

**Tool Path Selection and Feed Rate Scheduling Strategies for Complex
Sculptured Surfaces**

by

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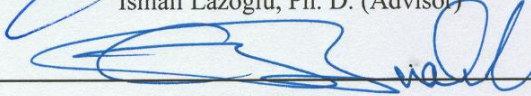
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ABSTRACT

Machining of non-monotonic sculptured surfaces with minimum cycle times has been one of the major priorities in most of the industries. Reductions in machining times with optimized NC codes are also the targets of CAM software packages developers. This target must be reached without violating the physical limits of the CNC machines. This paper presents that the cutting forces for very complex sculptured surfaces can be precisely predicted. Therefore, rather than using conventional constant feedrate all along the tool path for sculptured surfaces, it is recommended to utilize the new Forced based Feedrate Scheduling (FFS) strategy. In FFS technique, the resultant cutting forces are aimed to be kept constant by varying the feedrate along the tool path. Simulations and experimental validations are performed for non-monotonic complex sculptured surfaces. It is shown that with the new Forced based Feedrate Scheduling strategy; the cycle times of sculptured surface machining are decreased significantly.

Besides developing the force based feed rate scheduling strategy, an advanced mathematical model of cutting forces that is based on the kinematics and mechanics of the 3D sculptured surface machining is integrated with CAM packages in order to predict the complex tool-workpiece engagements and machining forces for any tool path. Machined 3D free form topographies and distributions of errors between the desired CAD and machined surfaces are also predicted in advance. An evaluation of different tool path selection strategies for 3D free form surfaces is made. Theoretical simulations of forces and surface topographies are presented and compared with experimental measurements.

Finally, with the help of the robust solid model based engagement determination algorithm, it is possible to model tool/workpiece intersections in complex sculptured surfaces in which engagement domain calculations are extremely difficult. Using engagement data, mechanistic modeling of 5-axis machining was performed and the effects of lead and tilt angles were investigated.

ÖZET

Monoton olmayan serbest şekilli yüzeylerin asgari sürede işlenmesi birçok endüstride önemli bir önceliğe sahiptir. İşleme süresinin eniyilenmiş NC kodları kullanılarak düşürülmesi aynı zamanda CAM yazılımı geliştiren firmaların da hedefidir. Bu hedef, CNC makinelerin fiziksel limitlerini aşmadan gerçekleştirilmelidir. Bu tez karmaşık serbest şekilli yüzeylerin işlenmesi sırasında oluşan kesme kuvvetlerinin hassas bir şekilde öngörülebildiğini sunmaktadır. Dolayısıyla, serbest şekilli yüzeylerde, bütün takım yolu boyunca alışılagelmiş sabit ilerleme kullanmak yerine yeni Kuvvet tabanlı İlerleme hızı Planlama stratejisinin (KİP) kullanılması önerilmektedir. KİP yönteminde, takım yolu boyunca ilerleme hızlarının değiştirilerek oluşan bileşke kesme kuvvetinin sabit tutulması amaçlanmaktadır. Bu çalışmada, monoton olmayan serbest şekilli yüzeylerin işlenmesi sonucu oluşan kesme kuvvetleri deneysel ve teorik olarak sunulmuştur. Kuvvet tabanlı İlerleme hızı Planlama stratejisinin kullanılması ile serbest şekilli yüzeylerin işleme sürelerinin önemli ölçüde azaltılabileceği gösterilmiştir.

Kuvvet tabanlı ilerleme hızı planlama stratejisinin geliştirilmesine ek olarak, kesme kuvvetlerinin kinematik ve mekanik tabanlı gelişmiş matematiksel modeli CAM yazılımlarıyla tümleşik hale getirilerek karmaşık takım-parça kesişimleri takım yoluna bağlı olmaksızın hesaplanabilmektedir. İşlenmiş yüzeylerin 3 boyutlu topoğrafyaları ve istenilen yüzeyle arasındaki farkların dağılımı ayrıca hesaplanmıştır. Farklı takım yollu seçme stratejilerinin değerlendirilmesi gerçekleştirilmiştir. Teorik kesme kuvveti hesaplamaları ve topoğrafyaları hesaplanarak deneysel ölçümlerle karşılaştırılmıştır.

Son olarak, katı model tabanlı kesişim hesaplama algoritmasının yardımıyla 5-eksenli takım yollarında meydana gelen takım-parça kesişimleri hesaplanarak, 5-eksenli sistemlerin mekanistik kuvvet modellemesi yapılmış ve değişik lead ve tilt açılarının işleme üzerindeki etkileri araştırılmıştır.

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NOMENCLATURE

x, y, z	coordinates of cutting edge of ball-end mill
R_b	ball radius of the cutter
r	tool radius in x-y plane at a point defined by ψ
β	lag angle between the tangent line at the tip of the flute and axial location z
x_c, y_c, z_c	coordinates of cutting edge of ball-end mill according to rotating frame
φ_{st}	start angle of each discrete disc
φ_{ex}	exit angle of each discrete disc
α	feed inclination angle
t_c	instantaneous chip load
t_x	feed per tooth
θ	immersion angle of cutting point
f_h	vertical feed component in mm/min
f_v	horizontal feed component in mm/min
ψ	cutting element position angle
$(t_c)_{kn_{new}}$	new instantaneous undeformed chip thickness for ball-end mill cutter
dA_c	differential chip load
F_r, F_ψ, F_t	cutting forces in tangential, radial and axial directions
dF_x, dF_y, dF_z	differential cutting forces in x, y, and z directions
$K_{rc}, K_{\psi c}, K_{tc}$	tangential, radial and axial cutting force coefficients in milling
$K_{re}, K_{\psi e}, K_{te}$	tangential, radial and axial edge force coefficients in milling
Ω	rotation angle of flute
N_f	number of flutes
n	flute number
β_k	lag angle between the k^{th} discrete point on cutting edge and the cutter tip
ω	spindle speed in revolution per minute
f	feedrate of the cutter in mm per minute
$d\theta$	Integration angle
dz	Integration height
CL	number of G codes for the tool path
$\Delta\theta$	discrete cutting element rotation angle

f_s	data sampling frequency
z_1	measured upper boundary distance from the tip of the sphere part
z_2	measured lower boundary distance from the tip of the sphere part
Δd	distance between consecutive two CL points
t	required time in seconds between consecutive two CL points
V	swept volume in mm^3 between consecutive two CL points
MRR	material removal rate in mm^3/sec
C	total number of CL points in the tool path
f_1	original constant feedrate for the tool path in mm/min
f_2	twice of f_1 feedrate in mm/min
F_1	maximum resultant force value in Newton for the f_1 feedrate value
F_2	maximum resultant force value in Newton for the f_2 feedrate value
$f_{\text{lim},i}$	scheduled feedrate value in mm/min for the i^{th} CL point
$F_{\text{lim},i}$	limiting constant resultant force threshold value
nod	normal offset distance
m	modal mass for transfer function
ζ	damping ratio for transfer function
w_n	natural frequency for transfer function
δ	cutter deflection at point z ,
I	area moment of inertia of cutter in mm^4
E	young modulus in MPa
L	projection length of cutter in mm
L_s	length of shank part of the cutter
K_s	clamping stiffness
z_c	applied force center in mm
dz	rise of cutter tip in z direction in mm
D	diameter of the cutter in mm
d	effective diameter of the cutter in mm
δ_t	resultant cutter bending deflection
δ_s	deflection of the shank
δ_f	deflection of the flute

δ_{sf}	deflection of the shank due to deflection angle
δ_{st}	deflection of the clamping part which is calculated from the stiffness
ϕ_s	deflection angle
e_f	error due to feed force
e_{cf}	error due to cross feed force
e_{total}	total error in z direction
s_1	stepover distance
s_2	scallop height

Chapter 1

INTRODUCTION

Machining is the process of removing material from a workpiece (mostly metals) in the form of chips. Machining is one the most important processes in the manufacturing industry. Compared to other manufacturing processes, such as molding, casting etc. machining has very low setup cost for low-volume of manufacturing. Otherwise, it becomes much more costly in high-volume manufacturing. Generally, in industry machining operations is used in finishing operations and during die-mold manufacturing where good surface finish and precise dimensional accuracy is necessary.

Understanding the mechanics of the machining processes is very important, because any mishandling or failure during machining can damage tool, workpiece, and even the machine. This situation also means loss of productivity and additional costs. Therefore using the physical principles of any machining operation can prevent undesired costs and it is possible to increase the productivity and surface quality. Productivity and the part quality of the machining operation depend on the Computer Numerical Control (CNC) machine, cutting conditions, tool path, workpiece hardness, and tool material.

Machining is a very complex and widely used process and large variety of milling tools are available and used in most of the industries, such as aerospace, automotive, home appliance and die-mold industries. Tool geometries are designed and optimized in order to maximize productivity and tool life while minimizing the cutting forces occurred during the operation. In the machining of free-form, non-monotonic sculpture surfaces, ball-end mill tools are used. Due to the complexity of cutting geometry of ball-end cutters, it is very difficult to model and predict

the cutting forces. Prediction of cutting forces allows user to achieve high quality and faster machining without sacrificing from the tool life.

Cutting forces occurred during machining cause deflection on the ball-end cutter and this result in considerable amount of surface error. Currently, the practices in industry, for each set of machining operations, conservative cutting conditions are used to overcome the deflection of the cutter. Conservative cutting conditions prevent excessive tool deflection, however, productivity and the feasibility of the operation becomes low. The importance of modeling and precisely predicting the cutting forces in ball-end milling for very complex sculptured surfaces is that it can be used to calculate the cutter deflection and surface error and it can be used to increase the productivity by applying feedrate scheduling strategies.

Complex free-form surfaces, nowadays, are widely used in industry due to the advancements in CAD and CAM technology. There are several reasons for the popularity of free-form surfaces in industry. For example, free-form surfaces provide more efficient, ergonomic, and aesthetical designs for new products. As the demand for free-form surfaces in industry increases, CAD/CAM software companies develop different tool path strategies for machining of complex sculptured surfaces. Users can now use concentric or radial lines etc. instead of conventional zigzag cut. However, since there are different tool paths available to carry out the same process, a question arises that which tool path strategy is the best choice for a specific free-form surface. As it can be predicted, each tool path strategy offers different cutting time, cutting force magnitude and surface quality.

In this study, an improved and enhanced cutting model has been developed according to the previous studies of Guzel and Lazoglu [1], and Erdim [2]. This cutting force model is used to improve the productivity in complex free-form surfaces by feed rate scheduling strategies and compared tool path strategies used in CAM software.

Chapter 2 provides necessary background and literature review on ball-end milling. Cutting mechanics, previous models for prediction of cutting forces, and tool path strategies are reviewed.

Chapter 3 describes the solid based engagement model by introducing a model which can determine the chip load for any type of surface and tool. Fundamentals of this solid based engagement model are described in detail.

Mechanistic cutting force model details are given in Chapter 4. Description of tool geometry is also introduced. Thereafter modeling of cutting forces is explained, determination of cutting constants, namely, calibration process is described.

Validation tests under various conditions are described and their results are given in Chapter 5, together with the discussion of the results. Validation tests include basic type of cutting and different free-form surfaces including both the monotonic and non-monotonic surfaces.

Chapter 6 describes the force-based feed rate scheduling strategy theoretically and experimentally; the mechanism underlying the approach is explained. It is shown that productivity of machining can be increased without changing the maximum cutting force.

In Chapter 7, a comparison of different tool path strategies were performed in terms of cutting forces, cycle time, and surface finish. A geometrical model is used to determine the surface finish of different tool paths and a mathematical model is proposed to estimate the machining errors. The tool was modeled as a cantilever beam consisting of the shank and the flute. Deflections are calculated using cantilever beam theory. By combining geometrical error induced by CAM software and static deflections, it is possible to calculate the surface finish for each tool path.

Chapter 8 presents the expansion of solid based engagement model and cutting force model to 5 axis machining. Besides mechanistic modeling, effects of lead and tilt angles were investigated. Theoretical simulations and experimental validation were presented at the end of this chapter.

The thesis is concluded with a short summary of the performed study.

Chapter 2

LITERATURE REVIEW

Since ball-end milling is widely used process in industry, there is lots of research done on this subject. Literature review about this thesis can be divided into four main sections; modeling of cutting forces in ball-end milling, feed rate scheduling strategies, tool path and surface analysis, and 5-axis machining.

Cutting forces occurred during machining is one of the most important parameter improving the productivity and part quality, because deflection, tool breakage, stability, surface quality and form errors are mainly influenced by cutting forces.

Determination of chip formation is the first step in mechanistic modeling of cutting forces. Early study of Martelotti [3] showed that the path of the tool tooth is trochoidal, rather than circular because of the combined rotation and translation of the tool towards the workpiece. Martelotti also claimed that when the feed per tooth is much smaller than the tool radius, circular tool path assumption is valid and the error is negligible.

There are many cutting force analyses for ball-end mills with helix angle in literature. Koenigsberger et al [4]. used experimentally determined cutting coefficients and related chip load to cutting forces. However, calibration method used in this study is far from the physics of the process, because empirical curve fitting technique was used instead of mechanistic or orthogonal calibration. Armarego and Deshpande [5] more accurately predicted cutting force by introducing cutting edge force component.

Mechanistic approach had limitations on milling with complex tools which have variable geometry along the axis of tool. Therefore, Yucesan and Altintas [6] presented a semi-mechanistic model to predict shear and frictional load distribution on the rake faces of ball-end mills. As an alternative to the mechanistic approach, orthogonal cutting parameters were

developed in order to eliminate the necessity of new calibration tests when the tool geometry changes. Armarego and Whitfield [7] applied the orthogonal to oblique transformations on cutting force predictions. The idea behind this study is to divide the tool geometry into segments of oblique cutting processes. Budak, Altintas and Armarego [8] identified the material properties such as shear flow stress and friction angle from orthogonal turning tests. This study presented an accurate model to transform the orthogonal cutting parameters to cutting force coefficients. Yang and Park [9] used a similar approach and they used cutting parameters of orthogonal tests and simplified the analysis by approximating oblique cutting on each flute by infinitesimal orthogonal processes. Lazoglu and Liang [10] established a closed-form model for ball-end mill process in the frequency domain using an angular convolution technique.

When the previous studies about feed rate scheduling and optimization are considered, there are not many research performed in the literature. Previous studies generally have developed a feedrate scheduling strategy based on volumetric analysis by using material removal rate (MRR) approach. Wang [11] developed a feedrate adjusting algorithm using MRR. Ip et al. [12] introduced a fuzzy based MRR approach by using spindle power and specific energy. Li et al. [13] proposed an offline feedrate optimization by relating the average power with MRR. White and Houshyar [14] employed an industrial engineering methodology dealing with optimization of a single item in single-stage and multi-stage metal cutting systems. Besides, some commercial software packages such as Vericut's Optipath [15] and MasterCAM's Hifeed [16] work on a volumetric analysis to adjust the feed rate.

Besides MRR approaches, some researchers have developed feed rate scheduling based on cutting force models. Yazar et al. [17] performed feed rate optimization based on cutting forces. Feng and Su [18] optimized the feed rate with the toolpath based on calculation of cutting forces and machining errors in 3D plane surface machining. Jerard et al. [19] presented a feed rate optimization procedure for that can schedule feed rates according to selected force value by user. Yun et al. [20] developed a feed rate scheduling model using cutting force model in straight-end milling. Ko et al. [21] presented a feed rate scheduling approach based on mechanistic cutting

force model for straight-end milling. Lim and Hsiang [22] proposed a cutting path adaptive feed rate strategy, which improves the productivity when subjected to force and dimensional constraints. Guzel and Lazoglu [1] proposed an off-line feed rate scheduling system for sculpture surface machining based on cutting force model. Erdim et al. [23] introduced analytical engagement model for monotonic sculptured surfaces. They also compared the Force based Feed rate Scheduling (FFS) and MRR based feed rate scheduling strategies. It is concluded that since FFS is controlling the force amplitudes, it is much reliable than MRR technique. In MRR based feedrate scheduling, the scheduled feedrate values may cause greater forces which can damage the cutter, workpiece and/or CNC machine tool.

Since complex free-form surfaces are widely used industry, resultant surface topography, surface form error, tool path generation and comparison and tool deflection models are getting more attractive to scholars. Lazoglu [24] employed a Boolean approach in the model and in addition to predicting the cutting forces, the model determined the resulting surface topography and scallop height variations along the workpiece for given cutter/workpiece geometries and CL file. Kim et al. [25] estimated the tool deflection and form error regardless of surface inclination affect by using Z-mapping method. Bouzakis et. al. [26] presented an algorithm that can predict the cutting forces and surface topomorphy in ball end milling. Ikua et al. [27] used a model for prediction of cutting forces and machining error under various cutting conditions. Fujii and Iwabe [28] performed an experimental study to determine the relationship between cutting force and machining error for ball-end milling of flat surfaces. Lim et al. [29] constructed an empirical model in order to predict surface error in sculpture surface machining.

There are also tool path generation and tool path comparison studies in literature. Researchers mainly focus on tool path generations, there is little research on tool path evaluation and comparing tool path selection strategies for complex sculptured surfaces. Baek et. al. [30] presented a chip volume prediction algorithm using a numerical control verification model. Previous studies on tool paths mainly focused on generation or improving tool paths rather than evaluating available tool paths in CAM software. Chen et. al [31] developed a model to calculate

scallop formation in ball-end milling process. Alberti et. al. [32] experimentally compared the dimensional error with cycle time in high-speed milling of aluminium alloy. There is some research performed on the comparison of different tool path strategies. Monreal and Rodriguez [33] presented the influence of tool path strategy on the cycle time of high speed milling. They investigated the effect of tool path orientation angle on the cycle time. Kim and Choi [34] compared the machining efficiency of direction-parallel tool path with contour-parallel tool path.

Nowadays, 5-axis machining is one of the hot topics in academic environment due to the increase in popularity of 5-axis machining in industry. Most studies on 5-axis machining is about tool path generation and post-processing, although there are few research on mechanistic modelling of cutting forces. Li and Feng [39] generated a tool path strategy in order to achieve constant scallop height tool paths for the efficient 5-axis machining of free-form surfaces. Lee and She [40] developed a postprocessor capable of converting cutter location (CL) data to machine control data to establish an interface between CAM systems and CNC machines which can be used with different types of machine tools. Roth et. al. [41] presented a method to simulate cutting forces and torque using a graphics rendering engine for mechanistic modelling of 5-axis machining. Lin and Shen [42] implemented a matrix summation approach for modelling of geometric errors of 5-axis machine tools. This approach reduces the computations. Fussell et. al. [43] integrated the geometric and mechanistic end milling models for 5-axis CNC sculptured surface machining and feed rate setting. Becze et. al. [44] investigated the issues related to high-speed five-axis milling of hardened tool steel.

Most of the studies reviewed in this section are valid for simple workpiece geometries. Force models are not capable of handling free-form surfaces, especially non-monotonic sculptured surfaces. Feed rate scheduling methods are not efficient and robust. Developing a precise cutting force model for complex free-form surfaces and studying the applications of improving productivity and part quality are the motivation of this study.

Chapter 3

MECHANISTIC CUTTING FORCE MODEL

3.1 Introduction:

Machining is a very complex and widely used process and large variety of milling tools are available and used in most of the industries, such as aerospace, automotive, home appliance and die-mold industries. Tool geometries are designed and optimized in order to maximize productivity and tool life while minimizing the cutting forces occurred during the operation. In the machining of free-form, non-monotonic sculpture surfaces, ball-end mill tools are used. Due to the complexity of cutting geometry of ball-end cutters, it is very difficult to model and predict the cutting forces. Prediction of cutting forces allows user to achieve high quality and faster machining without sacrificing from the tool life.

Cutting forces occurred during machining cause deflection on the ball-end cutter and this results in considerable amount of surface error. Currently, the practices in industry, for each set of machining operations, conservative cutting conditions are used to overcome the deflection of the cutter. Conservative cutting conditions prevent excessive tool deflection, however, productivity and the feasibility of the operation becomes low. The importance of modeling and precisely predicting the cutting forces in ball-end milling for very complex sculptured surfaces is that it can be used to calculate the cutter deflection and surface error and it can be used to increase the productivity by applying feedrate scheduling strategies.

In this chapter, an accurate and precise ball-end mill cutting force model with calibration is presented together with three modules: tool geometry, kinematics/chip load, and cutting force modules. The model presented here is flexible so that it is valid for any kind of tool-workpiece combination, any type of cutting geometry, and cutting condition. This cutting force model is

developed upon the previous studies of Guzel and Lazoglu [1] and Erdim et al. [2]. Force model is improved to cover the cylindrical sections of the ball-end mill and the calibration coefficients were determined for the cylindrical part of the tool.

3.2 Tool Geometry:

End-mills can be characterized with many aspects, such as the macro geometry (helical-end, ball-end, bull-nose, flat-end, tapered, etc.), the micro geometry (helix, rake, clearance angles), the tool material (WC, PCD, HSS), the coating material (nanocomposite PVD, TiAlN, TiCN, etc.), the area of usage (rough, semi-finish, finish, super-finish milling), and the workpiece material (steel, aluminum, titanium, etc.). Illustration of various milling operations is shown in Figure 3.1. Detailed explanation of the micro-geometric properties of the end-mills as follows,

- Positive rake angle improves the shearing and cutting while decreasing the cutting forces. On the other hand, it weakens the cutting edge and makes it more vulnerable to wear and breakage.
- High helix angle smoothens and reduces the impact force during entry cutting and it help to remove away the chip.
- Clearance angle reduces the rubbing on the machined surface; therefore, it increases the surface quality. However, it weakens the cutting edge and more importantly, it increase the possibility of chatter vibrations by reducing process damping. A second clearance angle should be provided to reduce the amount of grinding during sharpening.

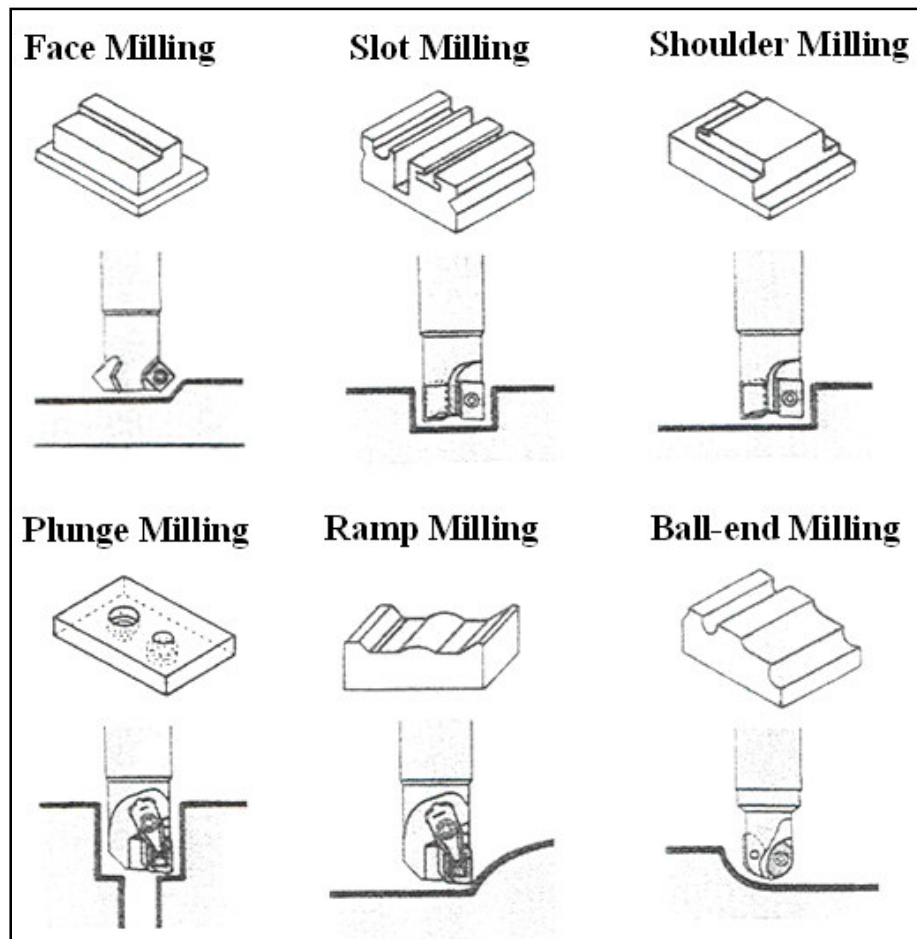


Figure 3.1: Various milling operations from Altintas [35].

