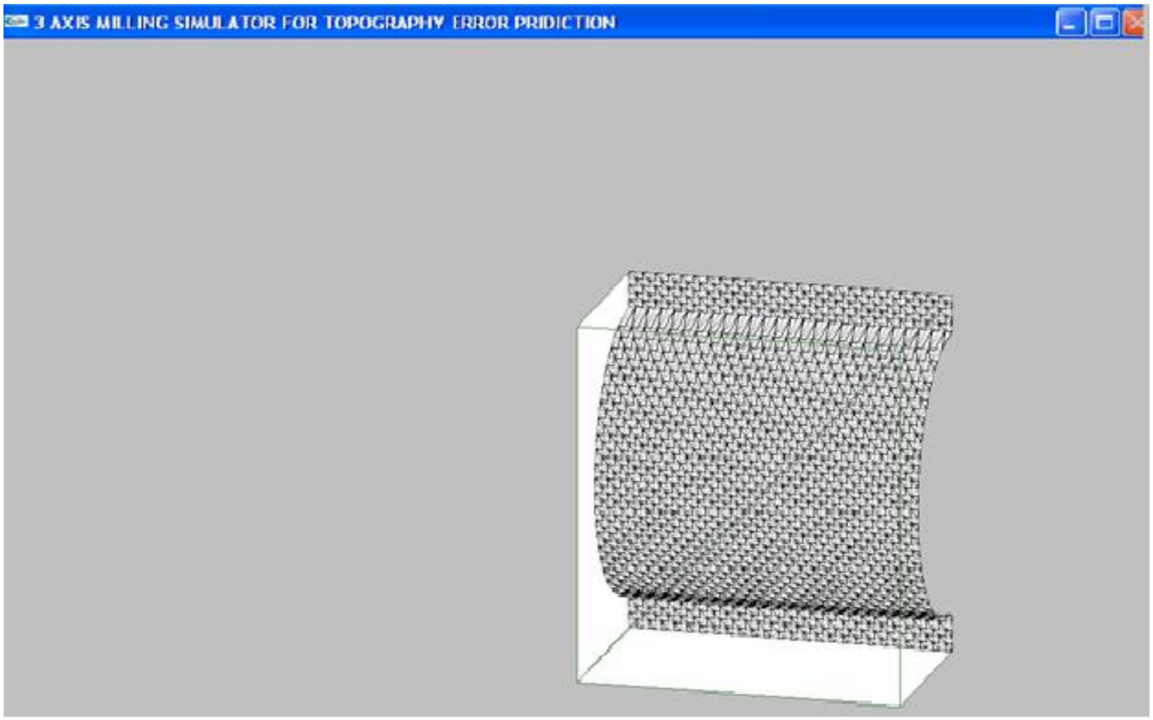


Fig.4.27 Final simulated surface of model 3

In order to evaluate the surface topography errors for model 3 comparison is done between the output file and the STL file(as shown in Fig.4.28) which contain the triangulated surface data of the full geometry.

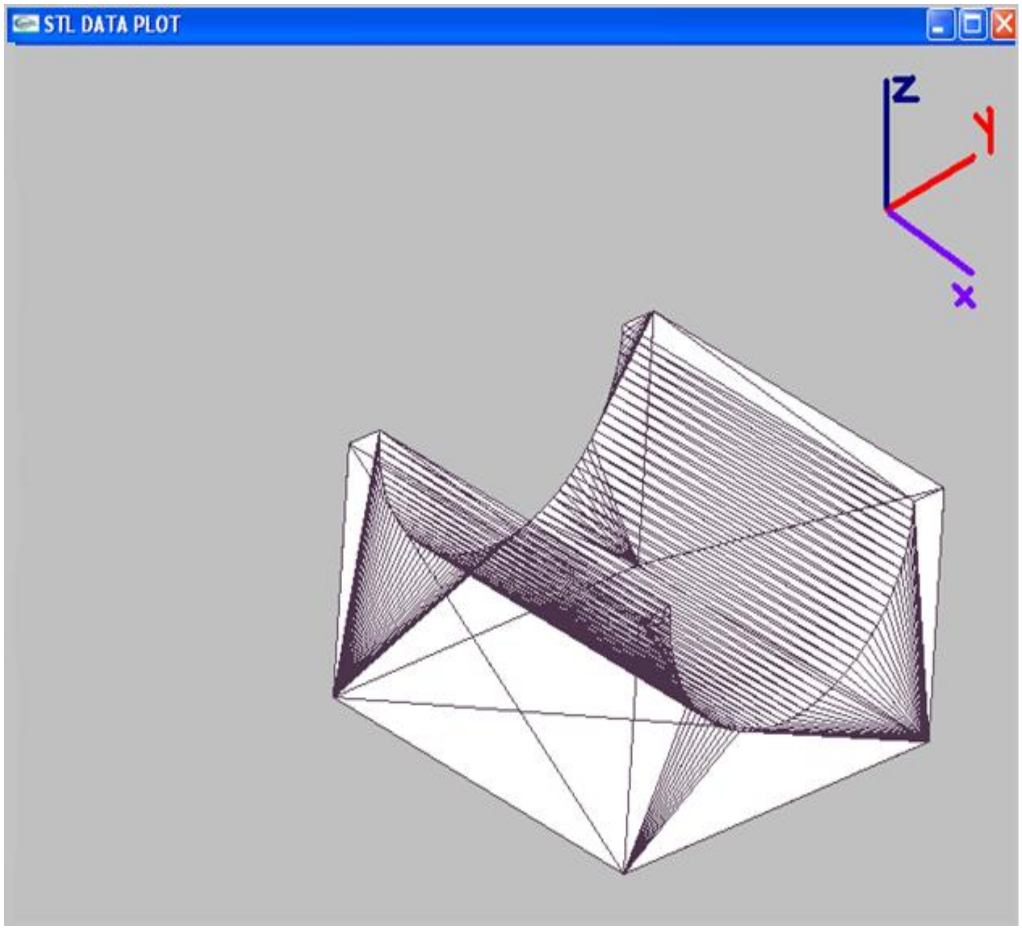


Fig.4.28 STL surface plot of model 3

The plot for the variation of the surface topography error between designed surface and the simulated surface for the model 3 is described in Fig.4.29 .The topography error plot is done along the cylindrical axis and perpendicular to the Cylindrical axis from the center.