Helical end-mills have constant radius and helix angle along the depth of cut. Ball-end mills differ from flat end mills by their ball part such that their radius varies along the ball-end. This varying radius r affects the cutting forces, because cutting speed changes with varying r . On the contrary, flat-end mills have constant cutting speed along the tool axis. The detailed geometry of a ball-end mill is shown in Figure 3.2. It can be observed that each flute lies on the surface of the hemisphere, and has a changing helix angle. Due to the decreasing radius towards the tip of the cutter, the local helix angle changes with varying cutting velocity for a discrete point along the cutting flute.

The equation of the geometry of the ball part is given by,

$$x^2 + y^2 + (R_b - z)^2 = R_b^2 \quad (3.1)$$

where x , y , and z are the coordinates of cutting edge ball-end mill according to the coordinate axes shown in Figure 3.2, and R_b is the ball radius measured from the center of the sphere. The cutter radius is zero at the tip and at axial location z , in plane x - y ,

$$r^2 = x^2 + y^2 \quad (3.2)$$

The ball-mill cutter used in calibration and validation tests was 12 mm diameter, two fluted ball-end mill from CoroMill series of Sandvik. Cutting edge geometry was taken from Erdim [2]. The author measured the cutting edge with a Coordinate Measuring Machine (CMM). Obtained data points were used to obtain following third degree polynomial that represents the cutting edge geometry for the cutting force model.

$$\beta = 0.0036 \times r^3 - 0.0205 \times r^2 + 0.0547 \times r - 0.041 \quad (3.3)$$

where r [mm] is the radius of an arbitrary point on the cutting edge perpendicular to the cutter axis, and β [deg] is the lag angle between the line which connects this arbitrary point to the tip and the line tangent to the cutting edge at the tip. Details of the cutting edge geometry can be seen in Figure 3.3. The cutting geometry can be represented in the cutter coordinate system as the following;

$$x_c = r \times \cos(\beta), \quad y_c = r \times \sin(\beta), \quad z_c = R_b - \sqrt{R_b^2 - r^2} \quad (3.4)$$

As a result, it is possible to determine cutting edge profile by varying radius (r).

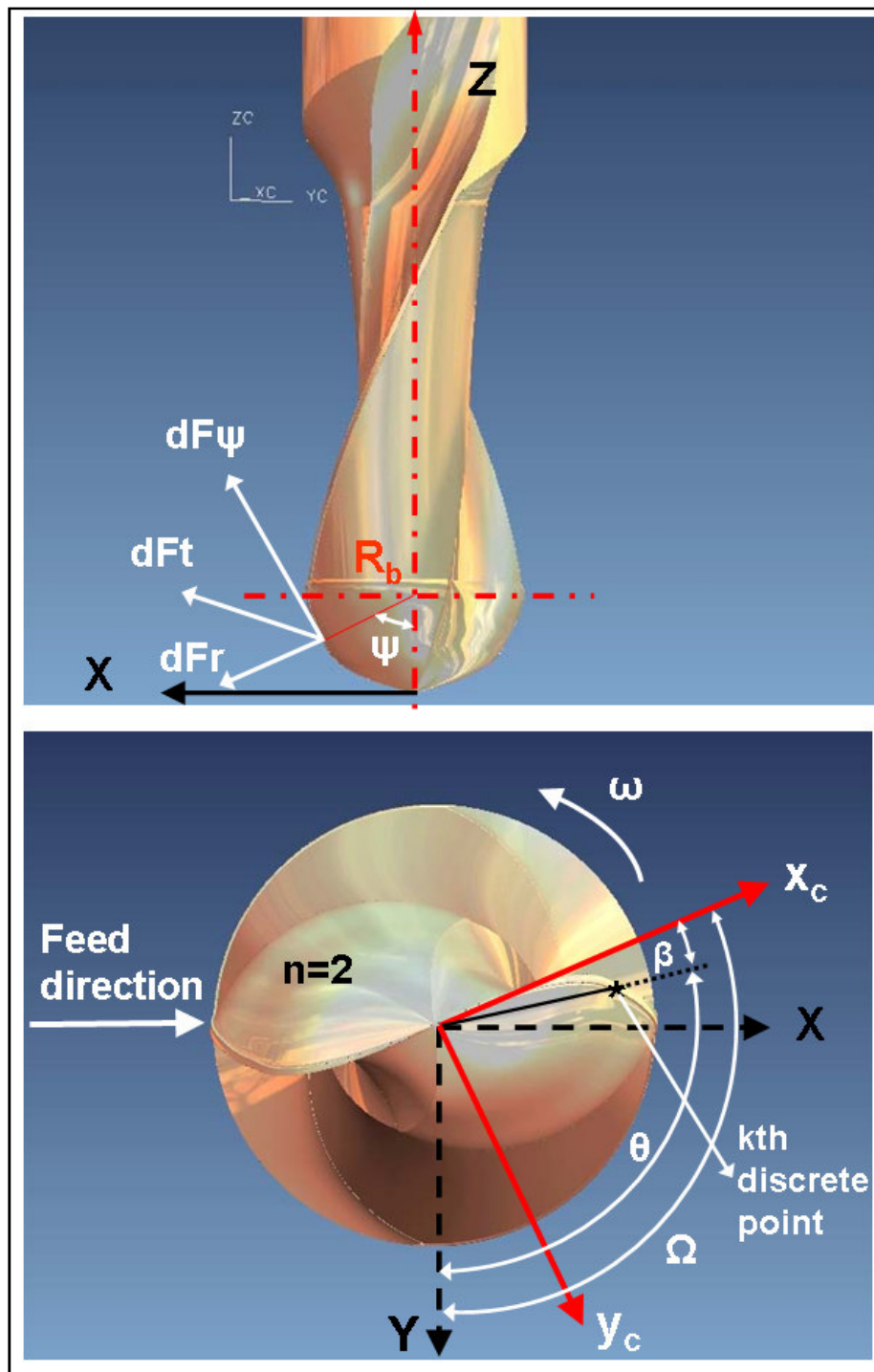


Figure 3.2 : Illustration of cutting force vectors and angular relationships.

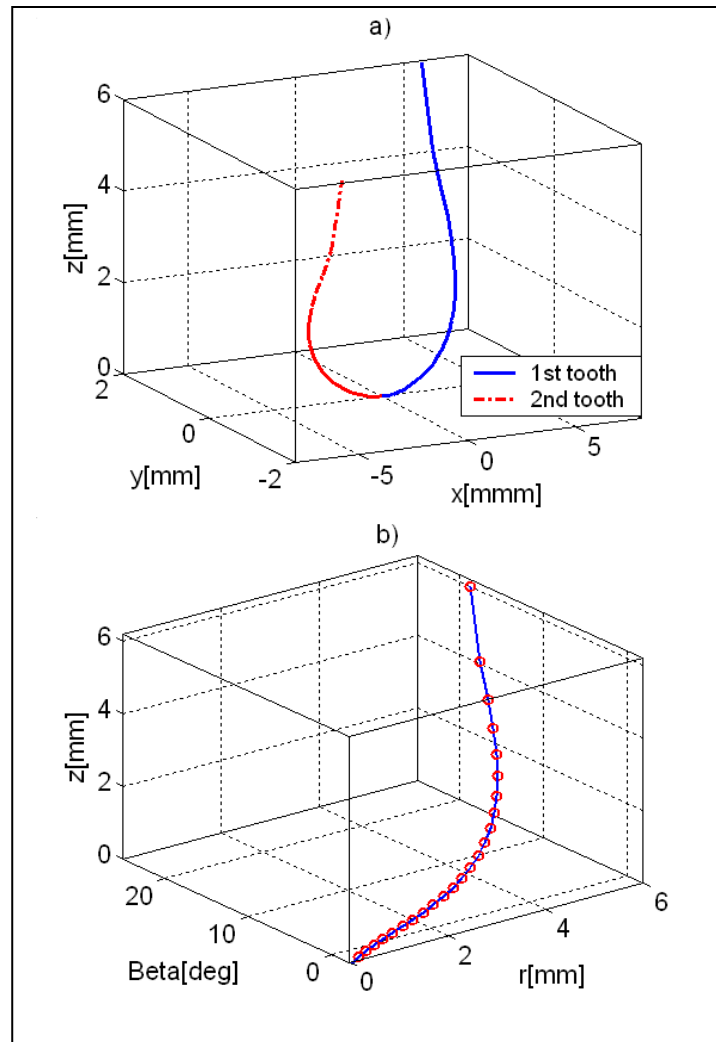


Figure 3.3: Cutter Geometry: a) Cutting edges, b) Third degree polynomial fitting for $\beta(r)$.

3.3 Chip Thickness:

There is so much research done on investigation of cutting forces in ball-end milling process. The aim and the motivation of this study are to develop an enhanced, robust and comprehensive model that can work with various cutting conditions and tool-workpiece combinations. Since

cutting forces are directly related to the instantaneous undeformed chip thickness, uncut chip thickness should be precisely calculated to improve the performance of the cutting force model.

It is possible to understand the chip load of ball-end milling process by examining the early analysis of Martelotti [3]. Martelotti stated that due to the combined rotational and linear motion of the cutter towards the workpiece, the true path of the cutter is an arc of a trochoid, rather than a circle. However, in most practical conditions where feed per tooth is much smaller than the cutter radius; circular toolpath assumption is valid, because the error is negligible. The chip formation geometry is shown in Figure 3.4. Chip formation on a flat-end mill is shown as;

$$t_c = t_x \times \sin(\theta) \quad (3.5)$$

where t_c is the instantaneous chip load, t_x is the feed per tooth and θ is the immersion angle of cutting point. This equation is valid for flat-end mills which have only rotational and linear straight motion. However, in order to accurately model instantaneous chip load for ball-end mills, non-horizontal feed motion and spherical part of the ball-mill should be considered.

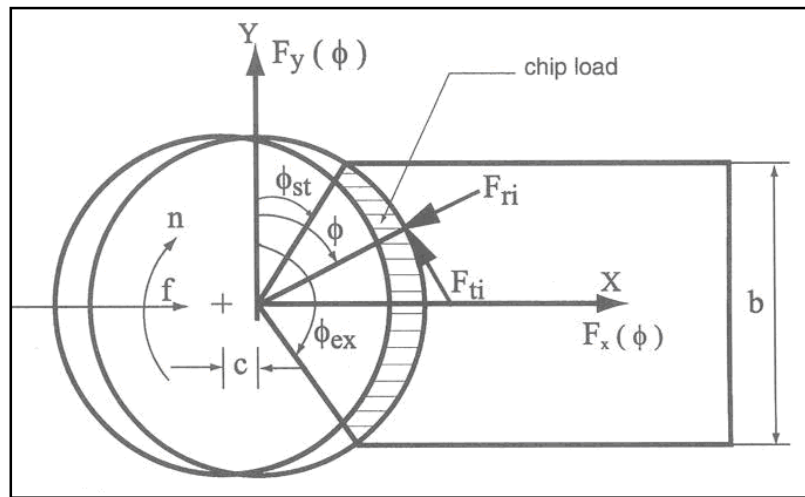


Figure 3.4: Geometry of chip formation in end milling from Altintas [35].

Figure 3.5 represents chip formation in non-horizontal tool motion. During non-horizontal motion, feed (f) can be divided into two components: f_h is the horizontal feed component and f_v is the vertical feed component. When the tool moves with an inclination angle, feed direction is not perpendicular to the toll axis, which results in a different undeformed chip geometry.

If the situation is downward ramping, in order to calculate the uncut chip thickness, due to the drilling effect, following term should be added to chip thickness formula. On the other hand, in upward ramping, this term should be subtracted.

$$\Delta t = t_x \times \cos(\psi) \times \sin(\alpha) \quad (3.6)$$

Modifying the instantaneous chip thickness formulation for non-horizontal motion results in;

$$(t_c)_{kn_{new}} = t_x \times \sin(\theta) \times \sin(\psi) \times \cos(\alpha) \pm t_x \times \cos(\psi) \times \sin(\alpha) \quad (3.7)$$

where $(t_c)_{kn_{new}}$ is the modified ball-end mill instantaneous chip load, t_x is feed per tooth, θ is the immersion angle of cutting point, ψ is the cutting element position angle and α is the feed inclination angle. Feed inclination angle (α) should be between 0° and 90° . Ko and Cho [21] and Kim et al. [25] also modified undeformed chip thickness for non-horizontal motion.

Following chip thickness formation determination, the infinitesimal chip load for each cutting disk which is in contact can be expressed as;

$$dA_c = (t_c)_{kn_{new}} \times (dz)_{kn} \quad (3.8)$$

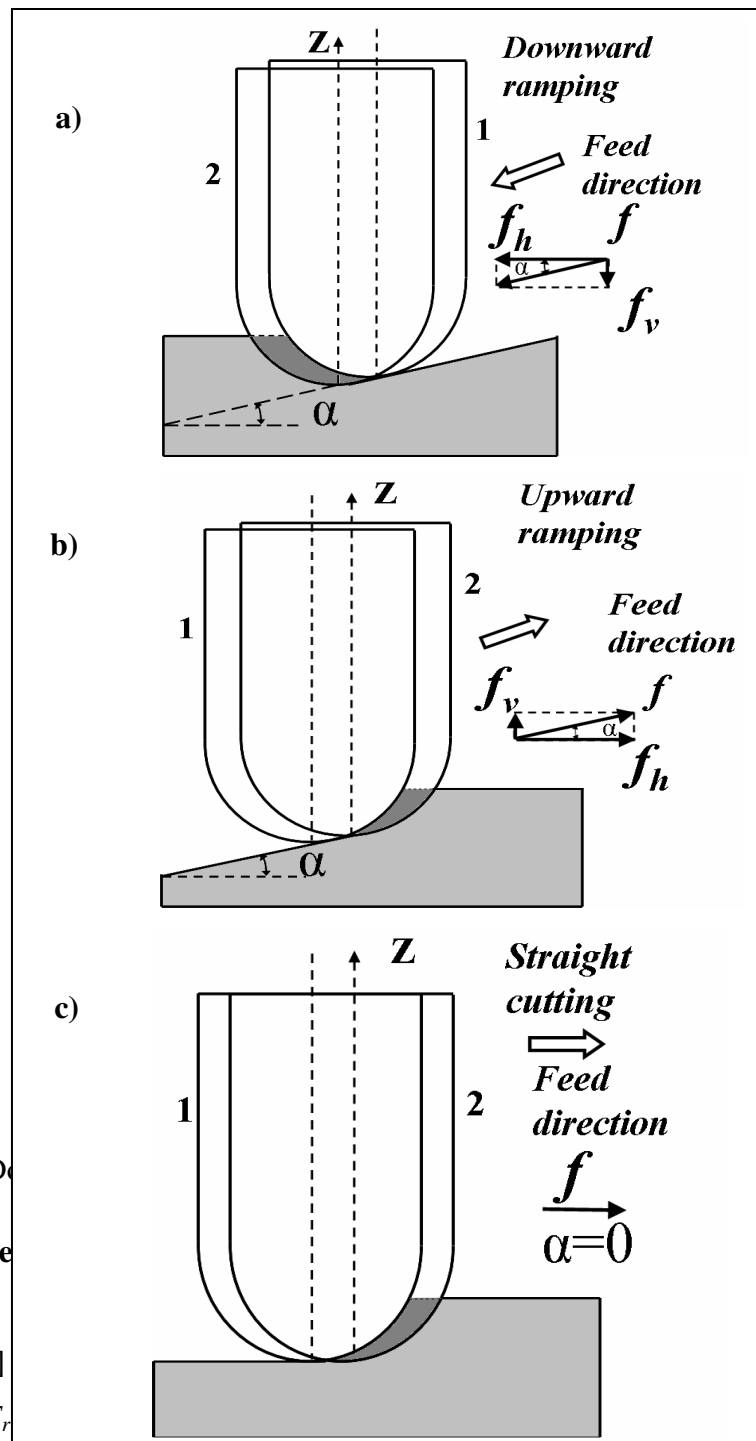


Figure 3.5: a) D

3.4 Cutting Force Mode

Guzel and Lazoglu [1] the differential radial (dF_r) forces can be expressed as,

nt domain,
(F_t) cutting

$$\begin{aligned}
dF_r &= K_{rc} \times dA_c + K_{re} \times dz \\
dF_\psi &= K_{\psi c} \times dA_c + K_{\psi e} \times dz \\
dF_t &= K_{tc} \times dA_c + K_{te} \times dz
\end{aligned} \tag{3.9}$$

where K_{rc} , $K_{\psi c}$, and K_{tc} are the radial, zenith, and tangential cutting coefficients and K_{re} , $K_{\psi e}$, and K_{te} are the related edge coefficients respectively. These specific cutting coefficients depend on tool-workpiece combination. These parameters were determined with calibration tests. These calibration tests were performed with 12 mm diameter Sandvik CoroMill series ball-end mill with a helix angle of 25° and an Al7039 workpiece material. Erdim [2] determined cutting coefficients for the same tool-material combination only for spherical part of the tool, thus calibration coefficients for spherical part of the ball-end mill were taken from this research. In Erdim's research, tool has been divided into 7 disks along the tool axis in the spherical part and cutting constants were evaluated for each region separately by performing incremental slot cutting tests with different feedrate values. Details of the calibration process will be explained at the end of this chapter. Once the differential radial (dF_r), differential zenith (dF_ψ), and differential tangential (dF_t) cutting forces were evaluated through the use of Equation 3.9, these cutting force components can be transformed into the global X-Y-Z coordinate system with the following equations;

$$\begin{bmatrix} dF_X \\ dF_Y \\ dF_Z \end{bmatrix} \bigg|_{k,n} = A \times \begin{bmatrix} dF_r \\ dF_\psi \\ dF_t \end{bmatrix} \bigg|_{k,n} \tag{3.10}$$

$$A = \begin{bmatrix} -\sin(\psi) \times \sin(\theta) & -\cos(\psi) \times \sin(\theta) & -\cos(\theta) \\ \sin(\psi) \times \cos(\theta) & \cos(\psi) \cos(\theta) & -\sin(\theta) \\ \cos(\psi) & -\sin(\psi) & 0 \end{bmatrix} \bigg|_{k,n} \tag{3.11}$$

$$\theta = \Omega + \frac{(n-1) \times 2\pi}{N_f} - \beta_k; \quad n = 1 \dots N_f \quad (3.12)$$

where θ is the immersion angle for flute n , K represents the total number of discrete points on a cutting edge, ψ is the cutting element position angle, Ω is the cutting edge rotation angle, N_f is the tooth number and β is the lag angle evaluated from Equation 3.3.

$$\begin{bmatrix} F_X \\ F_Y \\ F_Z \end{bmatrix} = \sum_{n=1}^{N_f} \sum_{k=1}^K \begin{bmatrix} dF_X \\ dF_Y \\ dF_Z \end{bmatrix} \bigg|_{k,n} \quad (3.13)$$

Next step is to be taken after prediction of cutting forces is to validate these predictions by performing validation tests. Validation tests and their results are shown in next chapter. The proposed cutting force model is summarized in Figure 3.6. Finally, a pseudo code of the force model is presented in Figure 3.7.

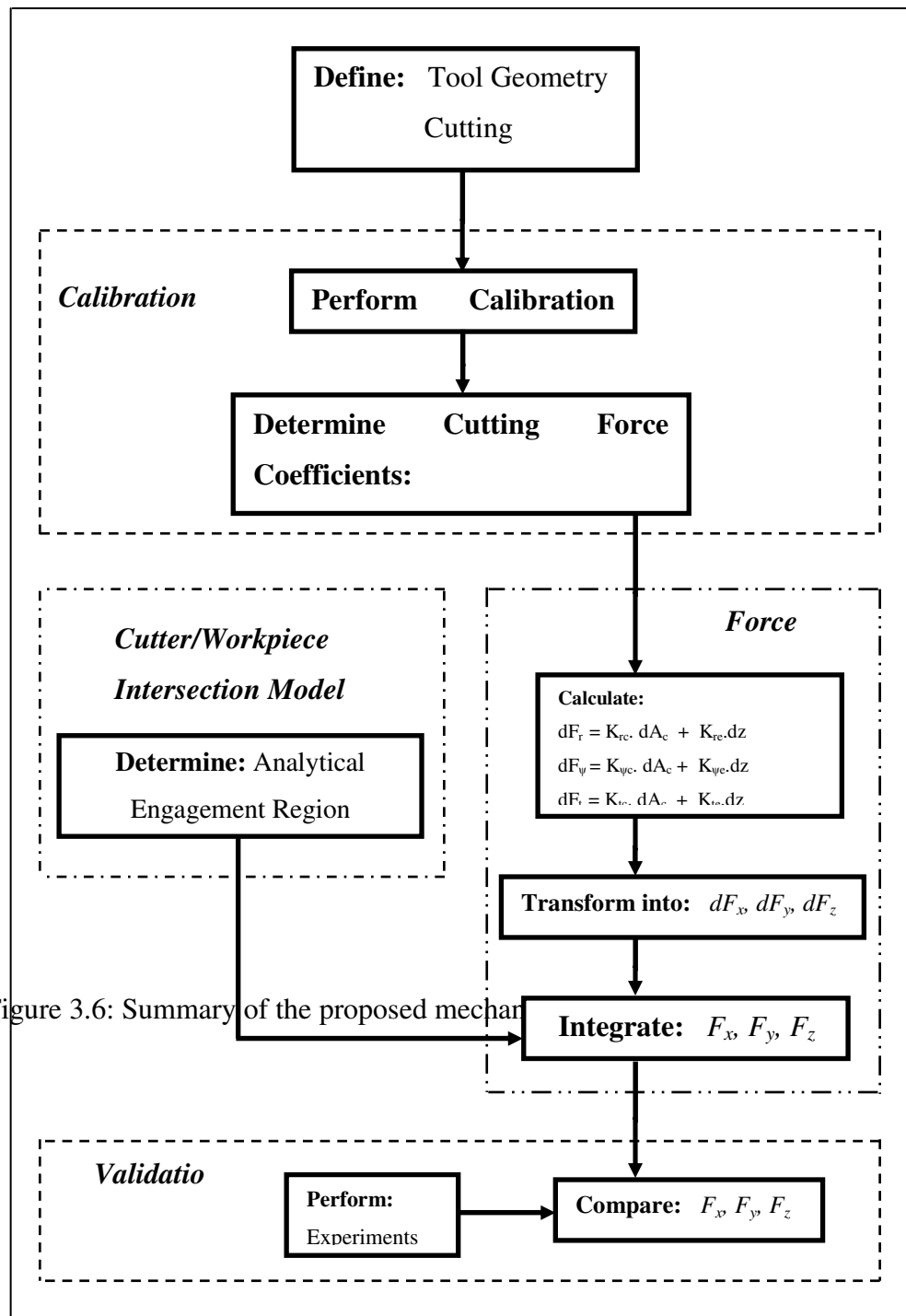


Figure 3.6: Summary of the proposed mechanistic cutting force model

Inputs:

Cutting conditions : w (spindle speed), f (feedrate)
 Tool geometry : D (diameter), β (lag angle), Nf (number of flutes)
 Integration angle : $d\theta$
 Integration height : dz
 Tool path G code : CL (number of G codes)

Outputs:

Cutting force history : Fx, Fy, Fz, Fres

Variables:

$K = \frac{D}{2 \cdot dz}$: Number of axial integration steps
 $M = \frac{2\pi}{d\theta}$: Number of angular integration steps
 j= 1 to CL : Integrate along the tool path (**1st loop**)
 i=1 to M : Angular integration loop (**2nd loop**)
 p=1 to Nf : Calculate the force contributions of all teeth (**3rd loop**)
 $\theta_1 = i \cdot d\theta + \frac{(p-1) \cdot 2\pi}{Nf}$: Immersion angle for tooth p
 k=1 to K : Integrate along the axial depth of cut (**4th loop**)
 $z(k) = k \cdot dz$: Axial position
 $r = \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - z(k)\right)^2}$: Cutting radius
 $\psi = a \sin\left(\frac{2 \cdot r}{D}\right)$: Cutting element position angle
 $\theta_2 = \theta_1 - \beta(r)$: Updated immersion angle due helix angle
 if $\theta_{st} < \theta_2 < \theta_{ex}$: θ_{st} : entry angle of contact, θ_{ex} : exit angle of contact (**if**)
 $tc_{kn} = \left(\frac{f}{Nf \cdot w}\right) \cdot \sin(\theta_2) \cdot \sin(\psi) \cdot \cos(\alpha) - \left(\frac{f}{Nf \cdot w}\right) \cdot \cos(\psi) \cdot \sin(\alpha)$
 : Chip thickness (α : inclination angle found for CL point)
 $dAc = tc_{kn} \cdot dz$: Differential chip load
 $dF_r = dAc \cdot K_{rc} + dz \cdot K_{re}$
 $dF_t = dAc \cdot K_{tc} + dz \cdot K_{te}$: Differential force
 $dF_\psi = dAc \cdot K_{\psi c} + dz \cdot K_{\psi e}$
 $dFx, dFy, dFz = A \cdot [dF_r, dF_t, dF_\psi]$
 : In orthogonal directions, A (transformation matrix)
 $Fx(i) = Fx(i) + dFx$
 $Fy(i) = Fy(i) + dFy$: Sum the cutting forces
 $Fz(i) = Fz(i) + dFz$
End (1st loop)
End (2nd loop)
End (3rd loop)
End (4th loop)

Figure 3.7: Pseudo code of cutting force model.

3.5 Calibration Process:

Cutting force coefficients are contributed by shearing action in radial, zenith, and tangential directions. They are assumed to be constant for tool-workpiece material pair, and can be evaluated either mechanistically or using classical oblique cutting transformations. In this study, mechanistic calibration approach was used. Although orthogonal calibration is desired, it requires turning tests; therefore mechanistic calibration was used. In order to determine the cutting coefficients in this study, Altintas' [35] approach for identification of cutting coefficients in milling has been utilized with certain changes.

First step to be taken is to obtain the cutting forces by conducting a set of milling experiments at different feedrate values. The spherical part of the ball-end mill has been divided into separate disks for detailed analysis. As stated before, Erdim's [2] study of calibration for the spherical part of the tool was implemented. Full immersion slot cutting tests were implemented and the average cutting forces can be expressed as a linear function of feedrate and an offset contributed by the edge forces.

All cutting forces at different depth of cuts for 192 mm/min can be seen in Figure 3.8. In order to determine the calibration coefficients for a certain disk following procedure has been applied:

1. Using the inverse transformation of the transformation matrix A given in Equation 3.11, collected force components which are in X-Y-Z global coordinate system have been transformed into radial, zenith and tangential force components F_r , F_ψ , and F_t respectively.
2. Maximum values of each tooth for all three components (r - ψ - t) of the cutting force have been found, and the averages of these peak points are taken for certain number of the revolutions in the collected data.

3. The differences between the average points have been obtained for each increment in the depth of cut (e.g., for 4-6 mm interval, cutting forces will equal the difference between 6 mm depth of cut and 4 mm depth of cut cutting forces).
4. Finally, once the F_r , F_ψ , and F_t values have been obtained for each depth of cut interval, these values have been plotted versus chip thickness in order to obtain the cutting coefficients. Illustration of this procedure is shown in Figure 3.8.

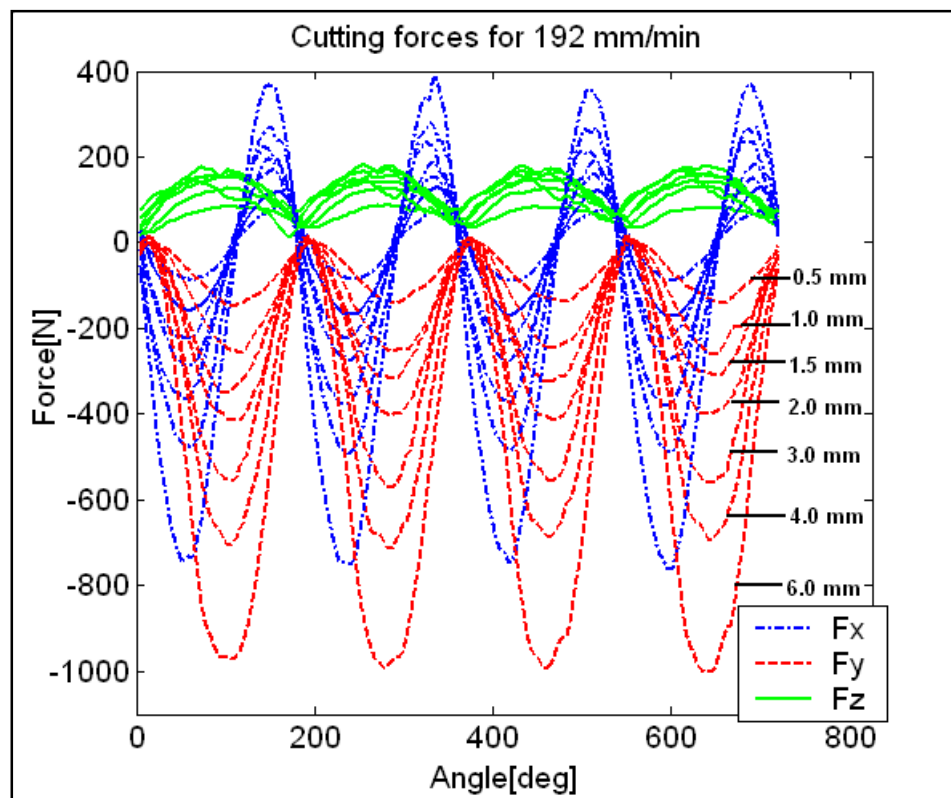


Figure 3.8: Cutting forces with different depth of cuts at $f = 192$ mm/min from Erdim [2].

Besides spherical part, since ball-end mills have cutter flute on the cylindrical part of the tool, cutting coefficients for the cylindrical part also should be determined. The same procedure applied for the cylindrical part, and since this part is identical along the tool axis, it is not necessary to divide the cylindrical part of the tool into disks. Radial, zenith and tangential forces versus chip thickness plot for cylindrical part of the tool is shown in Figure 3.9. The numerical values of the cutting coefficients determined with the calibration process can be summarized in Table 1. It is observed that K_{tc} is the most dominant cutting coefficient. The edge coefficients, on the other hand, exhibit an almost completely random behavior; no trend can be clearly identified by observing their behavior with different depth of cuts.

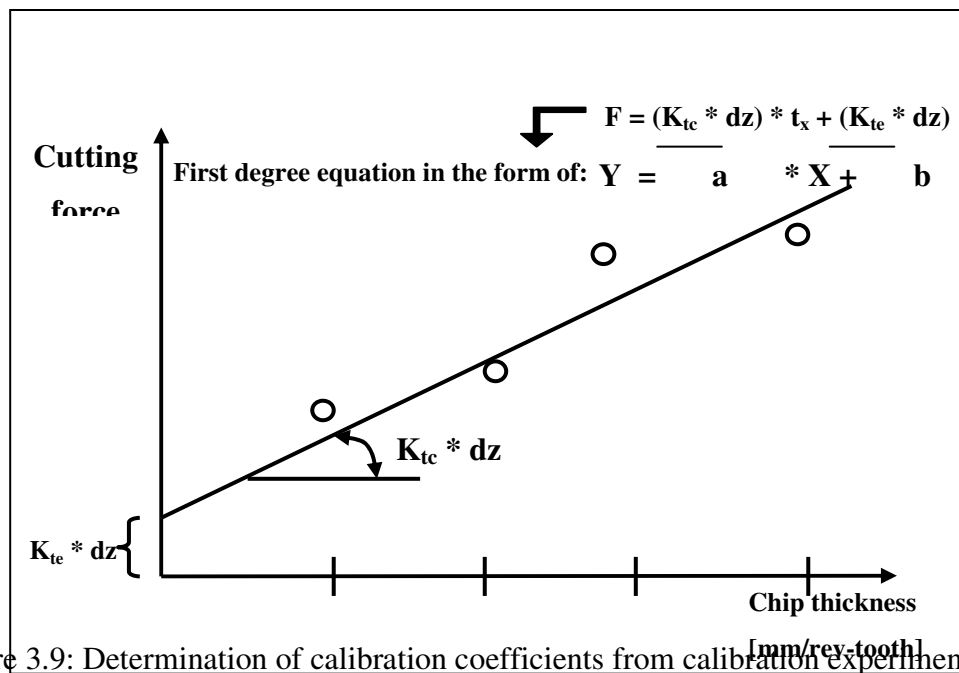


Figure 3.9: Determination of calibration coefficients from calibration experiments.

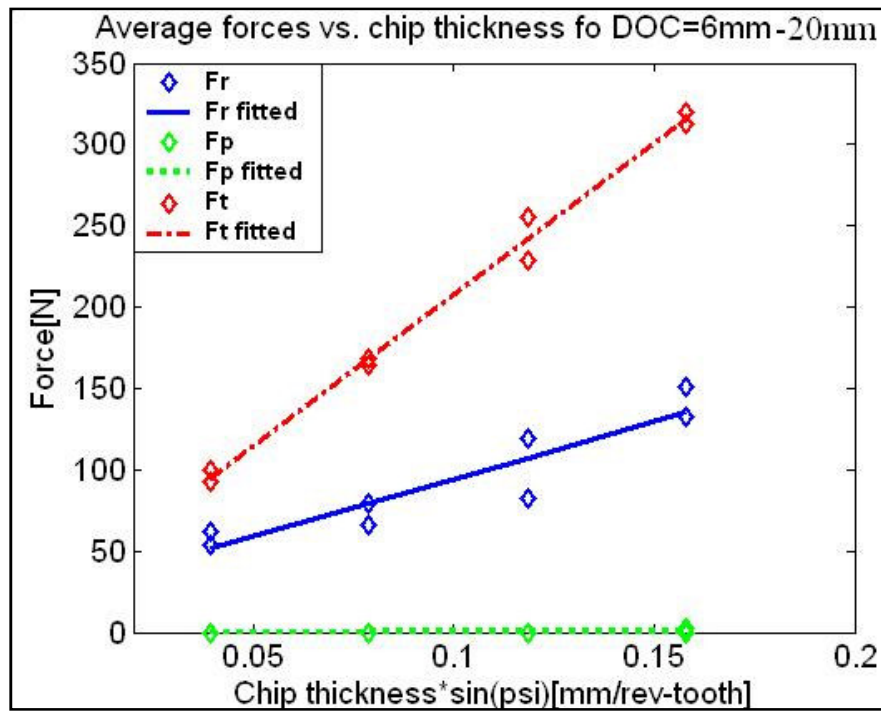


Figure 3.10: Cutting forces vs. chip thickness for 6-20 mm.

Table 3-1: Numerical values of cutting and edge coefficients for different intervals from tip.

Interval from Coefficients tip	0 - 0.5 [mm]	0.5 - 1 [mm]	1 - 1.5 [mm]	1.5 - 2 [mm]	2 - 3 [mm]	3-4 [mm]	4 - 6 [mm]	6 - 20 [mm]
K_{rc} [N/mm ²]	2991	695	22	196	105	483	353	268
K_{re} [N/mm]	31	10	9	2	7	15	12	3
$K_{\psi c}$ [N/mm ²]	1113	785	753	179	101	31	6	249
$K_{\psi e}$ [N/mm]	12	13	4	19	14	9	0	3
K_{tc} [N/mm ²]	5354	2549	1182	1429	971	848	932	829
K_{te} [N/mm]	37	17	30	3	16	17	11	12

Chapter 4

SOLID MODEL BASED ENGAGEMENT MODEL

4.1 Introduction:

Determining the tool-workpiece engagement is very critical, since it is directly related to the chip load and cutting forces. The aim of the tool-workpiece engagement domain determination model is to obtain which sections of the tool is engaged with the workpiece at any instant of machining process. Moreover, in order to produce parts with complex free-form surfaces in an optimum manner in terms of cycle time, cost and product quality, engagement model needs to be calculated fast and accurately. Therefore, for precise simulation of free-form surface machining, the most important parameter is the accurate determination of the instantaneous chip loads along the tool path.

In this chapter, solid based approach to the tool-workpiece engagement region is developed and used for 3D complex sculptured free-form surfaces with ball-end milling. Since other engagement domain calculation approaches (analytical, discretization, Boolean) do not cover non-monotonic surfaces or they are computationally expensive and slow, solid based engagement can be used for every kind of surface and is comparably faster and quite accurate than any other approaches. Another important aspect of the solid based engagement model is that it can also calculate engagement domain for any type of surface in five-axis machining. The solid based engagement model used in this study is developed in Moduleworks GmbH in Germany. Details of the solid based engagement model are presented in Kaymakci et al. [36]. In the process of tool-workpiece engagement model along the tool path, the output (CL file) of any commercial CAM package is post processed by this solid based engagement algorithm.

4.2 Tool-Workpiece Intersection Model

In the machining of free-form surfaces, axial depth of cut is not constant throughout the tool path. Consequently, engagement region changes at each CL point. Figure 4.1 shows a sample CL output of Unigraphics NX4 CAM module output. Each line represents a CL point. Red sections show the position of the tip of the ball-end mill according to the surface's coordinate system and blue sections show the orientation unit vector of the tool. For three-axis machining, orientation of the tool is constant and equals to (0, 0, 1).

```

SPINDL/RPM,600,CLW
FEDRAT/MMPM,500.0000
GOTO/-0.0148,171.6120,3.0000,-0.0034929,-0.3440710,0.9389371
FEDRAT/144.0000
GOTO/0.0035,156.9278,-2.2434,-0.0033907,-0.4265147,0.9044743
GOTO/0.0039,155.9354,-2.3649,-0.0034224,-0.4089396,0.9125550
GOTO/0.0042,154.9420,-2.4708,-0.0034562,-0.3890385,0.9212150
GOTO/0.0045,153.9475,-2.5586,-0.0034918,-0.3667484,0.9303136
GOTO/0.0046,152.9514,-2.6247,-0.0035284,-0.3420176,0.9396869
GOTO/0.0047,151.9543,-2.6648,-0.0035627,-0.3170480,0.9484028
GOTO/0.0047,150.9562,-2.6758,-0.0035919,-0.2941247,0.9557603
GOTO/0.0045,149.9576,-2.6597,-0.0036166,-0.2733135,0.9619182
GOTO/0.0043,148.9590,-2.6183,-0.0036374,-0.2546563,0.9670248
GOTO/0.0040,147.9608,-2.5533,-0.0036549,-0.2381769,0.9712149
GOTO/0.0036,146.9633,-2.4668,-0.0036694,-0.2238867,0.9746083
GOTO/0.0031,145.9668,-2.3619,-0.0036813,-0.2117846,0.9773094
GOTO/0.0026,144.9716,-2.2415,-0.0036909,-0.2020727,0.9793636
GOTO/0.0020,143.9773,-2.1061,-0.0036974,-0.1959602,0.9806049
GOTO/0.0014,142.9834,-1.9574,-0.0037010,-0.1936666,0.9810604

```

Position
Orientation

Figure 4.1: An example of a CL-file.

Using a tool-workpiece engagement model, the engagement between tool and workpiece can be calculated at any time of the machining within a controllable accuracy. The initial workpiece definition (stock), geometric definition of tool(s) and the motion of the tool in the workpiece coordinate system must be present to achieve this goal. Another important property of this approach is that engagement can be calculated for any type of tool if the geometric properties of tool (diameter, length, taper angle, flute length etc.) and tool holder (tool offset, diameter, length, taper angle, corner radius etc.) are present. Furthermore, a significant advantage of this model is that any arbitrary shaped model can be used as an initial stock, instead of a rectangular block. It is also possible that final stock also can be saved for various purposes, for example, engagement for rough milling, semi-finishing, and super finishing operation can be calculated individually by using the rough cutting output as a semi-finishing input. Figure 4.2, Figure 4.3, and Figure 4.4 shows roughing, semi-finishing, and finishing outputs of the model respectively.

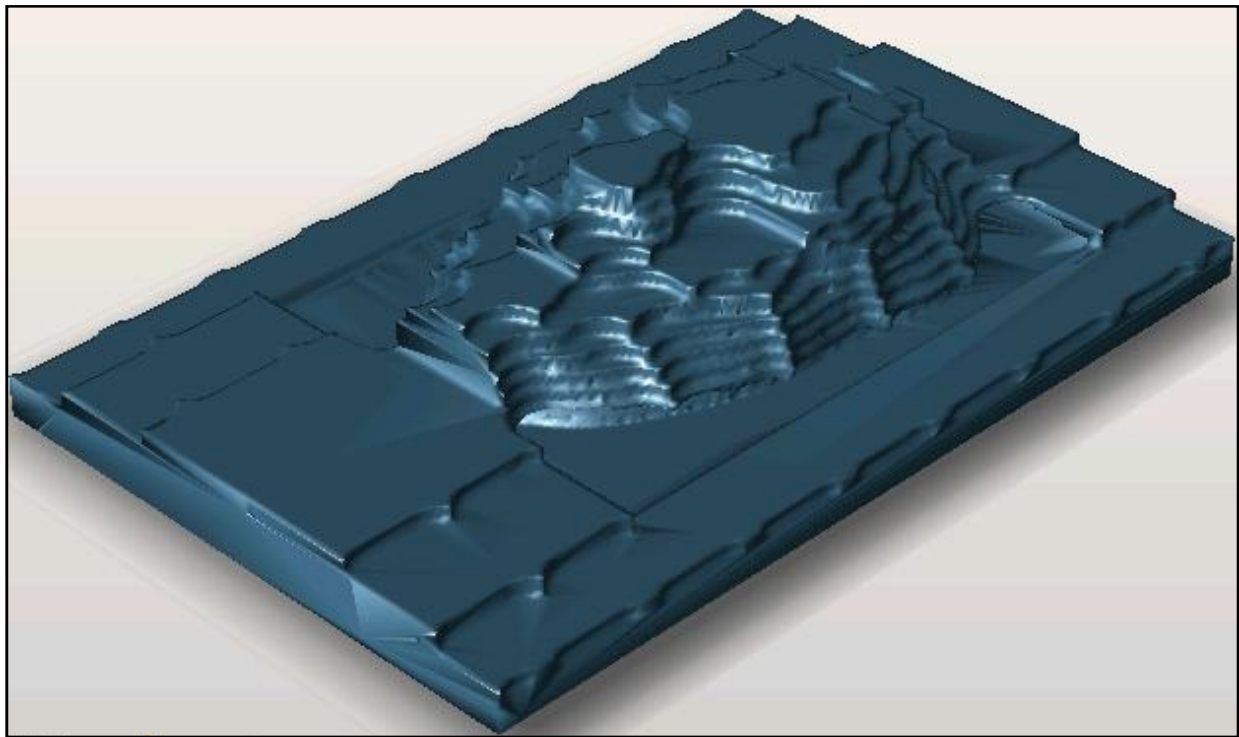


Figure 4.2: Rough milling output of the model for a sculptured surface.

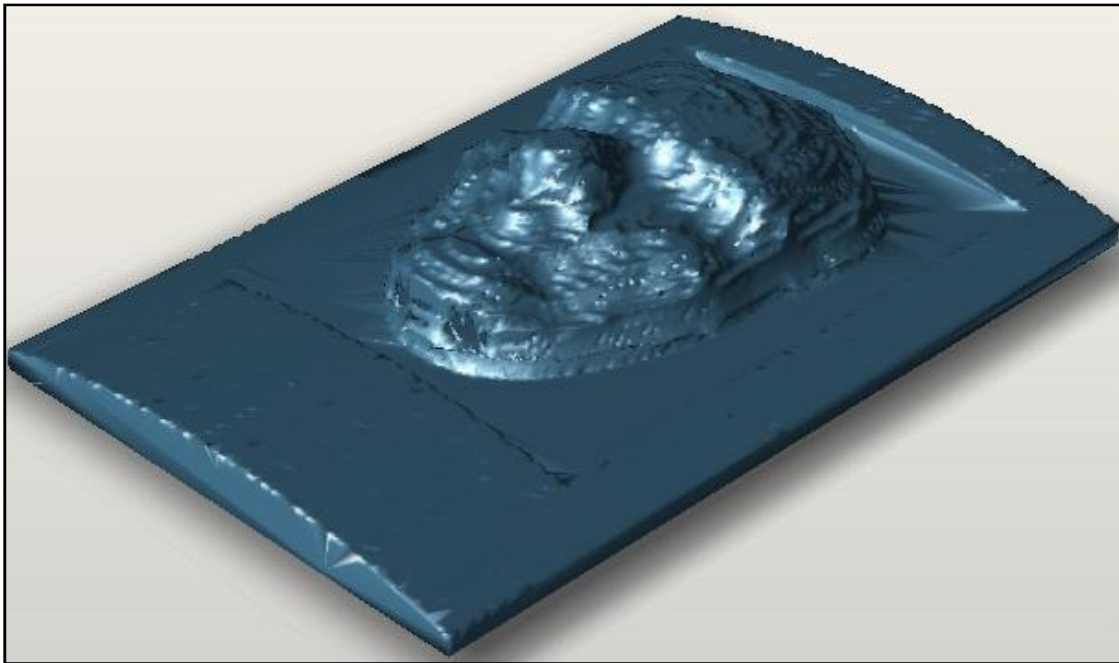


Figure 4.3: Semi-finish milling output of the model for a sculptured surface.

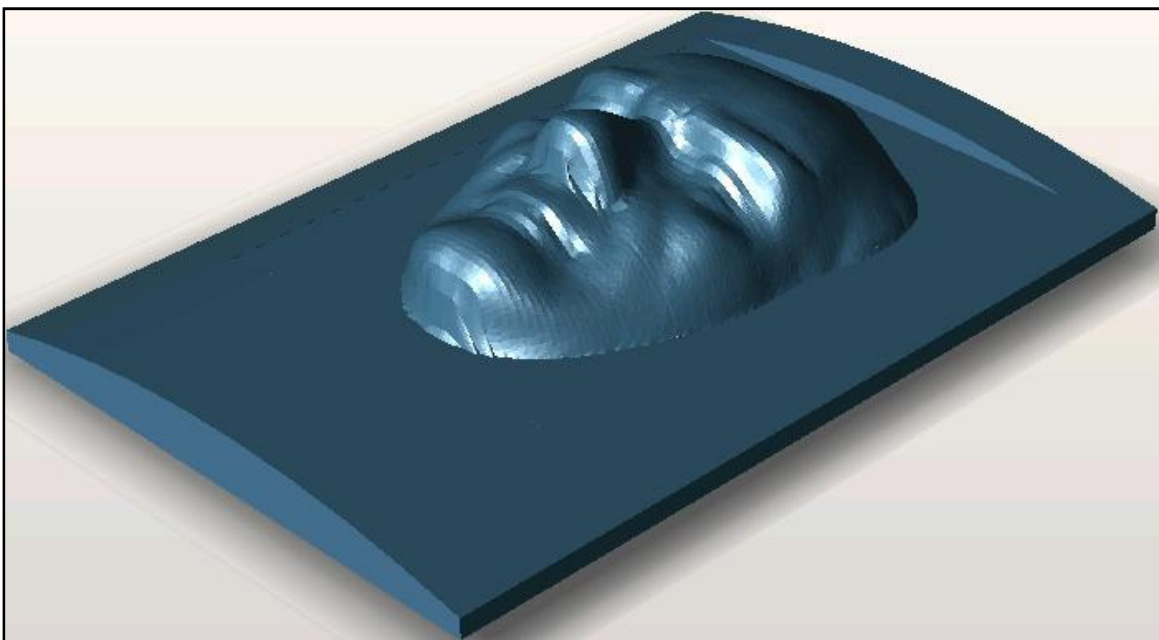


Figure 4.4: Finish milling output of the model for a sculptured surface.