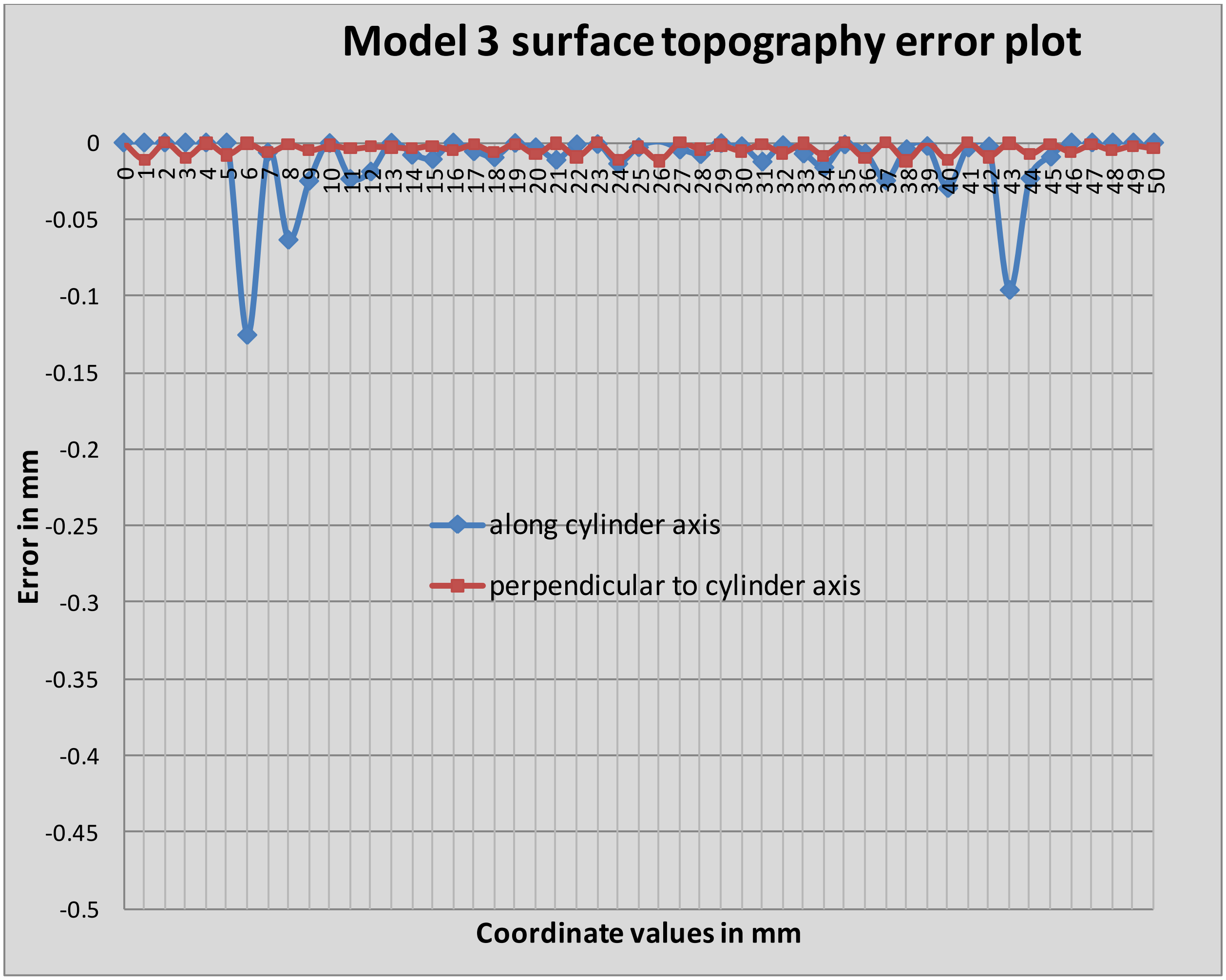


Fig.4.29 Topography error plot for model 3

It is concluded from the Fig.4.29 that the value of error is comparatively high at sharp corner points is because a constant side step of 0.793(1/32”) is used for generating the tool path file. Also tool profile is ball nose type thus sharp corner points remains uncut and error at corner points goes comparatively high.

The average value of the surface topography error(Ra value) perpendicular to the cylindrical axis comes out to be 8 microns.

Thus it is concluded from the above simulation verification that the value of surface topography error perpendicular to the cylindrical axis is negligible and along the cylindrical axis surface topography error average value (Ra value) is 21 microns.

It is concluded from the model 3 experimental validation that simulator is able to predict the surface topography error efficiently with high accuracy. The error is also measured with consistency at each point.

4.3.4. EXPERIMENTAL VALIDATION ON MODEL 4:

The machining simulation on model 4 is done by simulating the final finishing file by using the ball nose cutter of 3.175 mm (1/8") diameter .Various stages during machining simulation can be seen below in Fig.4.30, Fig.4.31, Fig.4.32, Fig.4.33