An axis-aligned 3 dimensional uniform grid of points is used to describe the initial workpiece prior to machining (Figure 4.5). The density of the grid is controlled through the grid distance which is identical along X, Y, and Z directions. In this study, grid distance which defines the resolution the tool and workpiece was selected as 0.0625 mm. A solid triangulated mesh defines an arbitrary shaped initial workpiece prior to machining. In order to initialize the grid points with this given mesh, all points inside the solid mesh are marked with collision time $t = \infty$. Outside points are marked with the collision time of $t = -1$. $t = -1$ points are the grid points on the bounding box which covers the workpiece; however they are not in the mesh defined by the workpiece.

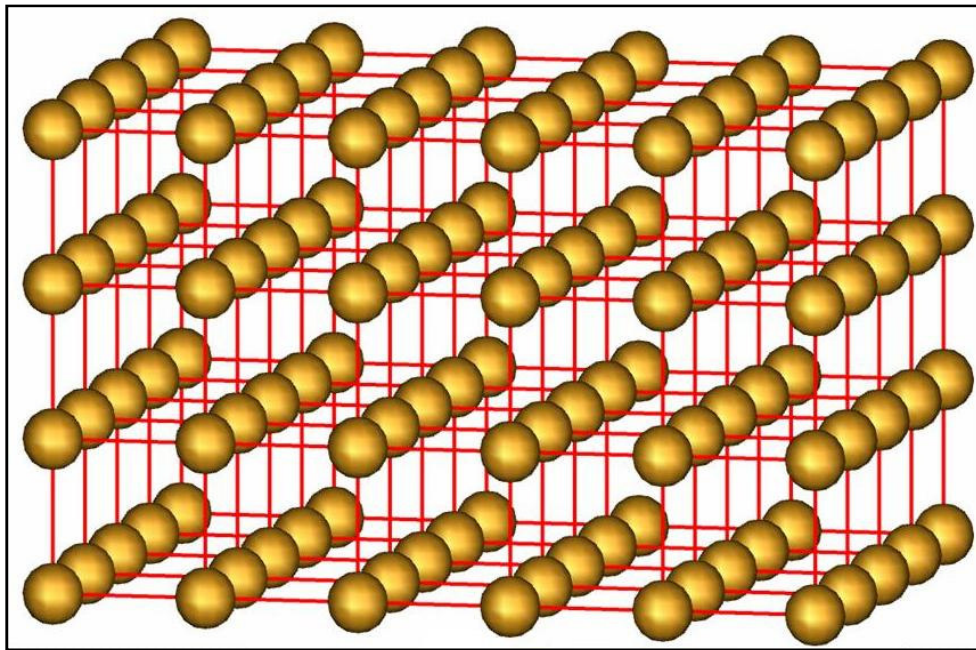


Figure 4.5: 3D grid of points used to describe the initial workpiece.

The motion of the toolpath is presented through the tip point of tool in space and the orientation vector of tool axis as a function of t allowing 3, 4 or 5 axis toolpaths to be used as input. Further a collision determination method has been implement that delivers the time of first

contact between the moving tool which consists of translation and rotation both and a grid point in space (Figure 4.6). For each time slice Δt , the motion of tool from t to $t + \Delta t$ is passed to the collision determination method together with all the points in the local region that might be hit by this sweep motion. Each grid point that has been hit by the tool motion is being marked by the time value of the collision and in the next time interval this grid point does not need to be re-checked for collision since it has been already hit in the past. Further, all the grid points that have been hit within the same time interval are referenced in a list dedicated to this time interval.

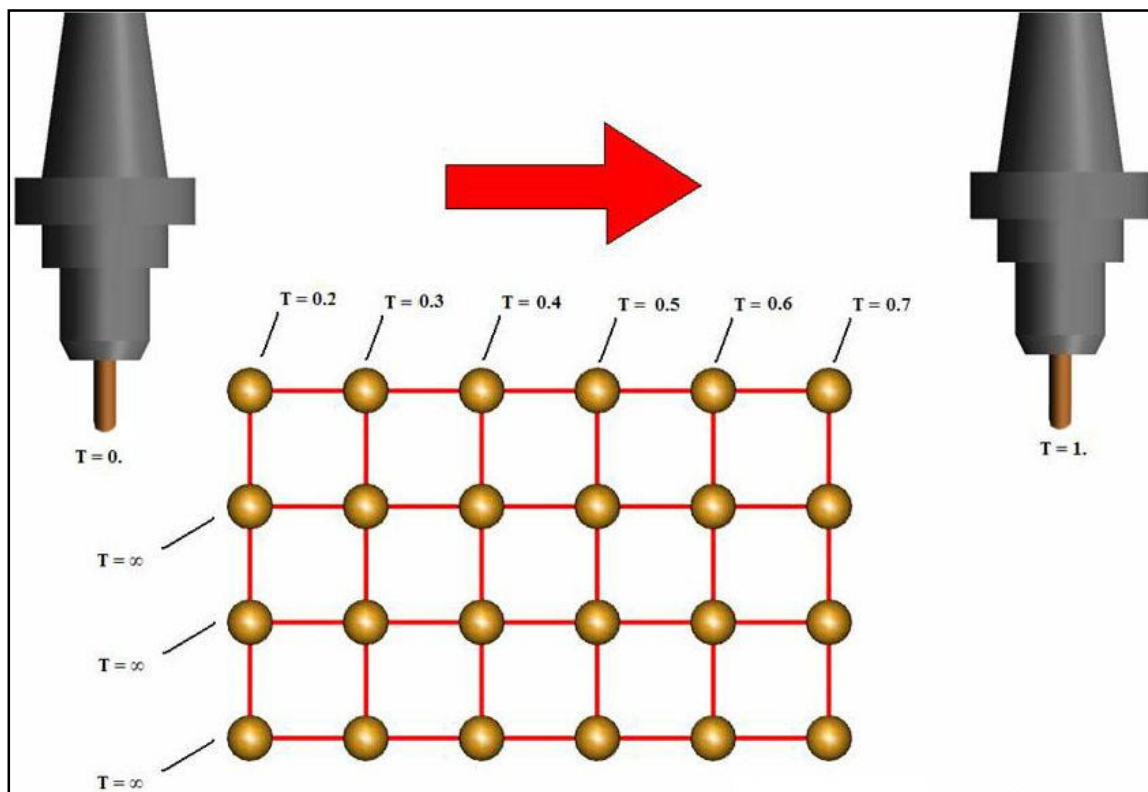


Figure 4.6: Grid cells and their collision time attribute T .

The engagement between tool and workpiece can be calculated for each time interval by analyzing the list of grid points for this time interval from the perspective of a stationary tool. This is done by transforming the mentioned grid points to the coordinate system of stationary

tool. Then the tool is sliced along the tool axis to slices with constant thickness. In this study, constant thickness (Δh) is selected as 0.1 mm. As the sliced tool length increases, the computation time increases, thus sliced tool length was determined according to the maximum depth of cut of the machining process. Each slice is between h and $h + \Delta h$ where h is the height of slice from the tool tip point. The grid points are distributed to slices and for each slice the signed minimum and maximum distances from the tool axis in the view defined by the tool motion direction is calculated using all grid points belonging to this slice. Doing this for each slice delivers the engagement for each slice (Figure 4.7).

After all the time intervals are processed, the 3D grid points are marked with different t values. All remaining grid points with the $t = \infty$ describe the remaining stock after the machining and could be used for a coarse visualization using various iso-surface extraction methods at the given level where the level of extraction is the desired time value t . Interesting is that the visualization is also possible for any given t value since each grid point “knows” when it has been hit by the tool. This opens an interesting perspective for rest-material determination at any stage of machining since the “history” of machining is stored in the 3D grid model.

The above described solid model has been implemented and used for the following cutting force calculation. The run time behavior of the tool-workpiece engagement model is $O(n^3)$ due to three dimensional grid. Computation time of the model for 50x50x6 mm. solid body with 0.0625 mm. grid distance resolution on Pentium 4 2.66 GHz with 2 GB of RAM is approximately 4 hours and 20 minutes.

The accuracy can be controlled through the grid distance, time step value Δt and the tool slicing step value Δh . The output of the solid based engagement model is shown in Table 4.1. In Table 4.1, the engagement is displayed as the minimum and the maximum distances from the tool axis for each discrete disk and that disk’s CL number. In force model, these distances were converted into φ_{st} and φ_{ex} entrance and exit angles respectively. Illustrations of these angles are shown in Figure 4.8. As stated before, it is impossible to calculate the engagement domain for non-monotonic sculptured surfaces using analytical methods. In sculptured surface machining,

the engagement between tool and the workpiece is very complex and variable. Variation of engagement domain for different CL points is presented in Figure 4.9 and Figure 4.10.

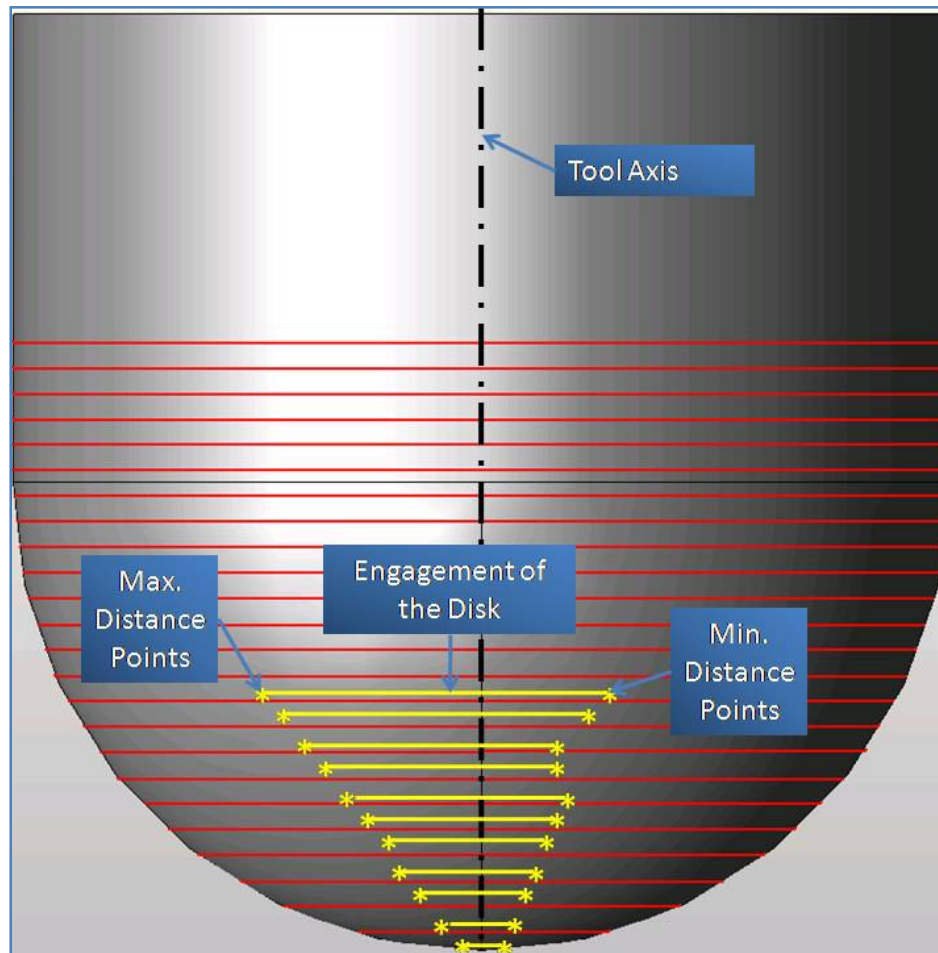


Figure 4.7: Determination of the minimum and the maximum distance from tool axis for each slice.

Table 4-1: Sample text output of the engagement model.

CL #	Start - End Distances of the Disks from the Tip of the Tool [mm]		Min Width [mm]	Max Width [mm]
19	4	4.1	0.75	5.6875
19	4.1	4.2	1.1875	5.6875
19	4.2	4.3	1.3125	5.75
19	4.3	4.4	1.625	5.75
19	4.4	4.5	1.8125	5.75
19	4.5	4.6	1.9375	5.8125
19	4.6	4.7	2.125	5.8125
19	4.7	4.8	2.25	5.875
19	4.8	4.9	2.3125	5.875
19	4.9	5	2.4375	5.875
19	5	5.1	2.5625	5.8125
19	5.1	5.2	2.625	5.75
19	5.2	5.3	2.75	5.6875
19	5.3	5.4	2.8125	5.625
19	5.4	5.5	2.875	5.4375
19	5.5	5.6	2.9375	5.3125
19	5.6	5.7	3	5.125
19	5.7	5.8	3.0625	4.875
19	5.8	5.9	0	0
19	5.9	6	0	0

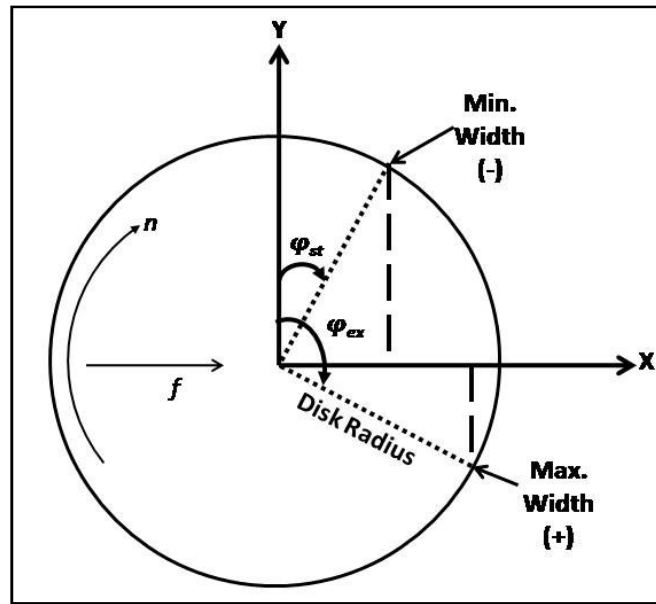


Figure 4.8: Illustration of start and exit angles.

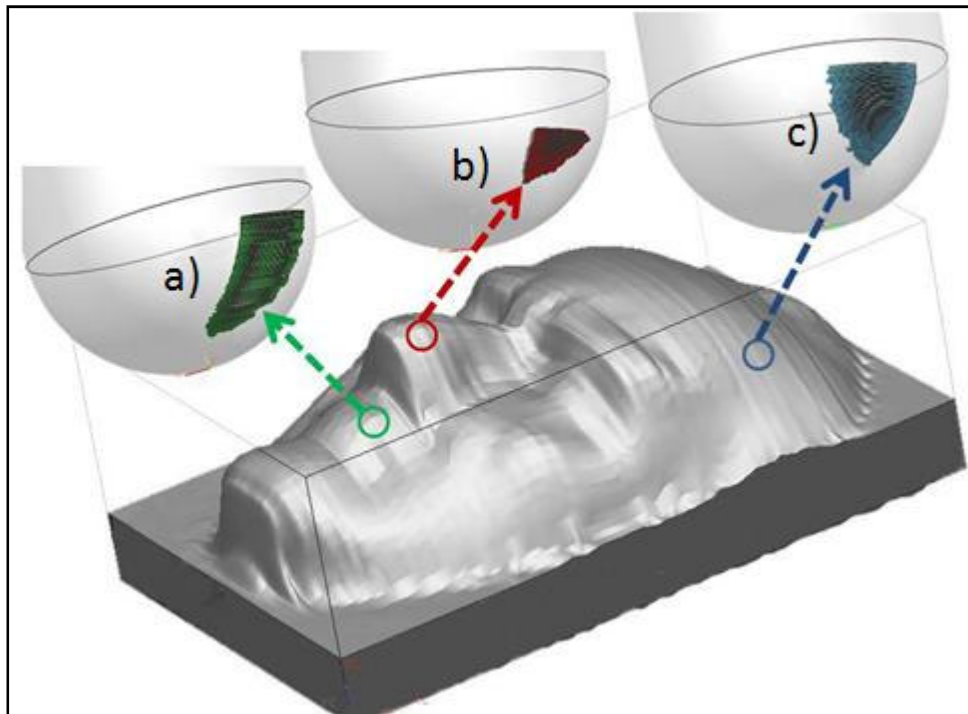


Figure 4.9: Variation of engagement domains along the tool path.

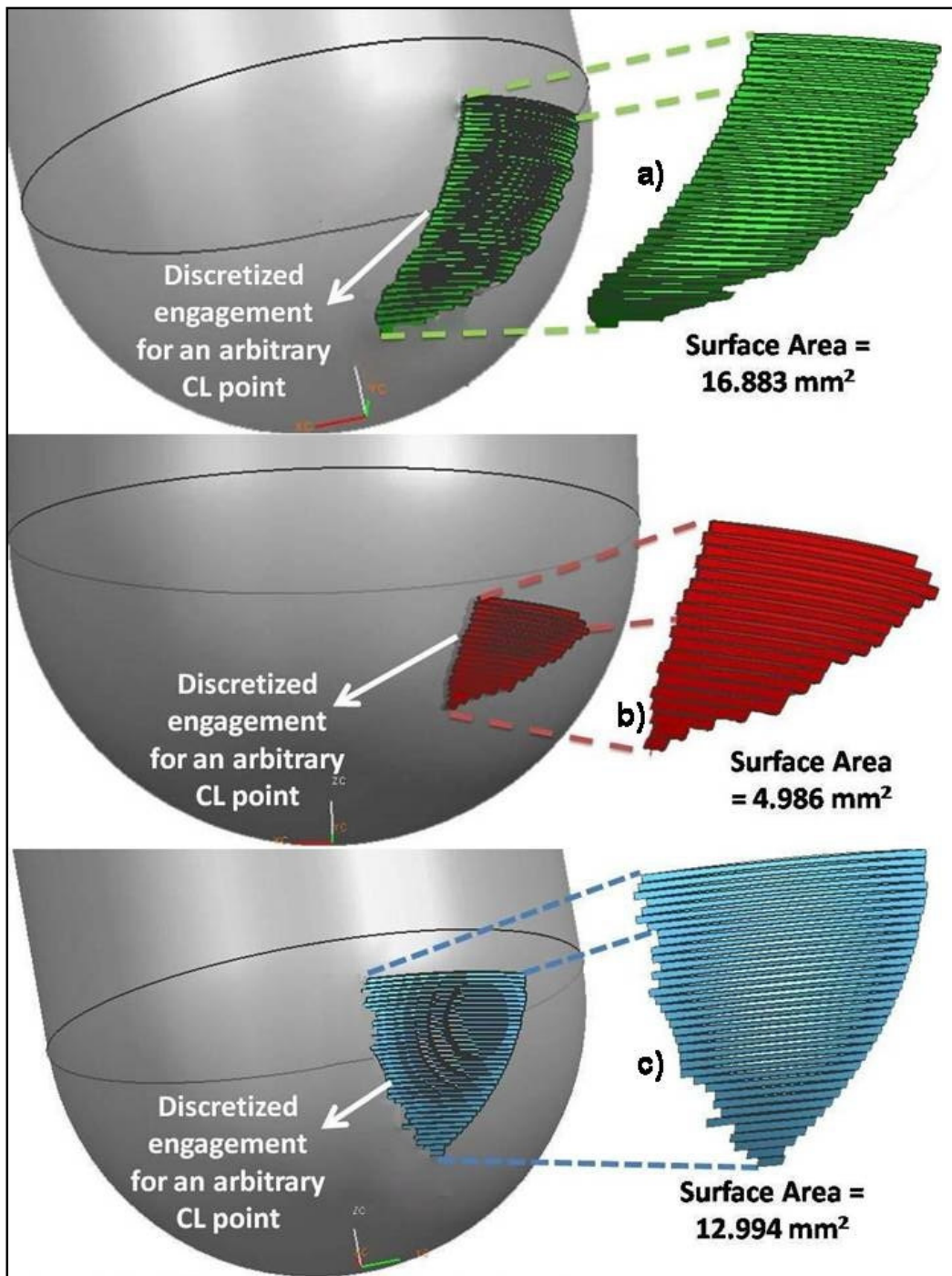


Figure 4.10: Illustration of engagement regions at a), b), and c).

Chapter 5

VALIDATION TESTS

5.1 Experimental Setup:

The experiments for calibration and validation were performed on Mazak FJV-200 UHS Vertical Machining Center (VMC) with 25000 rpm spindle motor, ± 2.5 micron sensitivity, and ± 0.7 micron repeatability. The tool was a carbide ball-end mill cutter from CoroMill Plura series of Sandvik with 12 mm diameter, 37 mm projection length and 30° helix angle. The workpiece material was aluminum blocks (Al7039) with dimensions of 250x170x38 mm. Kistler 3-component dynamometer (Model 9257B) and a charge amplifier have been used to measure cutting forces. The 3-component dynamometer has been fixed to the machine table using fixtures and the aluminum block was attached to the dynamometer using two M10 threaded screws as seen in Figure 5.1.

The cutting forces are sensed by the piezoelectric transducer in the dynamometer and an electric charge output is the outcome of this process. This electric charge is sent to the charge amplifier and converted into voltage output. The sensitivity values for the three channels (X, Y, and Z) of the amplifier were 7.93, 7.90, and 3.69 pC/N respectively. Amplifier gain for the device was set to 300 N/V for all channels. Subsequently, through use of a proper data acquisition card with 200 kS/s sampling rate, ± 10 V analog input and software, the voltage output is displayed and recorded as cutting forces in [N]. Displaying and recording of the measured data was performed with data acquisition software, MALDAQ module of CutPro 8.0. Figure 5.2 shows a sample output screen of CutPro 8.0. The complete actual testing environment can be seen in Figure 5.3.

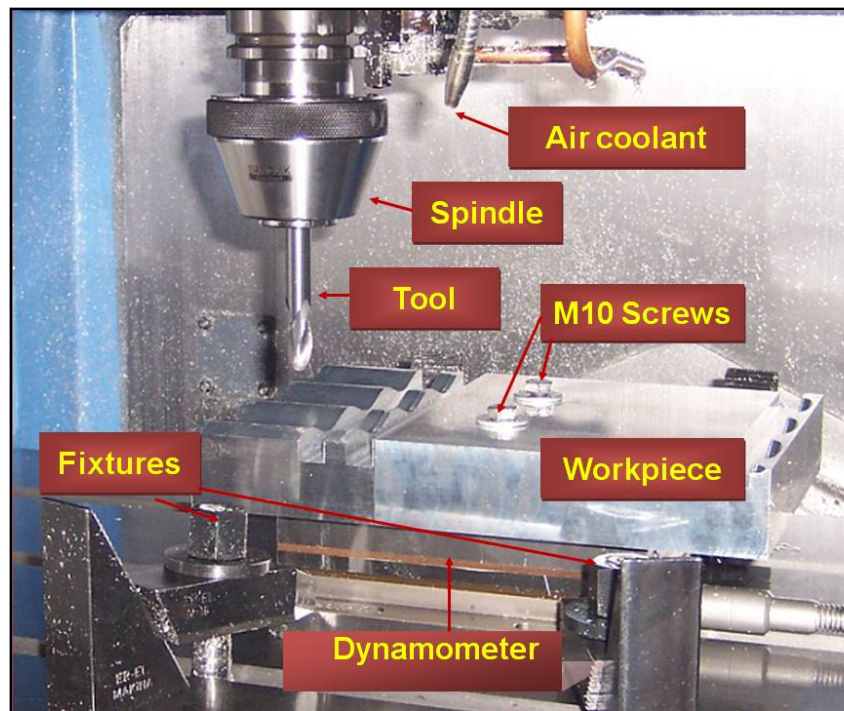


Figure 5.1: Workpiece and 3-component dynamometer fixed to VMC machine table for cutting tests.

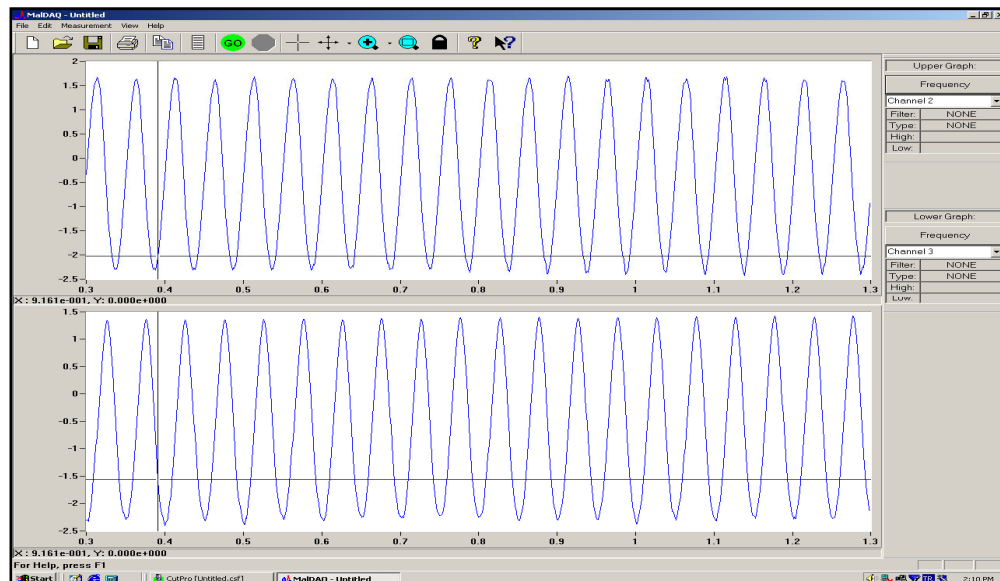


Figure 5.2: Sample output screen in CutPro 8.0 for cutting forces.

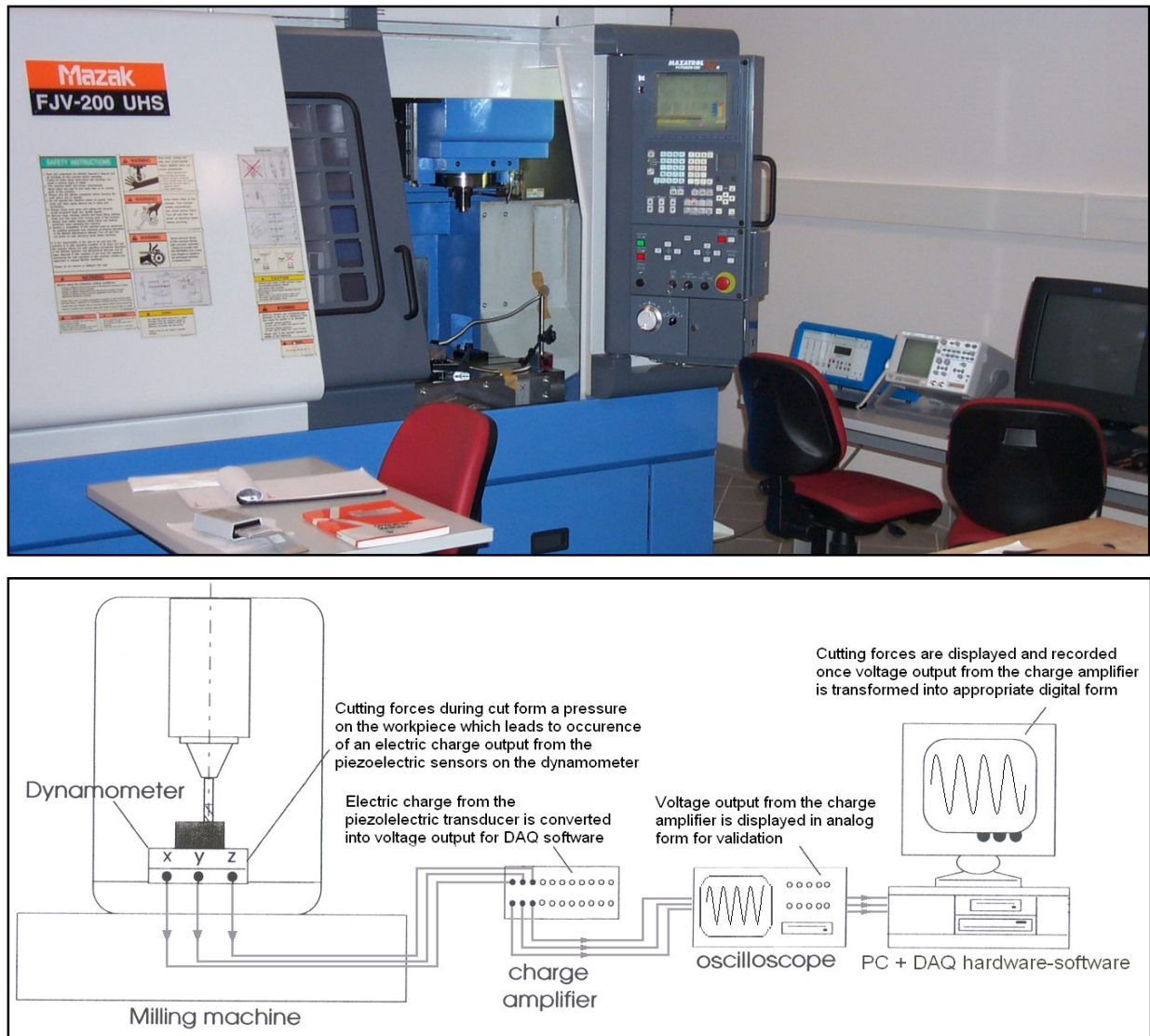


Figure 5.3: The experimental setup for measurement of cutting forces; a) Actual testing environment, b) Detailed illustration.

Various tests were performed for validation of the proposed cutting force model. Differential chip height and the differential rotation angle in simulations were selected to be 0.1 mm and 3.6° respectively which adequately resembled the actual cutting conditions for the mathematical force model. The applied conditions and the results of the performed cutting tests are described in this

chapter. Full immersion slot cutting and various free-form sculptured surfaces are presented in this chapter.

5.2 Full Immersion Slot Cutting Tests:

As the simplest type of cutting in ball-end milling, first of all, the validations of cutting forces were performed for full immersion slot cutting tests. The feed inclination angle (α) is zero for this case which is also known as plain cutting. The engagement domain is very simple for slot cutting case, since the tool contacts the workpiece at 0° and exits at 180° . The details of entrance and exit angles were presented in Figure 4.8. Predicted and measured forces showed good agreement in the performed slot cutting experiments. The tests were performed for different feed rate values and depth of cuts. Cutting conditions for slot cutting validation experiments are summarized in Table 5.1. Feed rate of the tool has been chosen as 48 mm/min. The resultant force magnitudes for different depth of cuts, which are also used during the calibration process, are given in Figure 5.4. Simulated and experimental forces are plotted versus rotation angle for two revolution of the tool in Figure 5.5 to Figure 5.7 for various axial depths of cuts. Simulated cutting force patterns and their magnitudes showed very good agreement with the measured ones. The tool was a two fluted ball-end mill, as a result two peaks are observed in a single rotation of the tool that corresponds to 360 degrees. For consistency, cutting force of two rotations (720°) of the tool is presented for each depth of cut.

Table 5-1: Slot cutting validation experiments cutting conditions.

Feed Rate	48 mm/min
Axial Depth of Cut	1– 2 – 3 – 4 – 5 – 6 mm
Spindle Speed	600 rpm
Sampling Frequency	1000 Hz
Workpiece Material	AL 7039
Amplifier Gains(x/y/z)	300/300/300 N/V

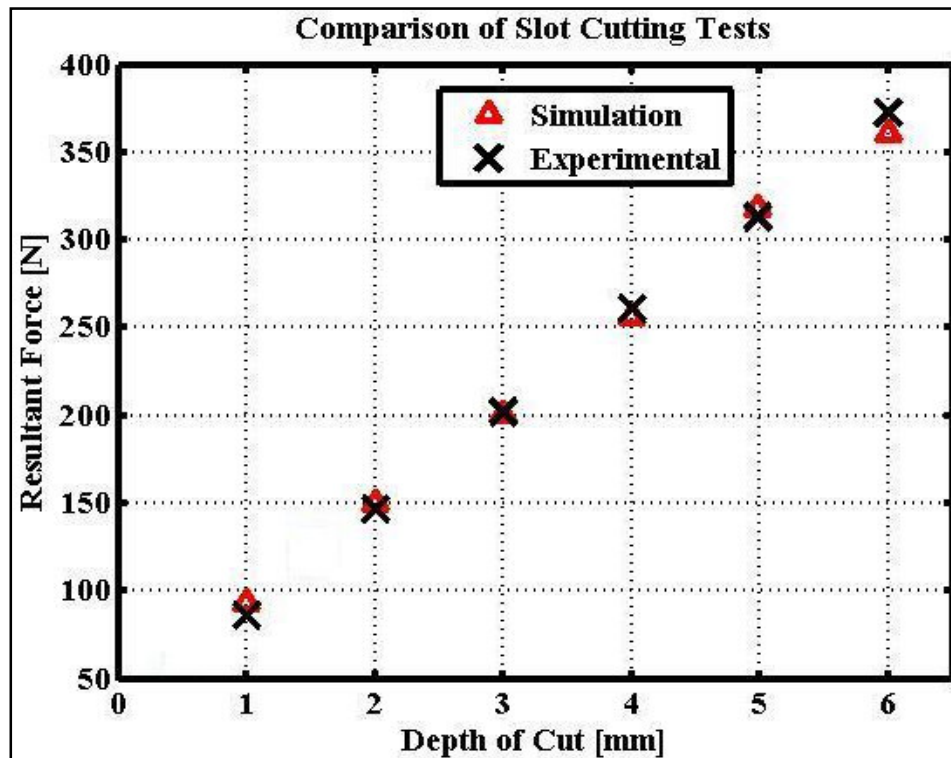


Figure 5.4: Comparison of slot cutting experiments under different depth of cuts.

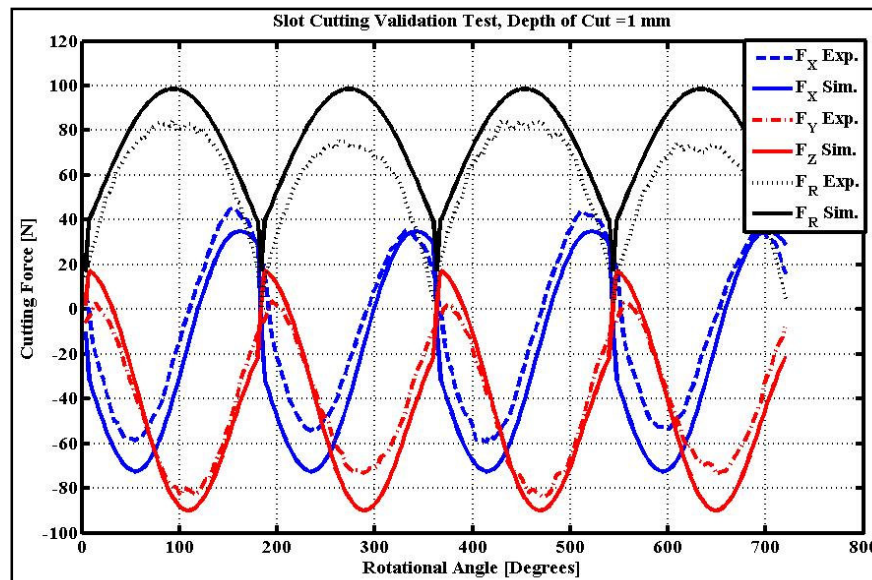


Figure 5.5: Simulated and experimental cutting forces for slot cutting validation tests for depth of cut of 1 mm.

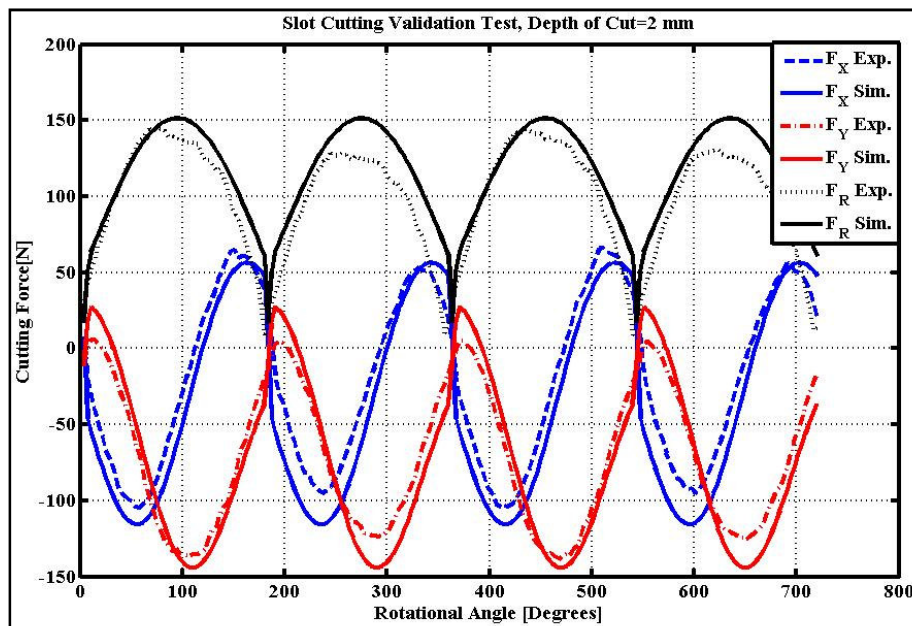


Figure 5.6: Simulated and experimental cutting forces for slot cutting validation tests for depth of cut of 2 mm.

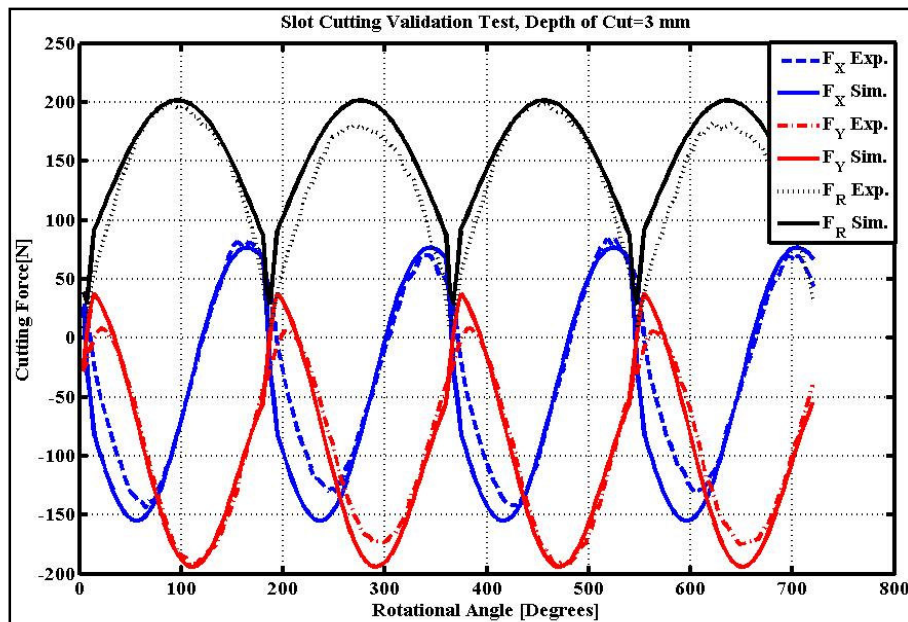


Figure 5.7: Simulated and experimental cutting forces for slot cutting validation tests for depth of cut of 3 mm.

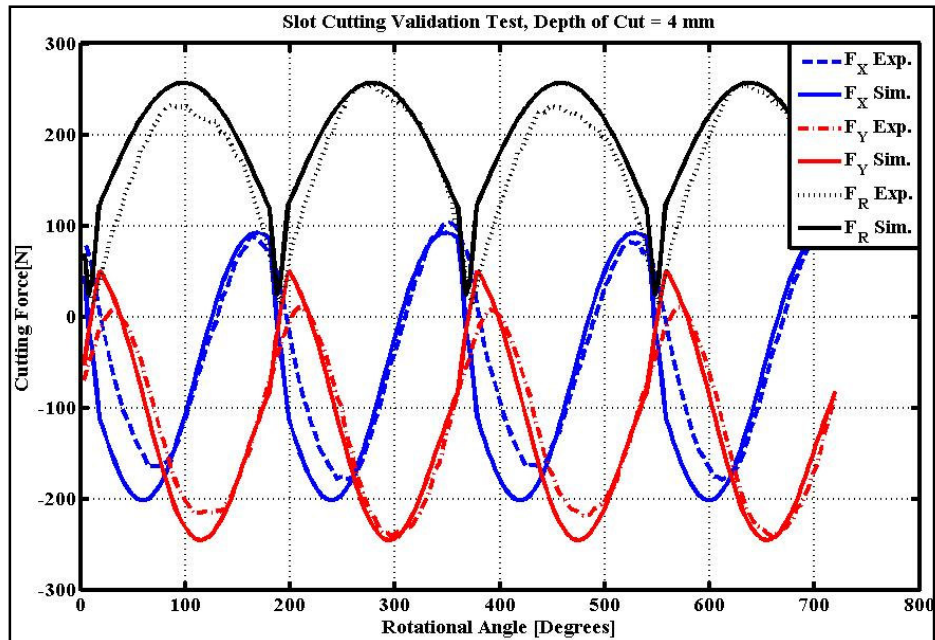


Figure 5.8: Simulated and experimental cutting forces for slot cutting validation tests for depth of cut of 4 mm.

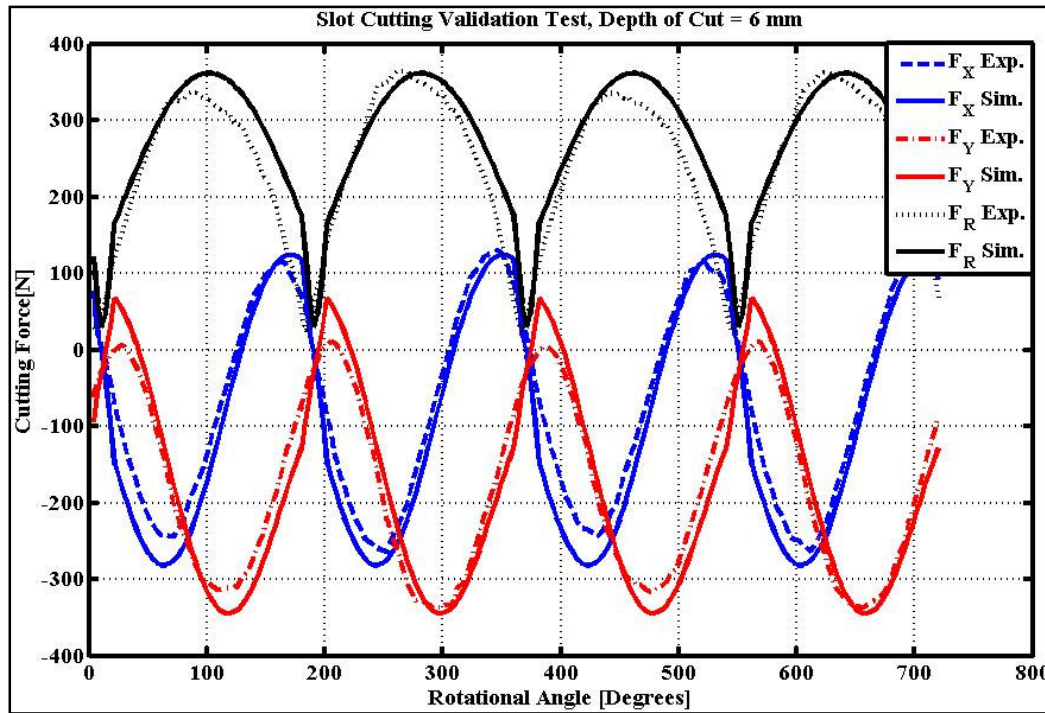


Figure 5.9: Simulated and experimental cutting forces for slot cutting validation tests for depth of cut of 6 mm.

5.3 Sculptured Surface Tests:

After obtaining satisfactory prediction results in slot cutting validation tests, cutting force model has been tested for free-form sculptured surfaces. Several tests were performed in sculptured surface tests including basic free-form surfaces (sinusoidal surface etc.) and non-monotonic surfaces (sine-cosine surface, portrait of Ataturk etc.).

5.3.1 Sinusoidal Surface:

The tool moved through a post-processed CAM file obtained from Unigraphics NX 4 Manufacturing application. The machined surface is shown in Figure 5.10. The part consists of

three sine waves each with amplitude of 3 mm. The wave length of the surface is 50 mm and the step-over is 3 mm/track. Surface was used to create on 150x30 mm blank workpiece. The equation of the sinusoidal shape is also provided in Figure 5.10. Cutting conditions are summarized in Table 5.2. Simulated and experimental cutting forces for sinusoidal surface machining are shown in Figure 5.11, Figure 5.12, Figure 5.13, and Figure 5.14. The simulated patterns and cutting force magnitudes showed good agreement with the experimental forces.

Table 5-2: Sinusoidal surface validation tests cutting conditions

Feed Rate	48 mm/min
Axial Depth of Cut	Max. 6 mm.
Spindle Speed	600 rpm
Sampling Frequency	1000 Hz
Workpiece Material	AL 7039
Amplifier Gains(x/y/z)	300/300/300 N/V

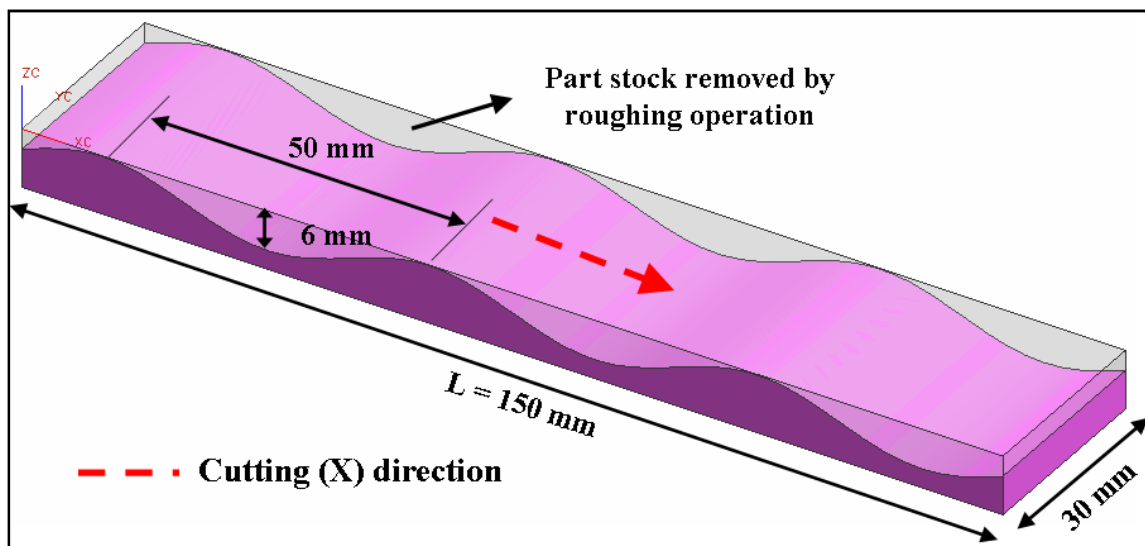


Figure 5.10: Part geometry of the sinusoidal surface.