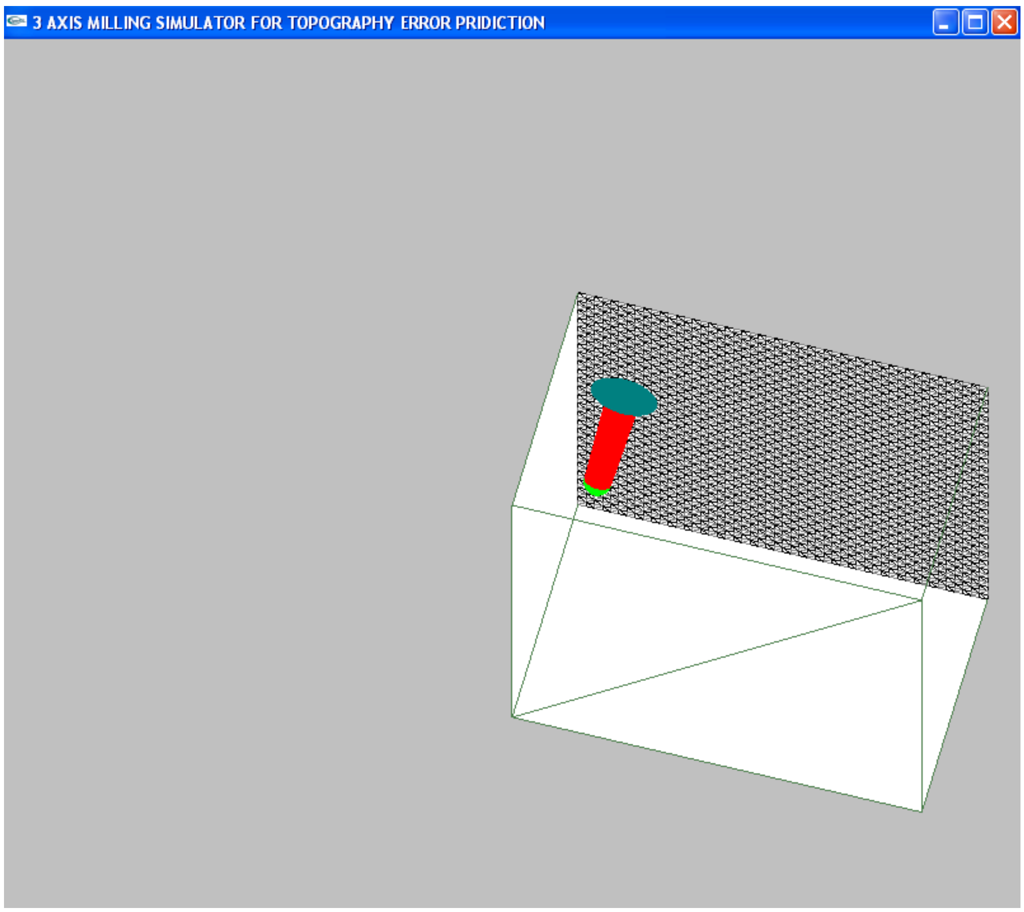


Fig.4.30 Start of machining simulation of model 4

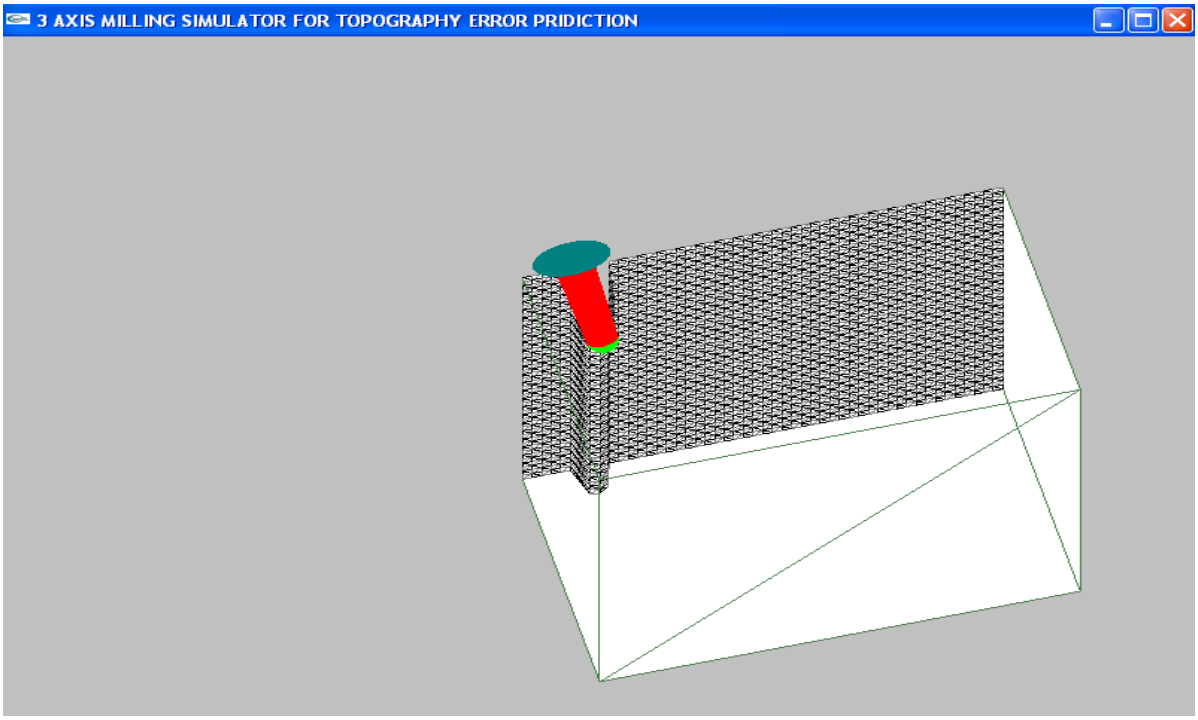


Fig.4.31 simulation showing generation of Triangulated top surface

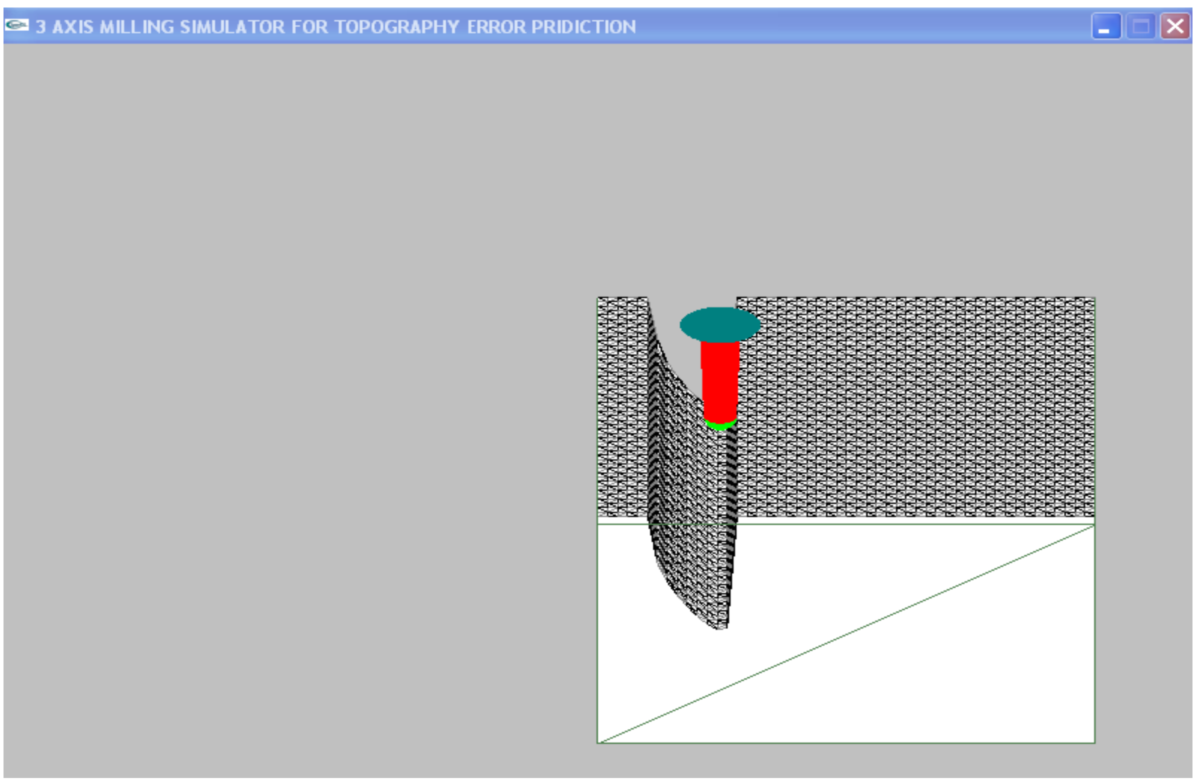


Fig.4.32 Machining simulation at different stage

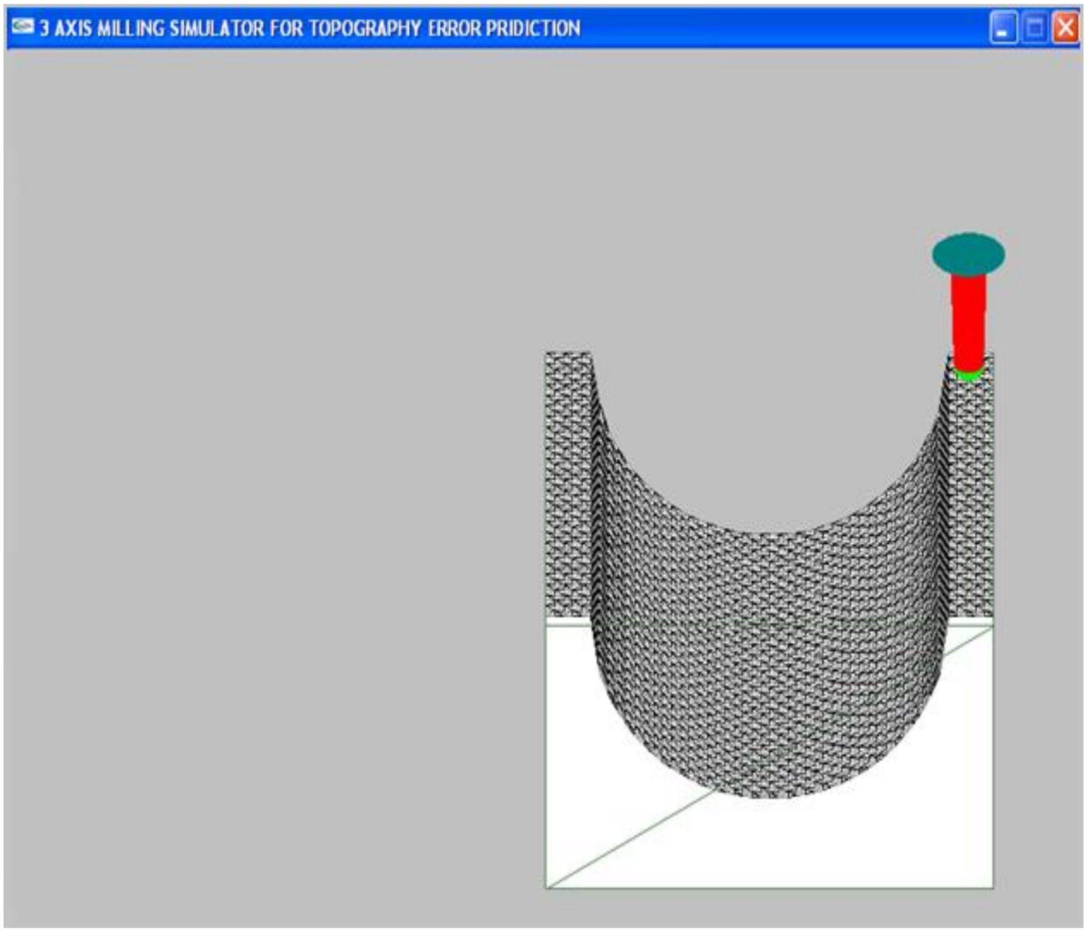


Fig.4.33 Final Generated simulated surface of model 4

In order to evaluate the surface topography errors for model 4 comparison is done between the output file and the STL file (as shown in Fig.4.34) which contain the triangulated surface data of the full geometry.

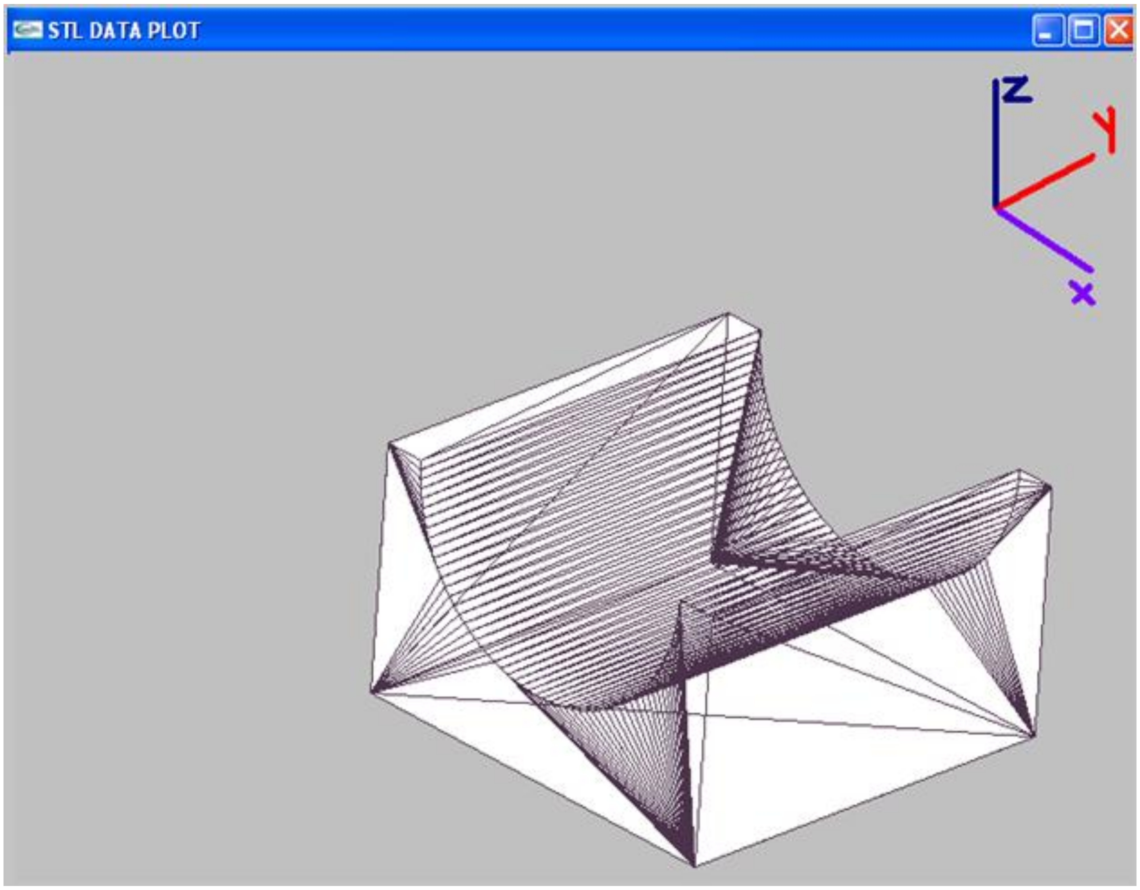


Fig.4.34 STL surface plot of Model 4

The plot for the variation of the surface topography error between designed surface and the simulated surface for the model 4 is described in Fig.4.35.The topography error plot is done along the cylindrical axis and perpendicular to the Cylindrical axis from the center.