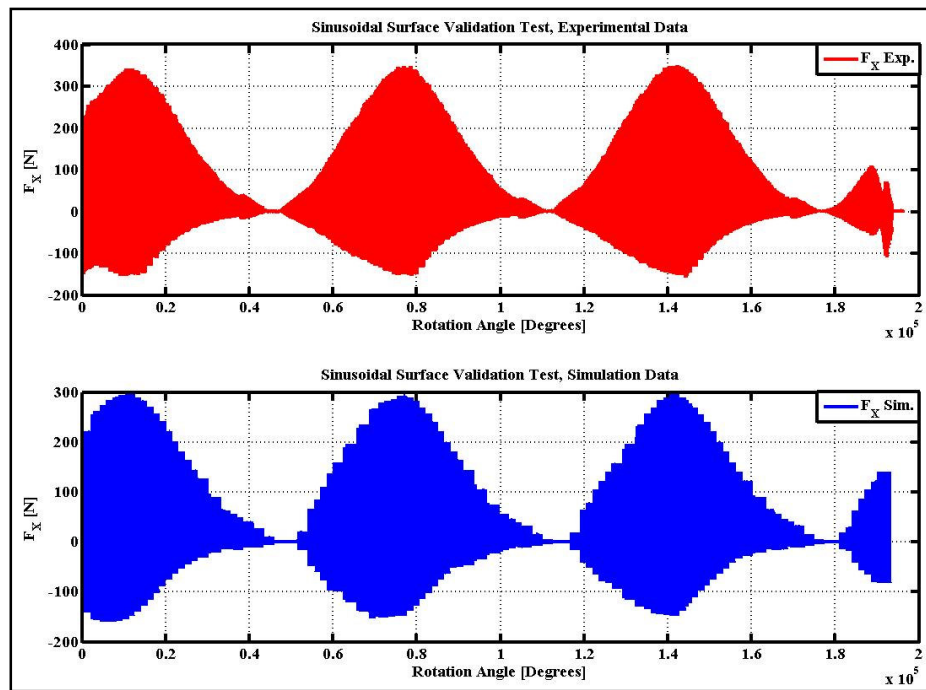


Figure 5.11: Experimental and simulation F_x cutting force component for the sinusoidal surface.

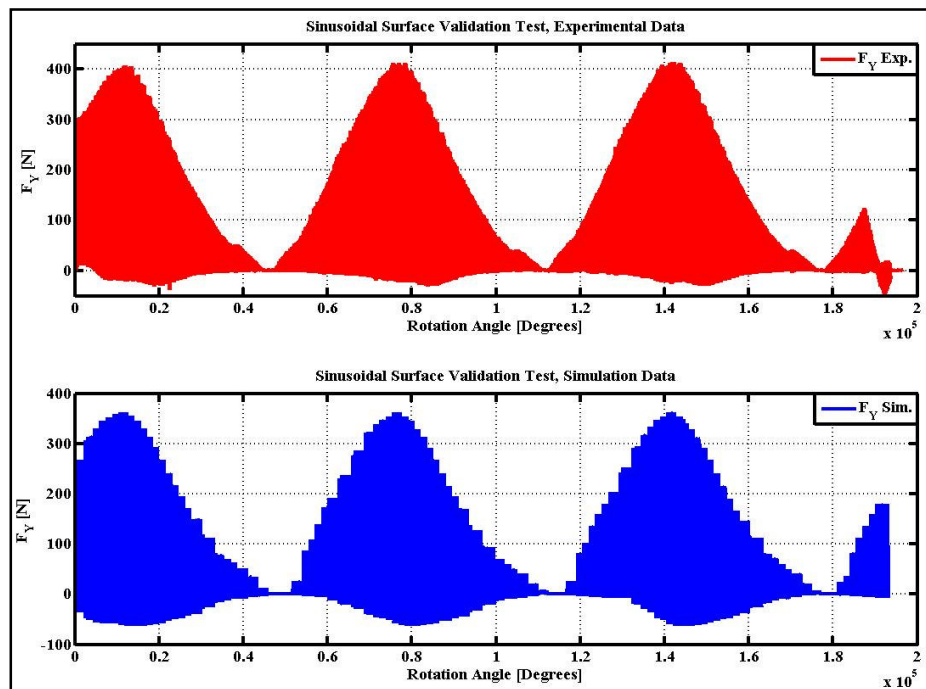


Figure 5.12: Experimental and simulation F_y cutting force component for the sinusoidal surface.

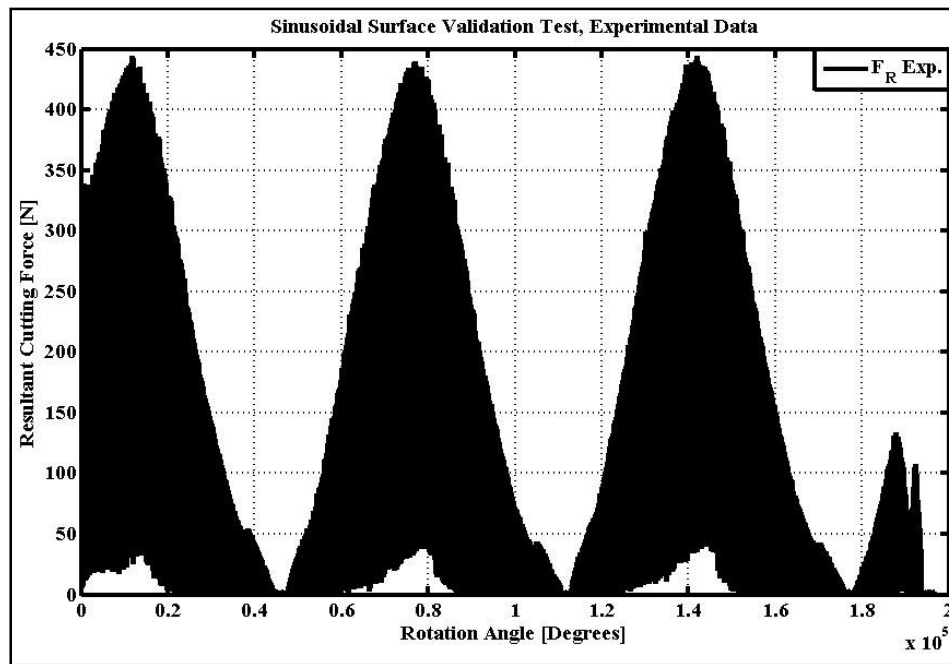


Figure 5.13: Experimental resultant cutting force component for the sinusoidal surface.

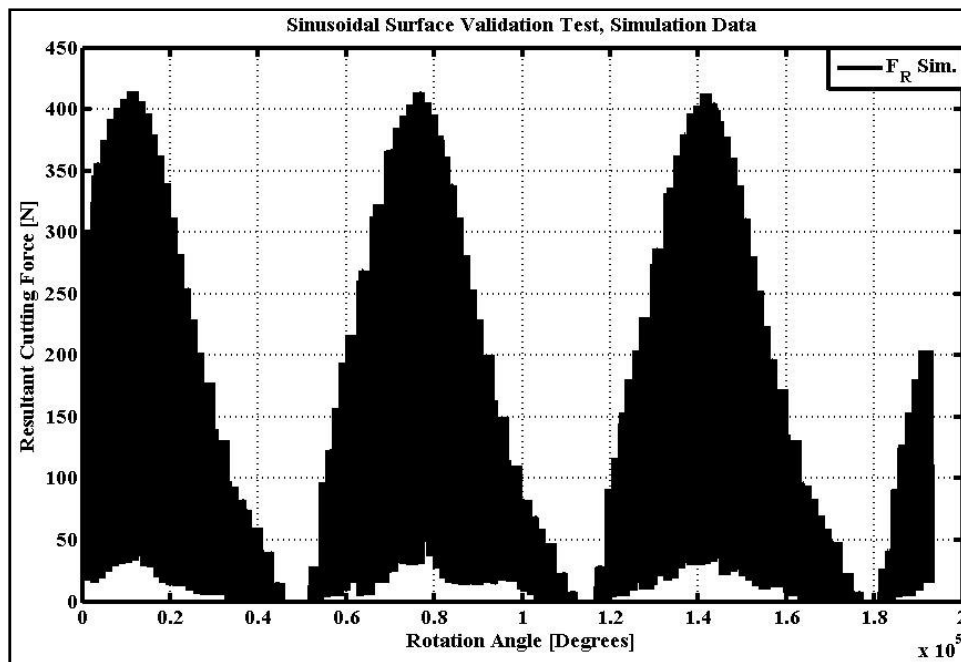


Figure 5.14: Simulation resultant cutting force component for the sinusoidal surface.

5.3.2 Sine – Cosine Surface:

The tool moved through a post-processed CAM file obtained from Unigraphics NX 4 Manufacturing application. The machined surface is shown in Figure 5.15. The part consists of a sine wave swept over a cosine wave. The step-over of 3 mm/track was used to create on 40x40 mm blank workpiece. Cutting conditions were summarized in Table 5.3, parallel to the sinusoidal surface. A two fluted ball-end mill with a diameter of 12 mm, nominal helix angle of 30°, and a projection length of 37 mm was used in experiments. The simulated and experimental force patterns showed good agreement. Experimental and simulated resultant forces are shown in Figure 5.16, Figure 5.17, and Figure 5.18.

Table 5-3: Sine – Cosine surface validation tests cutting conditions.

Feed Rate	48 mm/min
Axial Depth of Cut	Max. 4 mm.
Spindle Speed	600 rpm
Sampling Frequency	1000 Hz
Workpiece Material	AL 7039
Amplifier Gains(x/y/z)	300/300/300 N/V

5.3.3 Ataturk Portrait:

The tool moved through a post-processed CAM file obtained from Unigraphics NX 4 Manufacturing application. The machined surface is shown in Figure 5.19. The step-over of 3 mm/track was used to create on 47x31 mm blank workpiece. The experimental and simulated cutting forces for this free-form surface are shown in Figure 5.20, Figure 5.21, Figure 5.22 and Figure 5.23. Cutting conditions are summarized in Table 5.4, parallel to sinusoidal and sine – cosine surfaces. The maximum depth of cut for this shape is 18 mm; therefore not only spherical

but also cylindrical part of the ball-end mill was used. The simulated and experimental force patterns showed fairly good agreement with the actual force patterns.

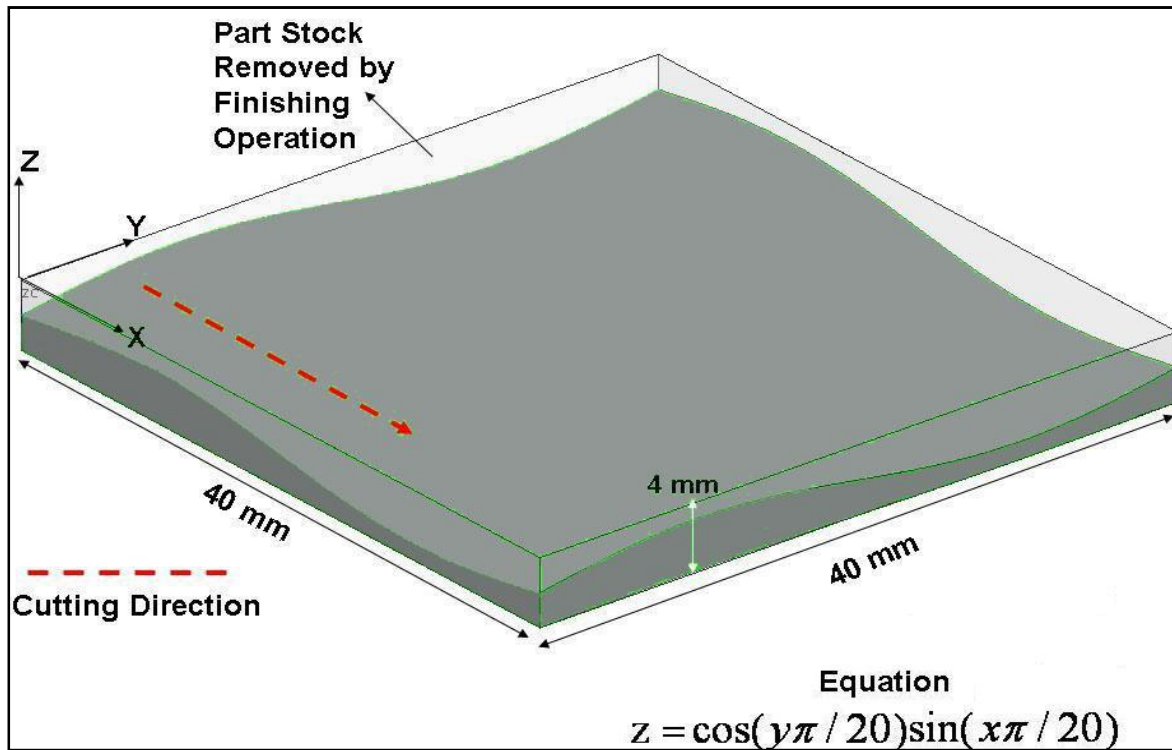


Figure 5.15: Part geometry of the sine – cosine surface.

Table 5-4: Ataturk portrait validation tests cutting conditions

Feed Rate	48 mm/min
Axial Depth of Cut	Max. 18 mm.
Spindle Speed	600 rpm
Sampling Frequency	1000 Hz
Workpiece Material	AL 7039
Amplifier Gains(x/y/z)	300/300/300 N/V

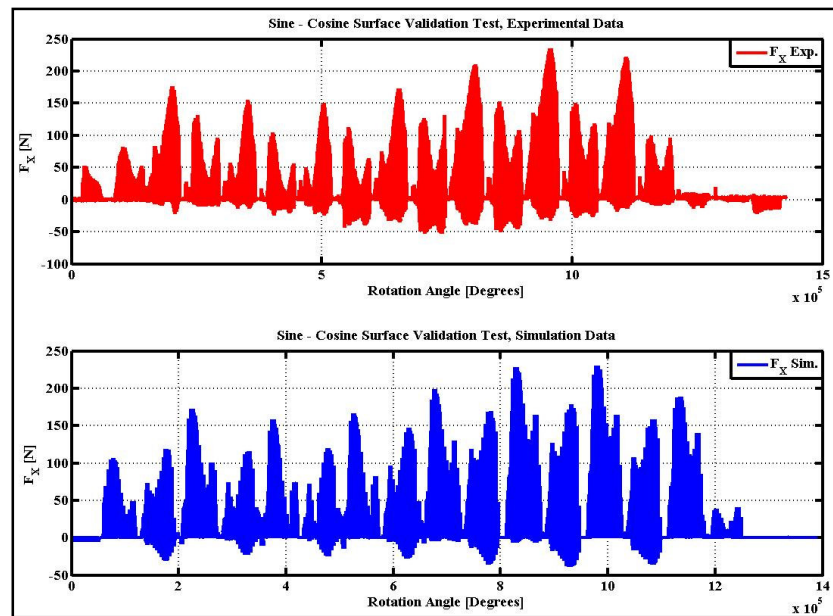


Figure 5.16: Experimental and simulation F_x cutting force component for the sine - cosine surface.

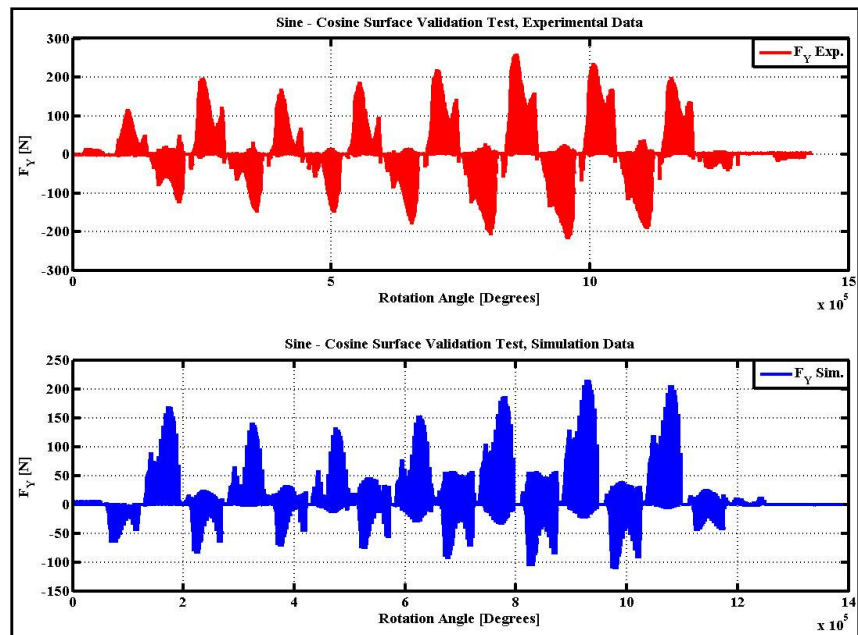


Figure 5.17: Experimental and simulation F_y cutting force component for the sine - cosine surface.

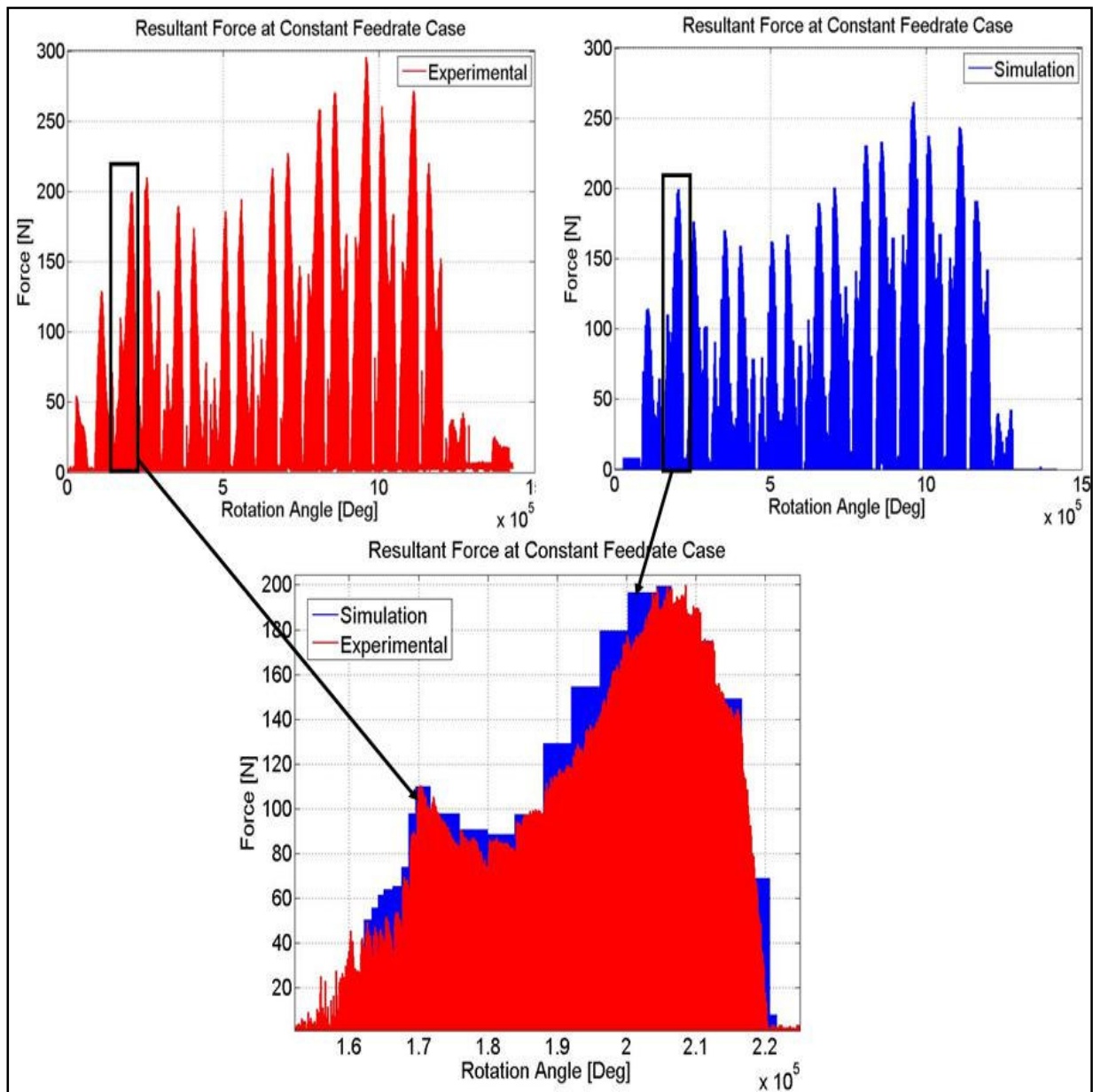


Figure 5.18: Comparison of resultant force components for sine – cosine surface machining.

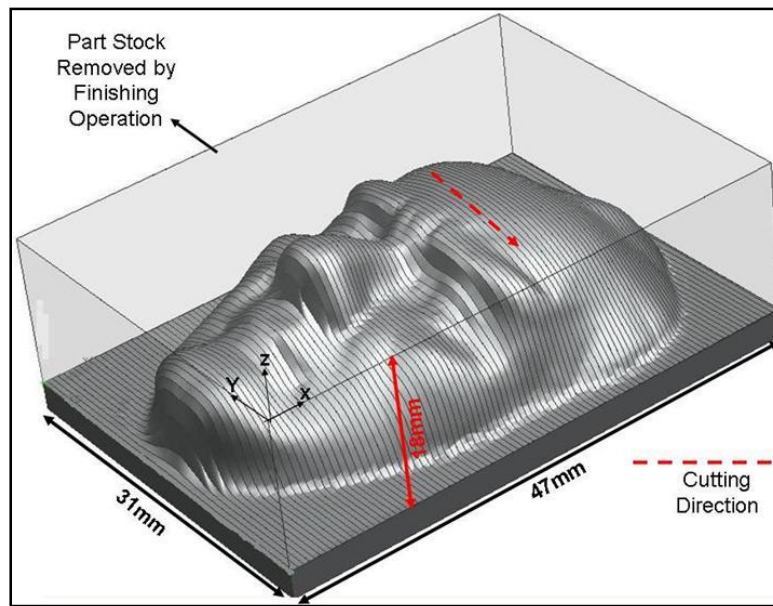
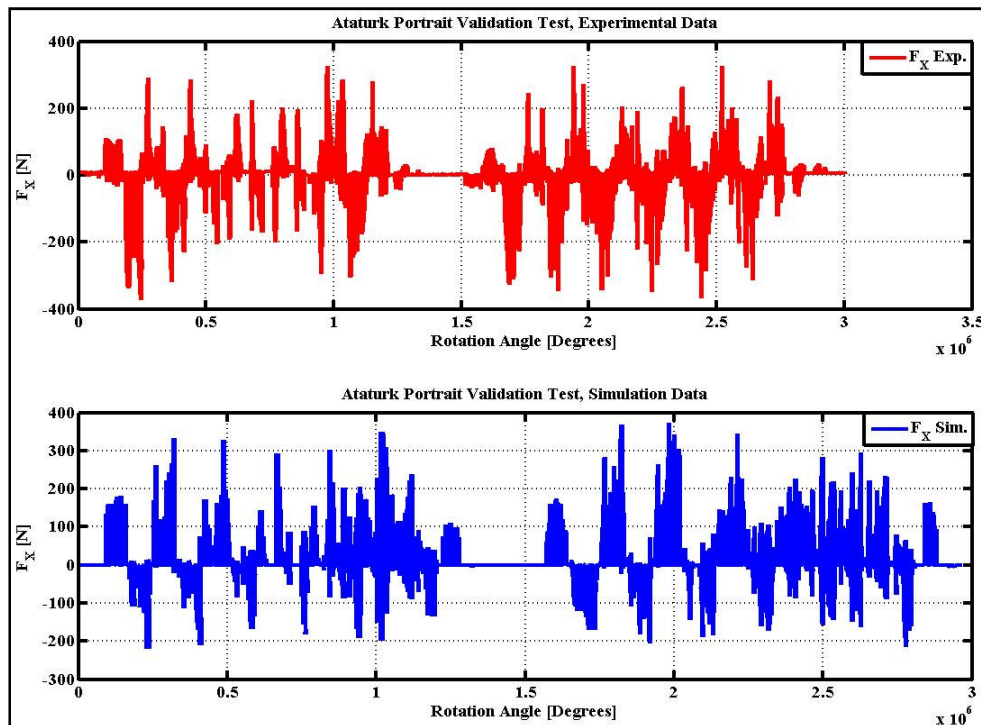


Figure 5.19: Part geometry of Ataturk portrait.