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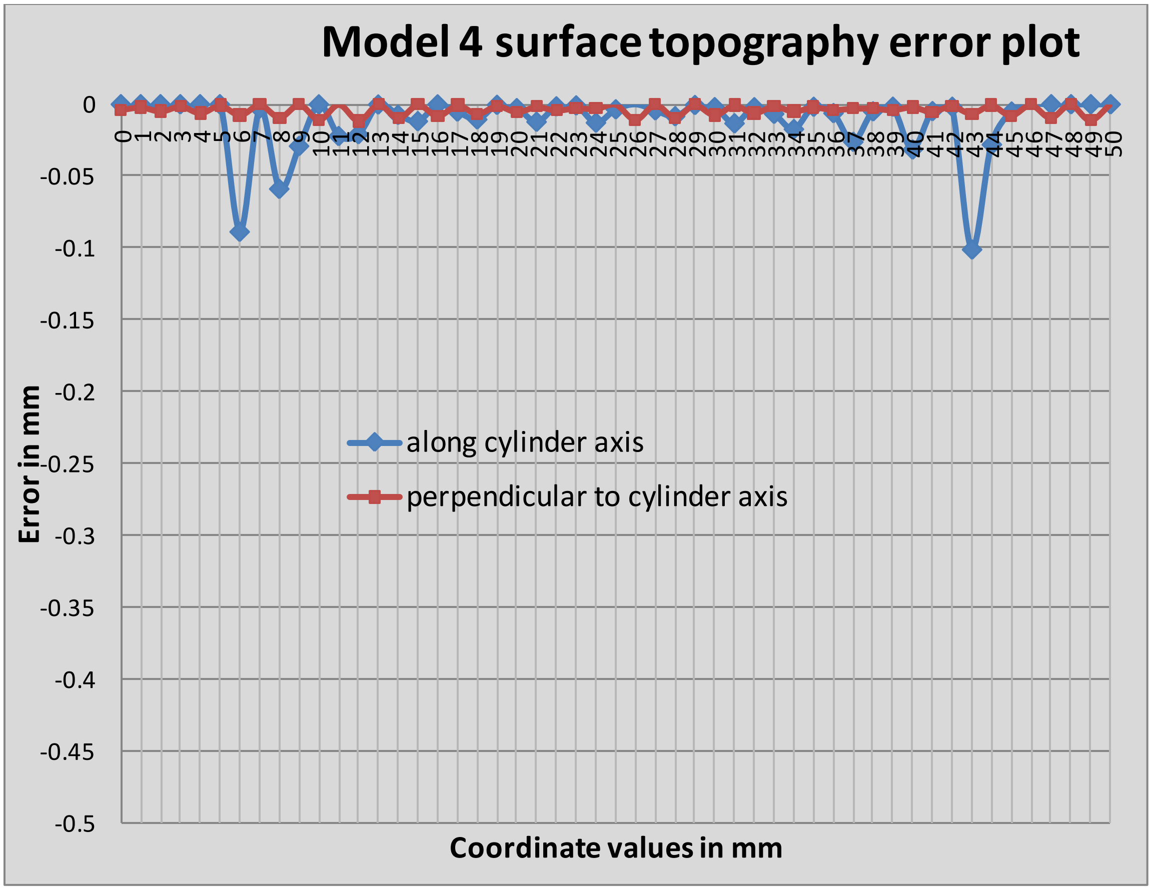

Fig.4.35 Topography error plot for model 4

It is concluded from the Fig.4.35 that the value of error is comparatively high at sharp corner points is because a constant side step of 0.793(1/32") is used for generating the tool path file. Also tool profile is ball nose type thus sharp corner points remains uncut and error at corner points goes comparatively high.

The average value of the surface topography error(Ra value) perpendicular to the cylindrical axis comes out to be 4 microns.

Thus it is concluded from the above simulation verification that the value of surface topography error perpendicular to the cylindrical axis is negligible and along the cylindrical axis surface topography error average value (Ra value) is 23 microns.

It is concluded from the model 4 experimental validation that simulator is able to predict the surface topography error efficiently with high accuracy.

4.3.5. EXPERIMENTAL VALIDATION ON MODEL 5:

The machining simulation on model 5 is done by simulating the final finishing file by using the ball nose cutter of 3.175 mm(1/8") diameter .Various stages during machining simulation can be seen below in Fig.4.36 , Fig.4.37, Fig.4.38, Fig.4.39, Fig.4.40.