Figure 5.20: Experimental and simulation F_x cutting force component for Ataturk portrait.

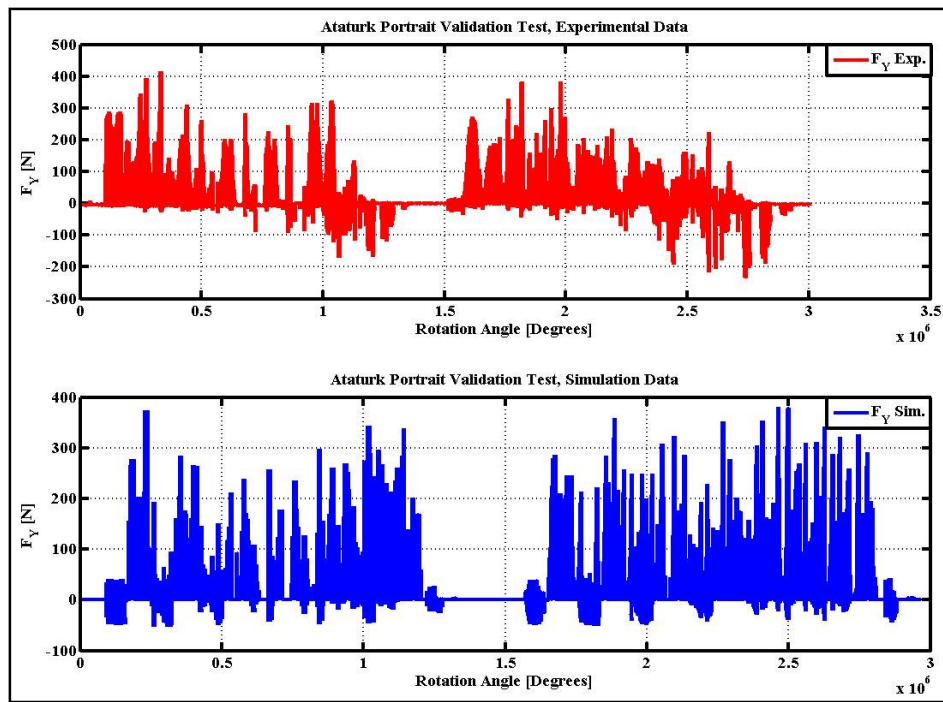


Figure 5.21: Experimental and simulation F_Y cutting force component for Ataturk portrait.

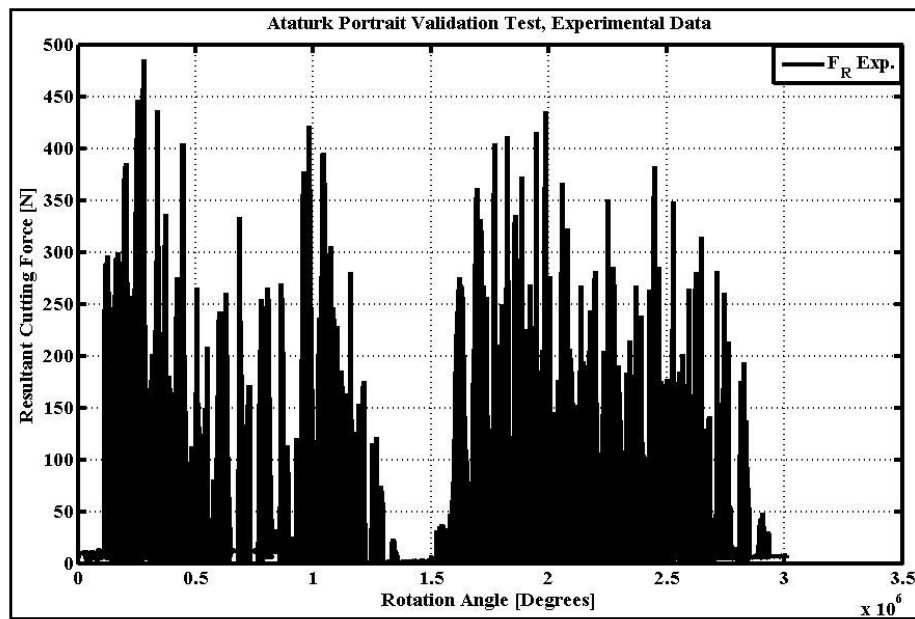


Figure 5.22: Experimental resultant cutting force component for Ataturk portrait.

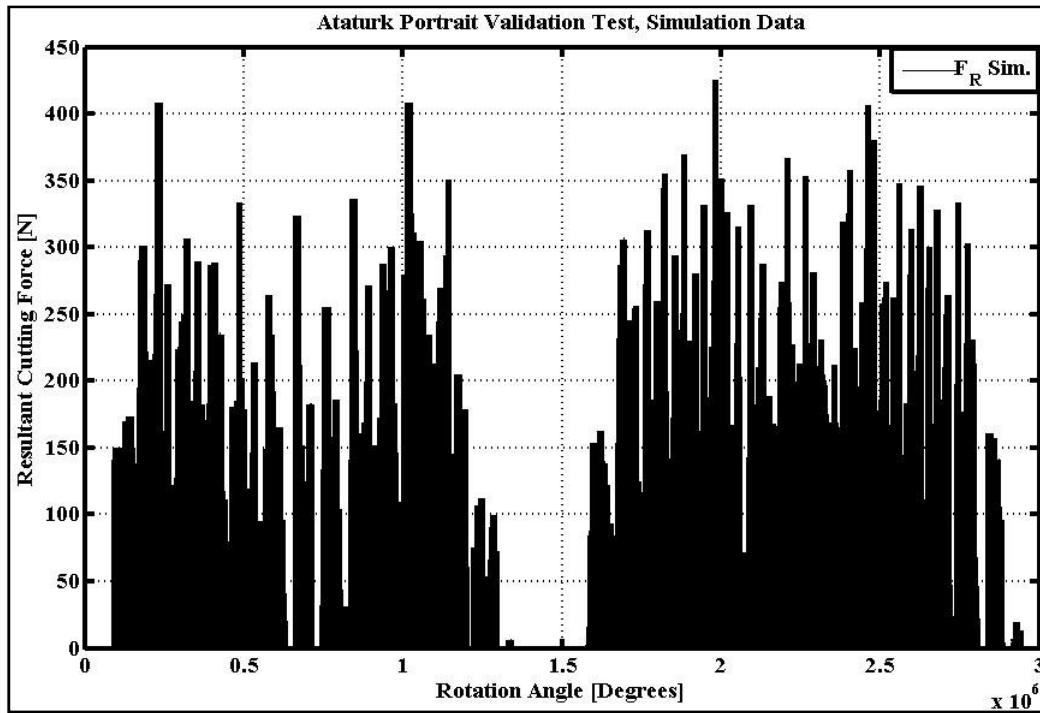


Figure 5.23: Simulation resultant cutting force component for Ataturk portrait.

5.4 Discussions:

Various tests were performed for validation of the proposed cutting force model. Flat slot cutting cases were tested initially. Feed inclination angle (α) is zero for slot cutting tests. Satisfactory results were obtained for these basic milling cases.

After obtaining good prediction results for these milling cases, the cutting force model has been tested for sculptured or namely ‘free-form’ surfaces. These surfaces include both convex and concave machining cases. Simulated and experimental forces showed very good agreement in these free-form tests as well.

When the tool moves at a non-horizontal feed direction, chip thickness is different at each CL point; however, the same coding of the force algorithm was used. The proposed simulation model in this study is a generic one in the sense that it predicts the cutting forces for different

cases without making any changes. The solid based engagement region results were the inputs of the cutting force model including start and exit angles of discrete tool disks at each tool position.

An accurate and robust cutting force model is introduced in Chapter and tested for various cases in this Chapter reflecting real life production examples. The estimations can be performed successfully at X, Y and R (resultant) directions. Reliable force model is important source for feed rate scheduling strategies which will be discussed in the next chapter, and the measured cutting forces are verified with the simulations in all cases.

Chapter 6

FEED RATE SCHEDULING STRATEGY

6.1 Introduction:

Free-form machining with ball-end mill is one of the most commonly utilized manufacturing process in industry. In free-form machining, user and process planner have to be conservative while selecting the process cutting conditions in order to avoid undesirable results, such as chipping, tool breakage, over-cut, under-cut, tool deflection etc., because the cutting geometry of 3D free-form machining is very complex.

Other than simulating and validating the force predictions, free-form surfaces are selected to improve the productivity by decreasing the production time. Conservative constant feedrate values have been mostly preferred up to now since there was a lack of physical models and optimization tools for free-form surfaces. Currently used CAM software systems are based on only the geometric and volumetric analysis, however not on the physics of the process. Feed rate scheduling also called as feed rate optimization is a process which adjusts the NC code of the machined part in order to cut at varying feed rate values instead of single and constant feed rate value. Improving productivity can be improved by two approaches namely the volumetric and force based feed rate scheduling strategies. In this chapter only force based feed rate scheduling strategies are investigated theoretically and experimentally for ball-end milling of free-form surfaces. Erdim [2] showed that volumetric feed rate scheduling strategy is insufficient for determining the optimum feed rate values, since it does not rely on the physics of ball-end milling.

6.2 Force Based Feed Rate Scheduling Strategy:

Off-line feed rate scheduling strategy adjusts the original constant feed rate values according to the reference cutting force which is determined by the user. In order to increase the resultant force to the desired reference value, a simple linear equation is found between the feed rate and the pre-determined reference limiting cutting force. After the calibration is performed, cutting force model is simulated for slot cutting cases at which the calibration tests are performed.

From the slot cutting tests, it is observed that the both the simulated and experimental resultant cutting forces increase linearly with increasing feed rate. This phenomenon is presented in Figure 6.1; therefore, this simple relation is found for the feed rate scheduling formula and it is also verified for complex free-form surfaces.

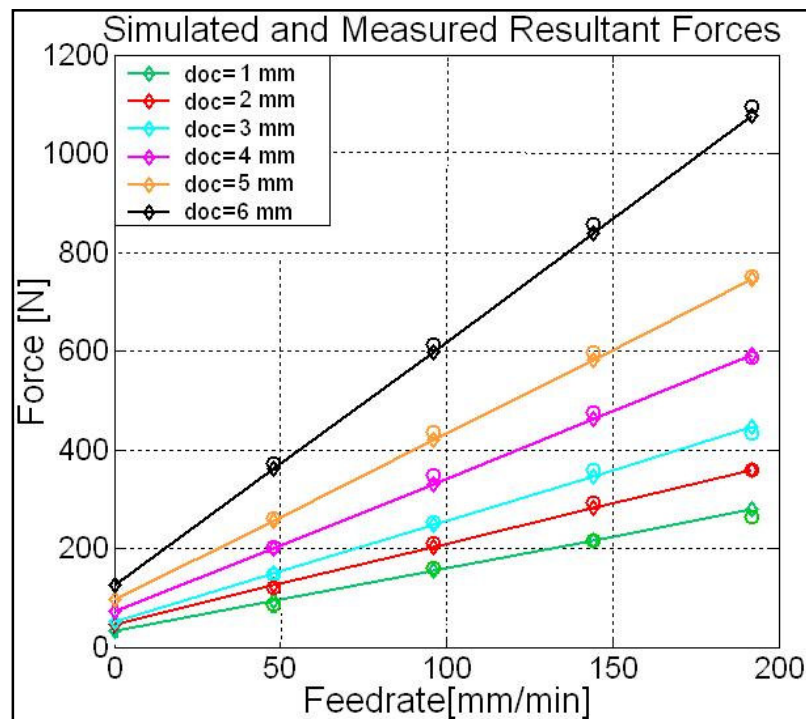


Figure 6.1: Slot cutting resultant force components for different depth of cuts vs. feed rate values.

Feed rate and cutting force relation can be seen for slot cutting tests for various depths. As it can be observed from Figure 6.1, the equation of line is changed for each depth of cut value, so that the feed rate scheduling formula should change for each depth of cut.

When the feed rate is zero, it could be thought that there is no force acting on the tool, since the tool is not moving. However, there is a force which occurs due to the edge coefficients and rubbing effect between tool and workpiece. This effect causes shearing mechanism at the tip of the tool. For ball-end mill tool the instantaneous undeformed chip thickness is obtained as follows;

$$(t_c)_{kn_{new}} = t_x \times \sin(\theta) \times \sin(\psi) \times \cos(\alpha) \pm t_x \times \cos(\psi) \times \sin(\alpha) \quad (6.1)$$

As it is seen from Equation 6.1, the undeformed chip thickness is found from feed per tooth value which can be found from the feed rate. The instantaneous infinitesimal chip load is written as follows;

$$dA_c = (t_c)_{kn_{new}} \times (dz)_{kn} \quad (6.2)$$

For a differential chip load (dA_c) in engagement domain, the differential cutting forces in radial, zenith, and tangential directions (r, ψ, t) is written as follows;

$$\begin{aligned} dF_r &= K_{rc} \times dA_c + K_{re} \times dz \\ dF_\psi &= K_{\psi c} \times dA_c + K_{\psi e} \times dz \\ dF_t &= K_{tc} \times dA_c + K_{te} \times dz \end{aligned} \quad (6.3)$$

As it is observed from Equation 6.2 and Equation 6.3, there is a linear relation between these equations and feed rate. It is also seen from the differential cutting force equation, the differential

cutting force consist of cutting and edge parts like calibration coefficients. This relation concludes a derivation of a linear equation depending on feed rate.

$$dF_i = A \times f + B \quad (6.4)$$

The model is processed to keep the resultant force at the desired constant limit level along the tool path. The limiting feed rate equation for the i^{th} CL point is given as follows;

$$f_{lim,i} = (F_{lim,i} - F_{1,i}) \times \frac{f_2 - f_1}{F_{2,i} - F_{1,i}} + f_1 \quad (6.5)$$

where $i = 1, 2, \dots, CL$, and CL is the total number of CL points in the tool path, f_1 [mm/min] is the original constant feed rate of the tool path, f_2 [mm/min] is the two times f_1 in order to obtain the linear relation for the i^{th} CL point's depth of cut value. F_1 [N] is the maximum resultant cutting force value for the i^{th} CL point for f_1 , F_2 [N] is the maximum resultant cutting force value for the i^{th} CL point for f_2 , $F_{lim,i}$ is the pre-defined limiting constant resultant cutting force value which the cutting forces will be under this threshold value, and $f_{lim,i}$ is obtained as scheduled feed rate value [mm/min] for the i^{th} CL point.

In order to test the feed rate scheduling that is based on the cutting force model, some experimental validation tests were performed on Mazak FJV-200 UHS Vertical Machining Center using Al7039 workpiece material. A two fluted ball-end mill with a diameter of 12 mm, nominal helix angle of 30°, and projection length of 37 mm was used in experiments. Kistler three-component dynamometer (Model 9257B) has been used to measure cutting forces. Displayed validation experiments were run at a spindle speed of 600 rpm. The original and unmodified constant feed rate values were 48 mm/min for all tests. In the simulation, tool was discretized into disks of 0.1 mm height, and the force calculations were performed in every 3.6° of the tool rotation.

Off-line force based feed rate scheduling was applied to sinusoidal surface (Figure 5.10), sine-cosine surface (Figure 5.13), and Atatürk portrait (Figure 5.15) in order to reduce the machining time and to adjust the maximum cutting forces to the reference value. The force based feed rate scheduling logic was applied to free-form surfaces with the modified NC codes, and the optimal scheduled feed rate values were obtained. The procedure is as follows, first of all, the NC file of the part created in Unigraphics NX 4 Design Application is called in. The original NC code is modified and scheduled according to the limiting resultant force and it adapts force model and feed rate scheduling equation. In order to validate the proposed method, the workpiece was machined along the tool path using the scheduled feed rate values. Figures 6.4, 6.8, and 6.12 illustrate that the simulated feed scheduled cutting forces do not exceed the pre-determined threshold cutting forces for the following parts. Figures 6.5, 6.9, and 6.13 also show the measured feed scheduled cutting forces.

Figures 6.6, 6.10, and 6.14 illustrate that the cutting forces can be well adjusted to reference threshold value and the machining time can be reduced significantly. The force envelopes before and after the force based feed rate scheduling were shown and compared. Production times in these examples were reduced considerably corresponding to 38.1 % to 55.3 % decrease compared to constant feed rate case.

6.3 Sinusoidal Surface:

The validation of force based feed rate scheduling strategy was firstly done with sinusoidal surface. Off-line feed rate scheduling was performed for a given set of NC code to adjust cutting forces to the determined threshold cutting forces. The details of feed rate scheduling for this geometry were given in Figures 6.2, 6.3, 6.4, 6.5, and 6.6. Reference threshold force value was set to 360 N and maximum scheduled feed rate value was set to 600 mm/min.

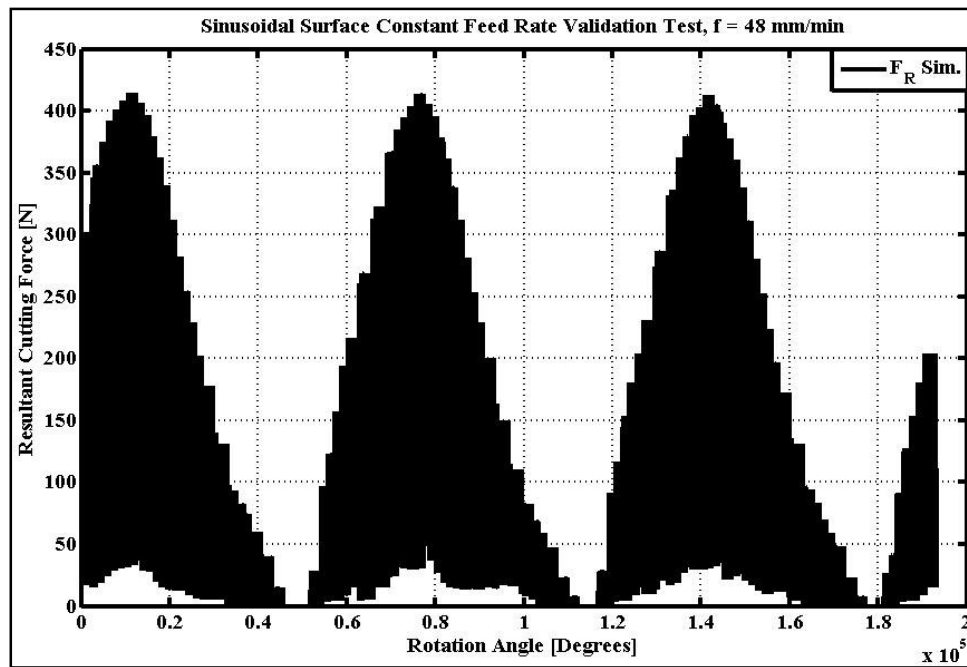


Figure 6.2: Constant feed rate resultant cutting force for the sinusoidal surface.

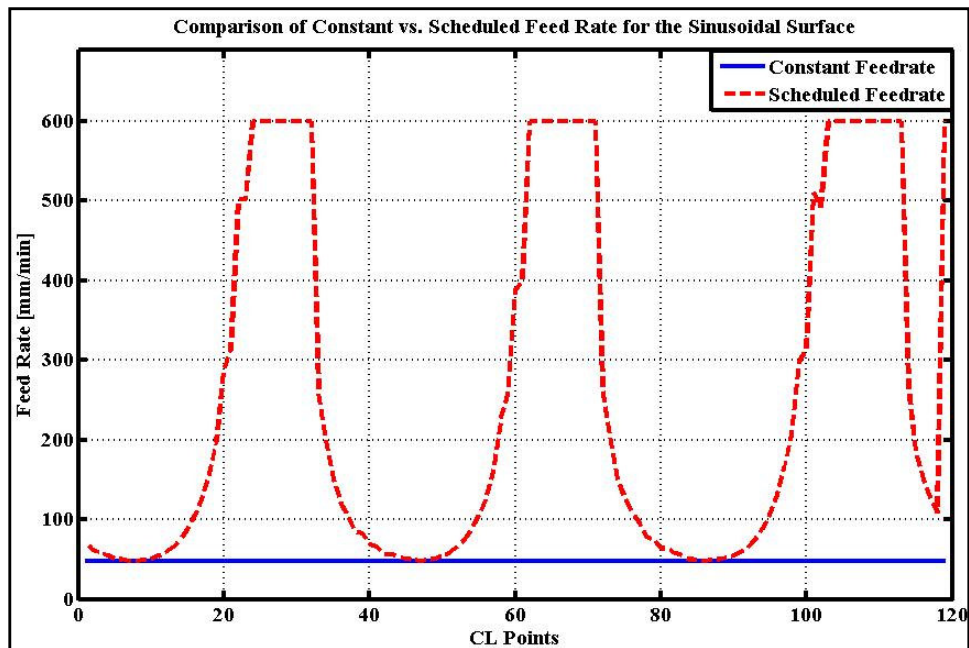


Figure 6.3: Comparison of scheduled feed rate values vs. constant feed rate.

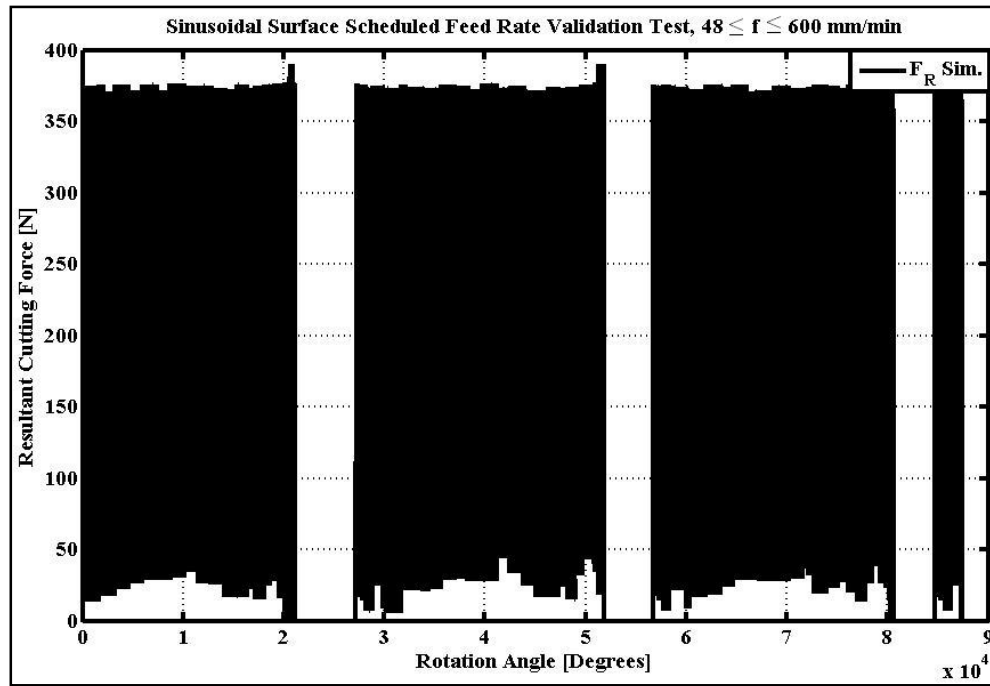


Figure 6.4: Simulated feed scheduled resultant cutting force for the sinusoidal surface.