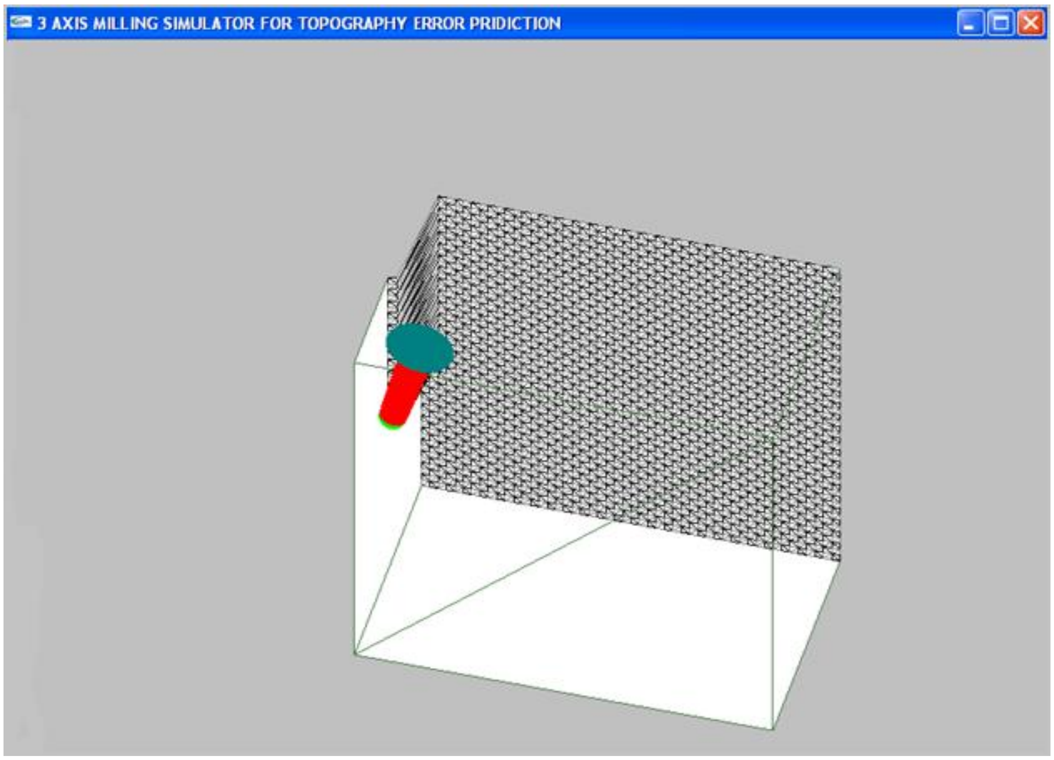

Fig.4.36 Start of machining simulation of model 5

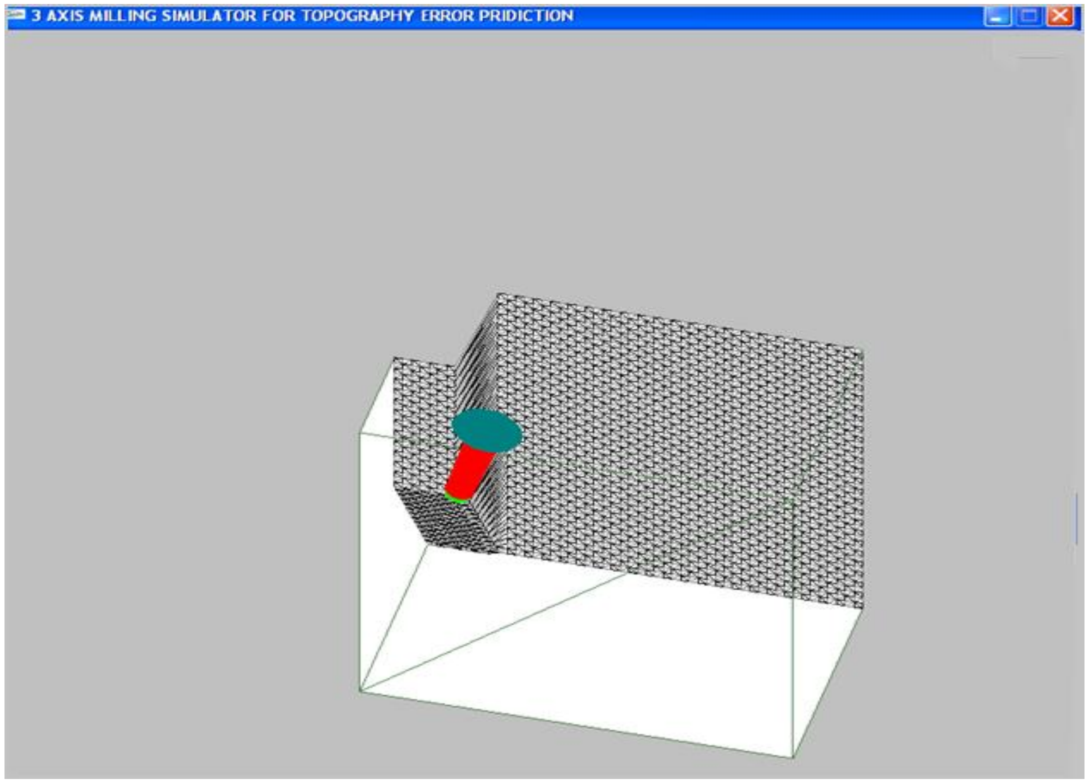

Fig.4.37 simulation shown at different stage

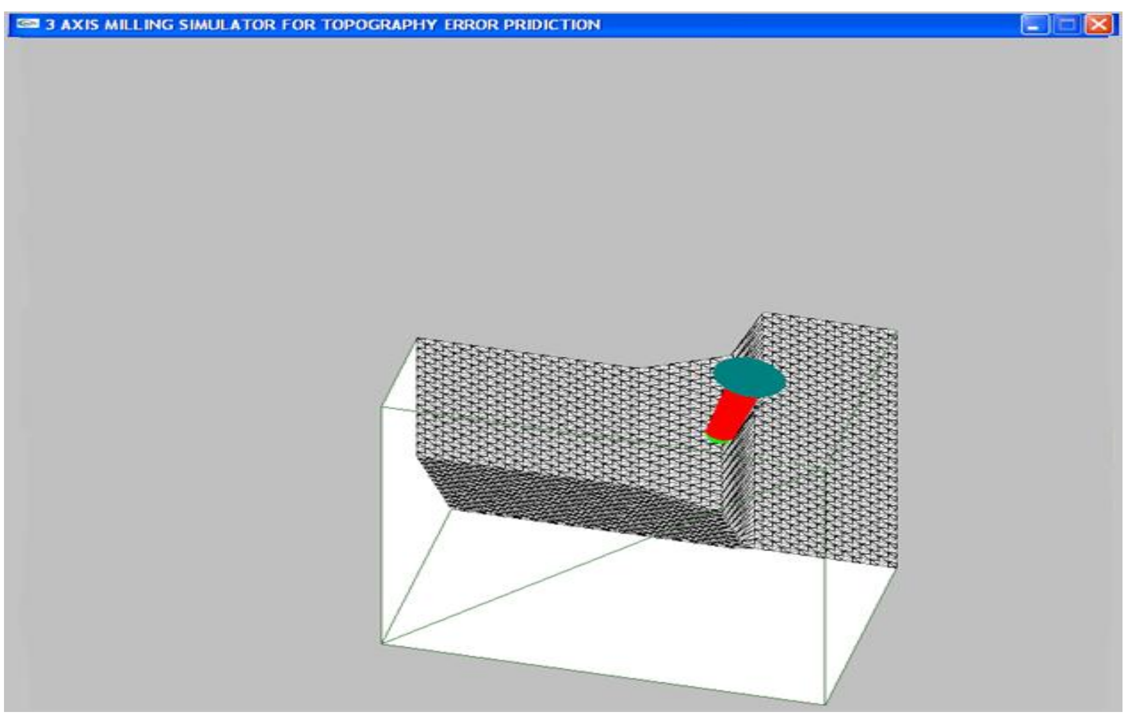

Fig.4.38 simulation shown at different stage

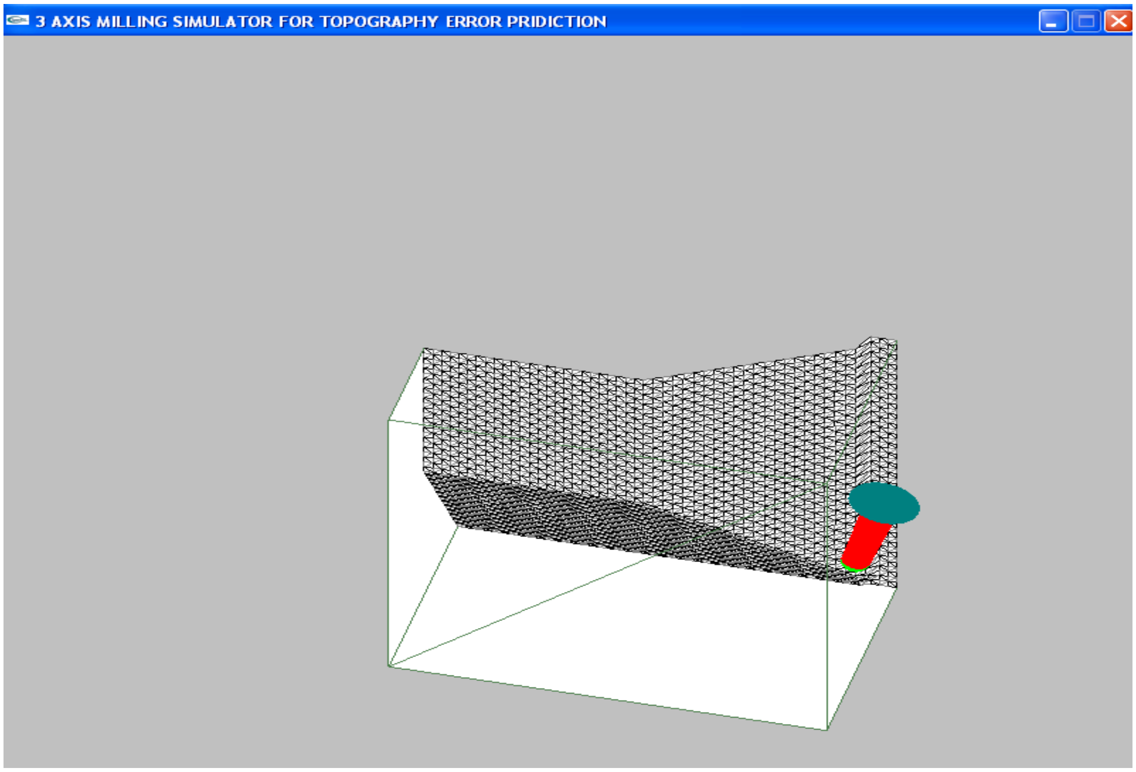

Fig.4.39 Machining simulation at different stage

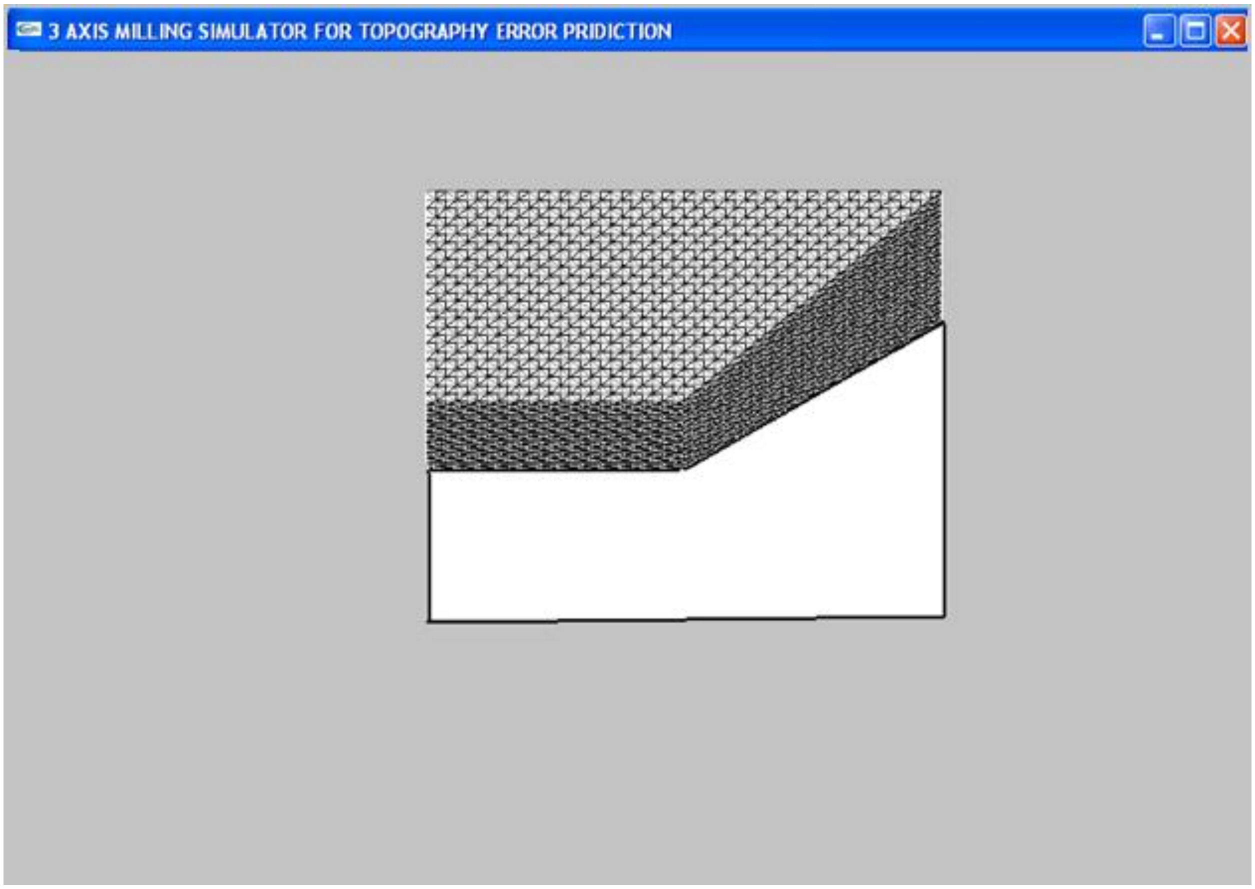

Fig.4.40 Final generated surface by simulator of model 5

The plot for the variation of the surface topography error between designed surface and the simulated surface for the model 5 is described in Fig.4.41. The topography error plot is done along the cylindrical axis and perpendicular to the cylindrical axis from the center.

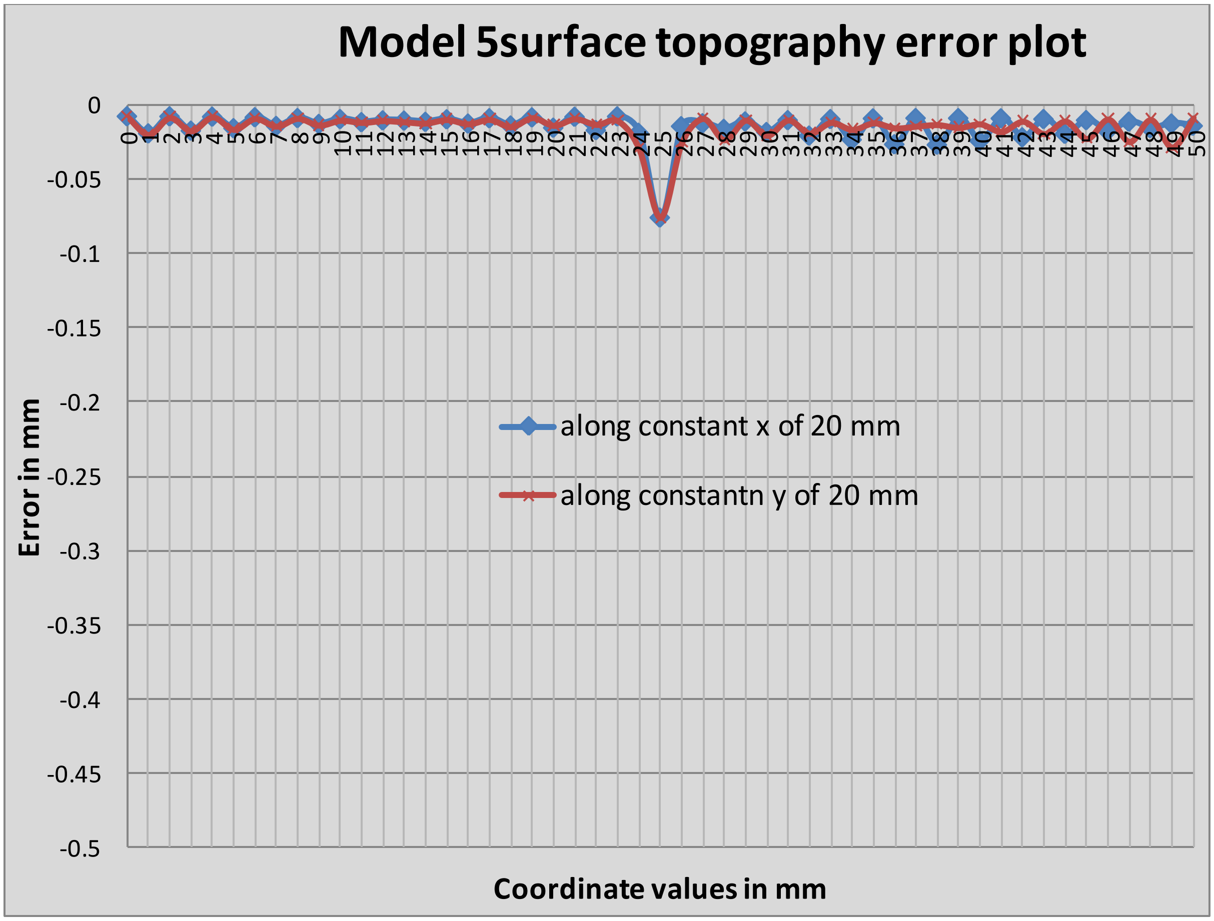

Fig.4.41 Topography error plot for model 5

It is conclude from above graph plot that the average value of the surface topography error (Ra, value) at a constant distance of 20 mm along 'X' direction is 18 microns Also the average value of error at constant distance of 20 mm along 'Y' direction is 18 microns.

Also seen from Fig. 4.41 that at middle of the surface the topography error is deviated and comparatively high this is due to ball nose cutter used for the experimental verification as sharp corners cannot be cut with ball nose cutter.

CHAPTER-5

CONCLUSIONS

As after performing the experimental validation on different models and comparing the results of the simulator the achievements and the limitation of the proposed simulator is discussed in detail below.

4.1. DISCUSSIONS

The various discussions for the above results are described below:

1. Repeatability and consistency of the program for any geometry.
2. Simulation as well as surface topography error is obtained by the simulator itself and thus no physical machining of the workpiece is required for predicting the surface topography errors.
3. The proposed simulator needs only the final finishing path file for generating the surface topography error if only error measurement is the main concerned, however it can simulate the rough as well as finish files if toll path also need to be visualized and then the final finishing tool path file can generate the surface topography error.
4. The proposed simulator can also predict the machining accidents due to collision.
5. Takes maximum of 4-5 hours for simulating the complex part geometry and predicting topography error.
6. The data generated from the simulator can be visualized graphically as discussed above thus provides a clear picture of the error location and thus tool path file refinements can be done accordingly.
7. Thus can be used for very high precision machining simulation where the machining accuracy is of the prime importance.

4.2. LIMITATIONS OF THE SIMULATOR

As with the benefits attached their also some of the drawbacks for the proposed simulator that are discussed below:

1. As simulator uses the STL data as basis for error comparison that itself contains the error thus some deviation from the actual value is definitely going to contribute.
2. Proposed simulator speed goes on decreasing with increasing size of grass density as well size of the tool path file because computations increasing and thus demands for the fast computing processors for fast execution of the simulation and error measurement.
3. Errors in the tool path data cannot be obtained with this simulation and thus simulate even the wrong tool path also.
4. No refinements of the tool path are done for compensating the surface topographic errors.

4.3. FUTURE SCOPE FOR THE PROPOSED SIMULATOR

1. Proposed simulator can be integrated with other modules and algorithms for predicting the other geometric errors measurement than contribute to machining inaccuracies.
2. Tool path file refinement module can also be integrated with the proposed simulator for achieving the desired topography.
3. Since the proposed simulator is for the 3–Axis milling thus for higher axis machining and training centers new algorithm needs to be developed to incorporate the machining.
4. Speed of the simulator can also be increased by implementing the new advanced hardware applications.
5. Can be incorporated for different types of the machining simulations for example; Lathe, Lathe mill, Surface grinders.

CHAPTER-6

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