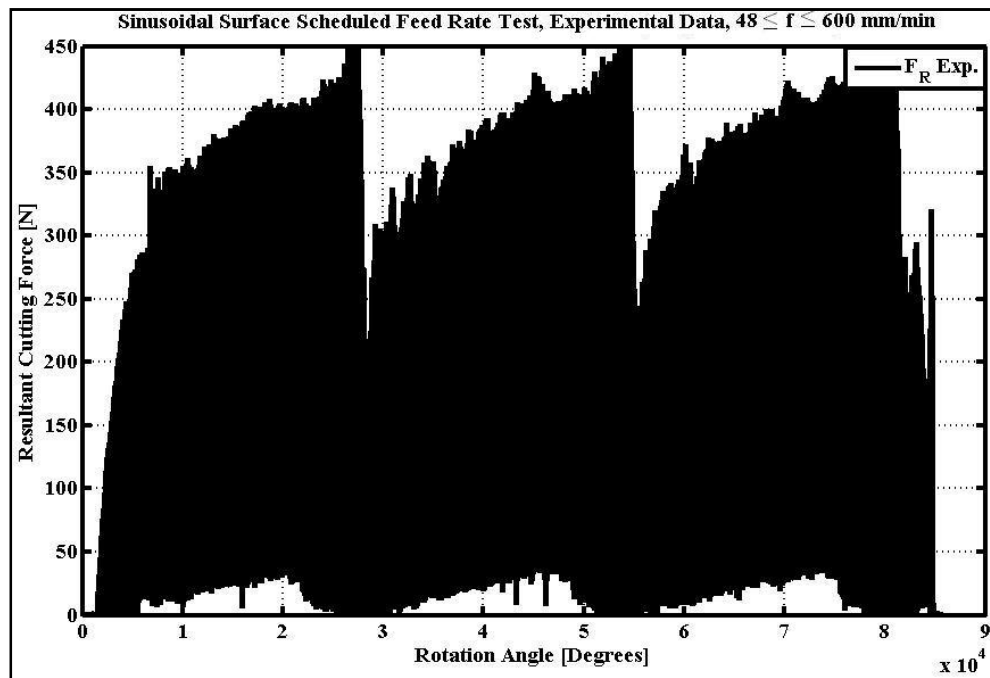


Figure 6.5: Experimental feed scheduled resultant cutting force for the sinusoidal surface.

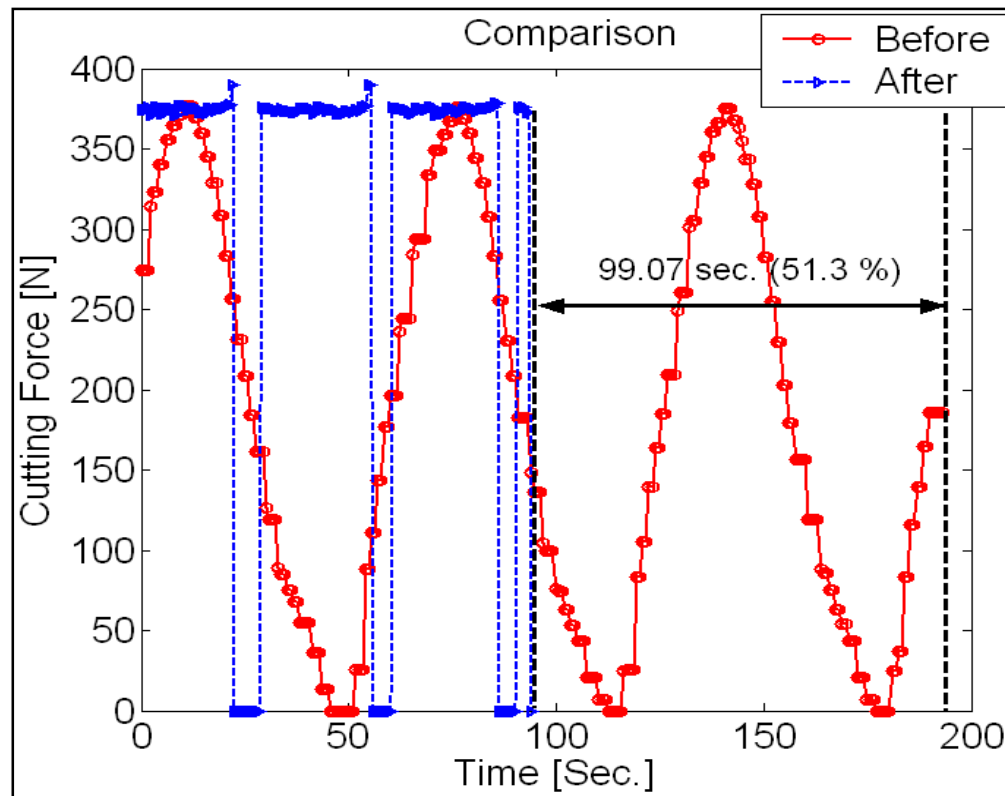


Figure 6.6: Comparison of cycle times of the sinusoidal surface.

6.4 Sine – Cosine Surface:

The validation of force based feed rate scheduling was secondly done with sine – cosine surface. Off-line feed rate scheduling was performed for a given set of NC code to adjust cutting forces to the determined threshold cutting forces. The details of feed rate scheduling for this geometry were given in Figures 6.7, 6.8, 6.9, 6.10 and 6.11. Reference threshold force value was set to 250 N and maximum scheduled feed rate value was set to 150 mm/min.

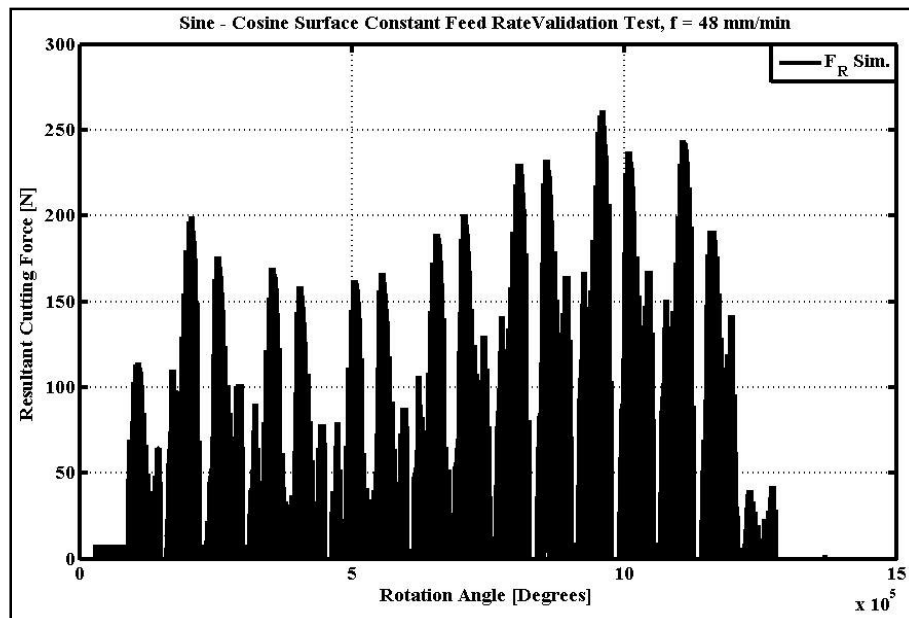


Figure 6.7: Constant feed rate resultant cutting force for sine – cosine surface.

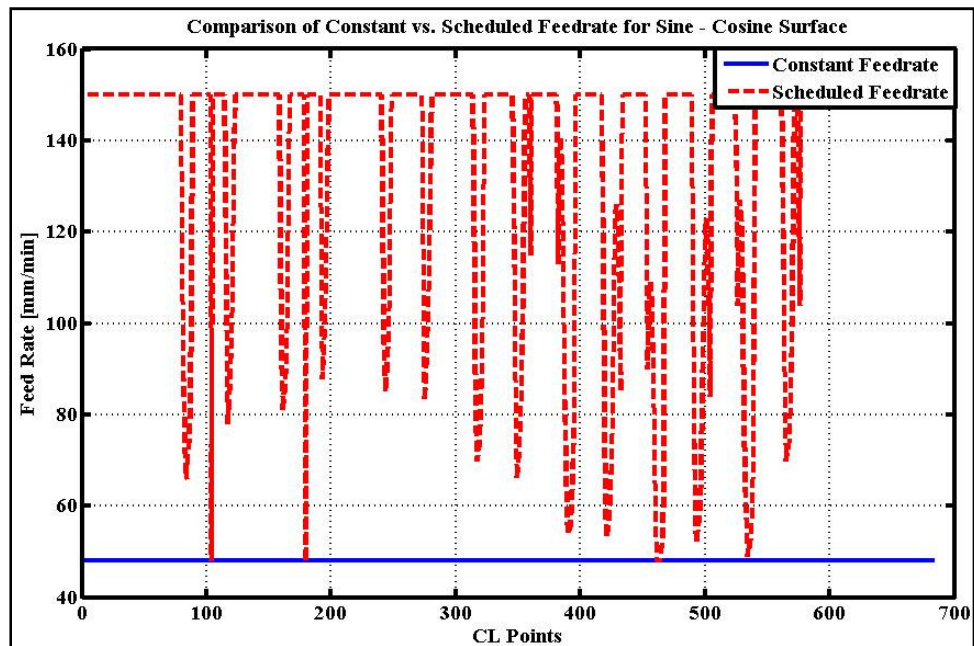


Figure 6.8: Comparison of scheduled feed rate values vs. constant feed rate for sine – cosine surface.

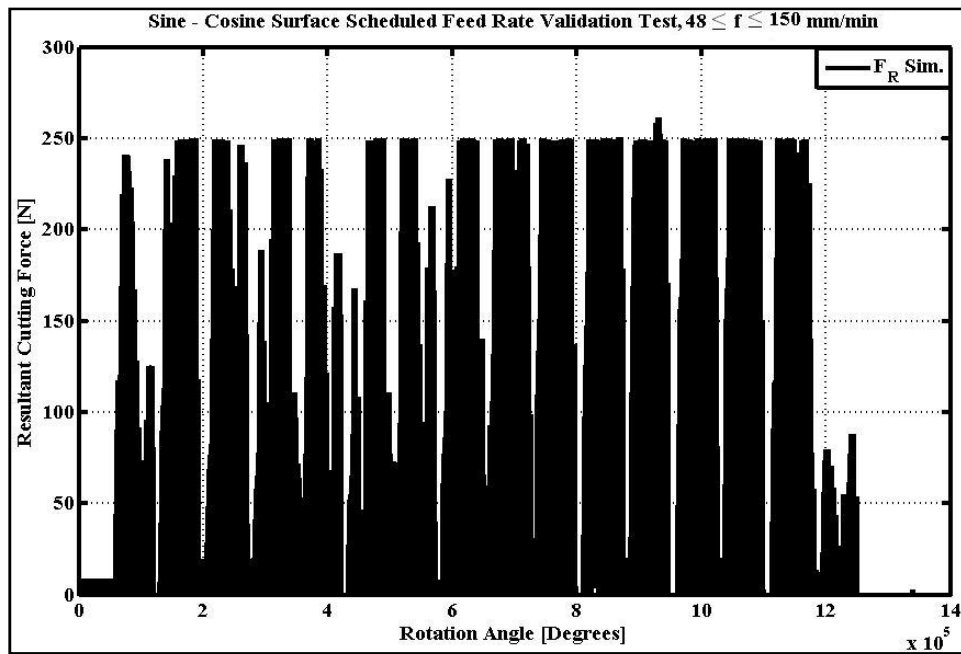


Figure 6.9: Simulated feed scheduled resultant cutting force for the sine – cosine surface.

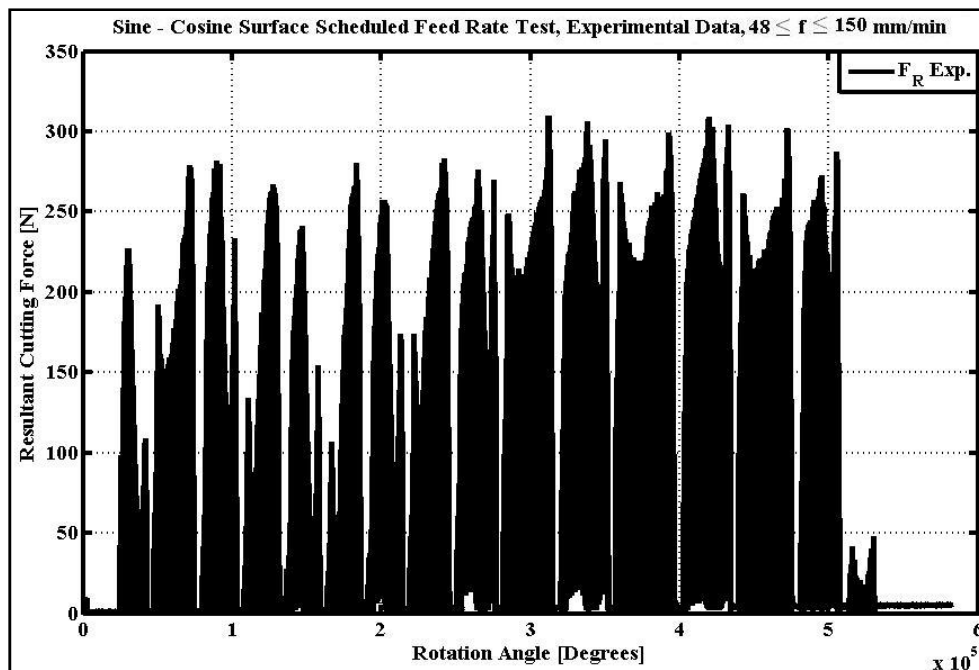


Figure 6.10: Experimental feed scheduled resultant cutting force for the sine – cosine surface.

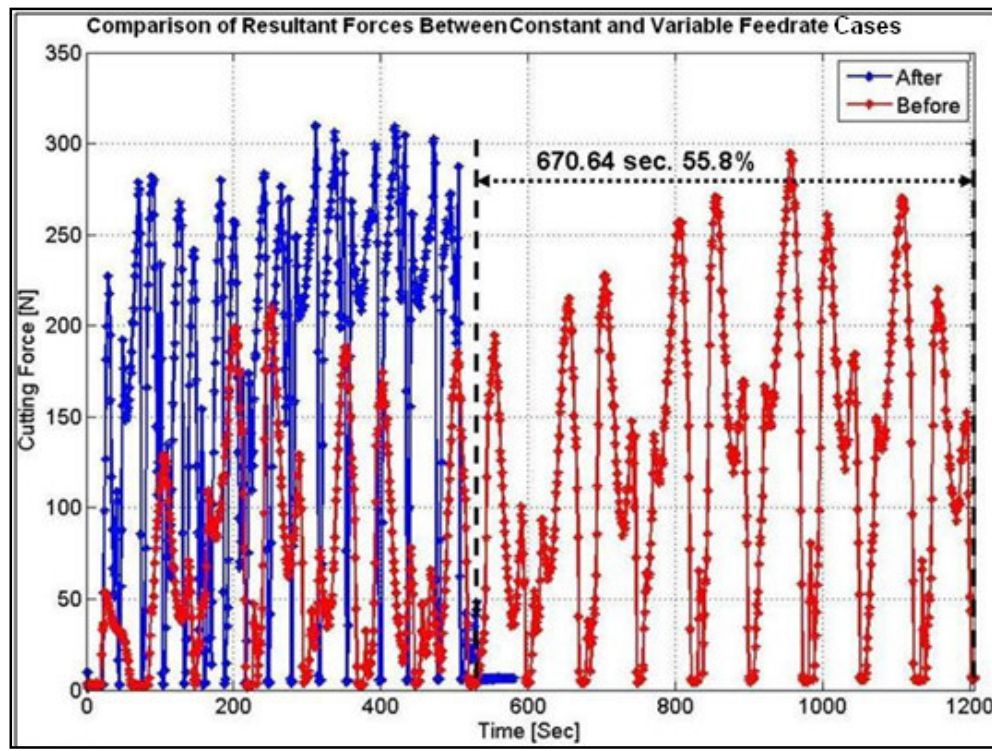


Figure 6.11: Comparison of cycle times of the sine – cosine surface.

6.5 Ataturk Portrait:

The validation of force based feed rate scheduling was secondly done with sine – cosine surface. Off-line feed rate scheduling was performed for a given set of NC code to adjust cutting forces to the determined threshold cutting forces. The details of feed rate scheduling for this geometry were given in Figures 12, 13, 14, 15, and 16. Reference threshold force value was set to 250 N and maximum scheduled feed rate value was set to 150 mm/min.

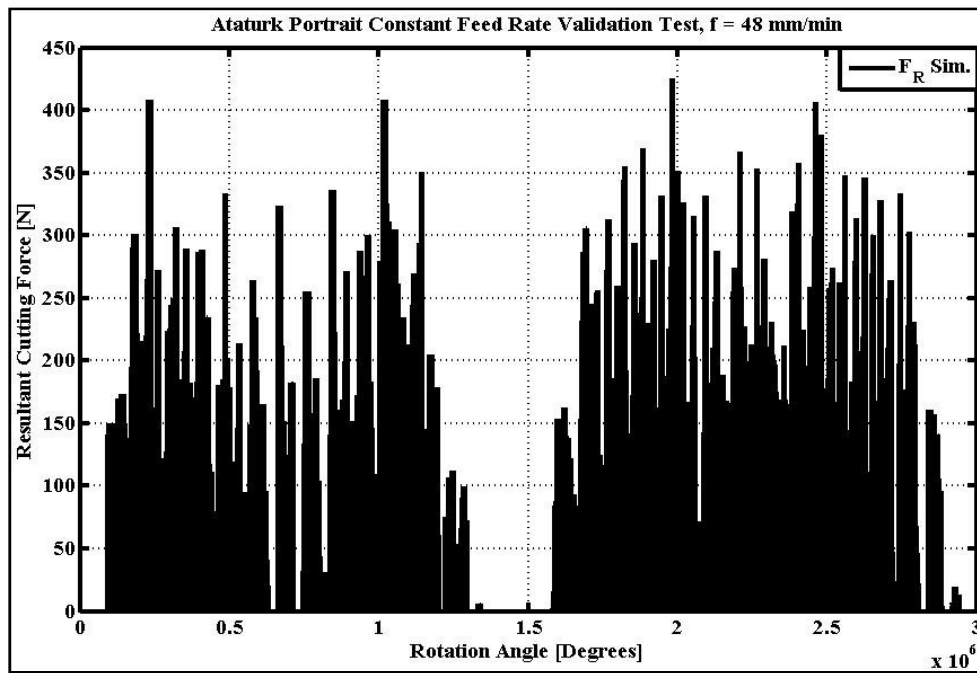


Figure 6.12: Constant feed rate resultant cutting force for Ataturk portrait.

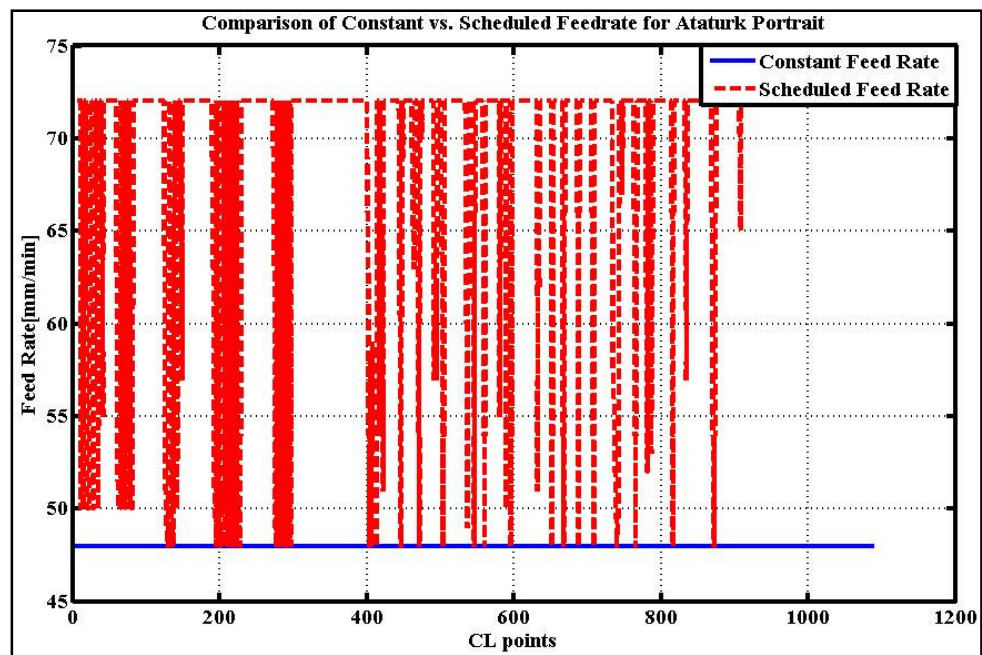


Figure 6.13: Comparison of scheduled feed rate values vs. constant feed rate for Ataturk portrait.

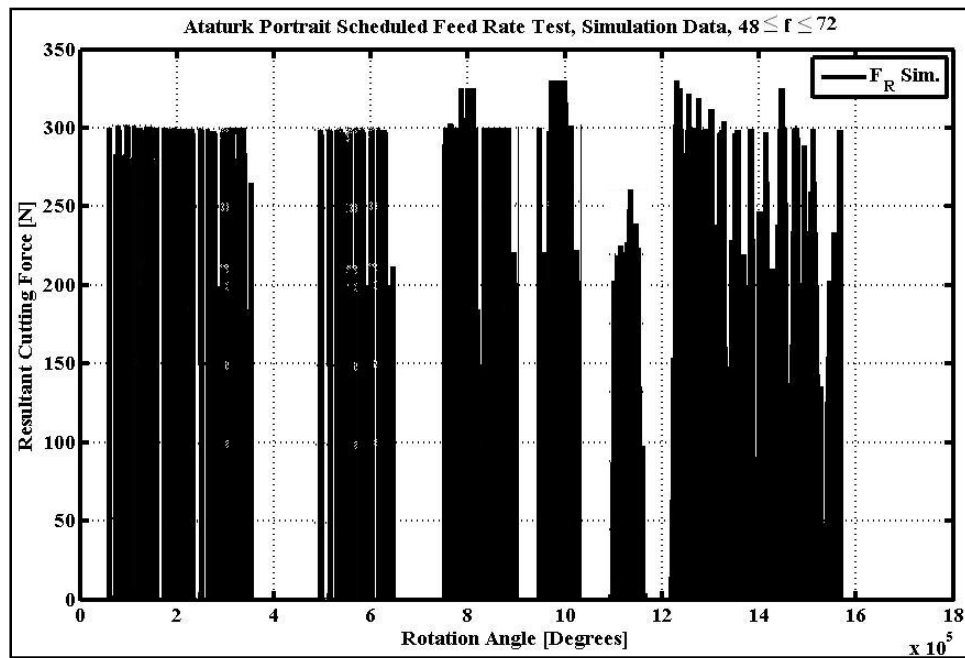


Figure 6.14: Simulated feed scheduled resultant cutting force for Ataturk portrait.

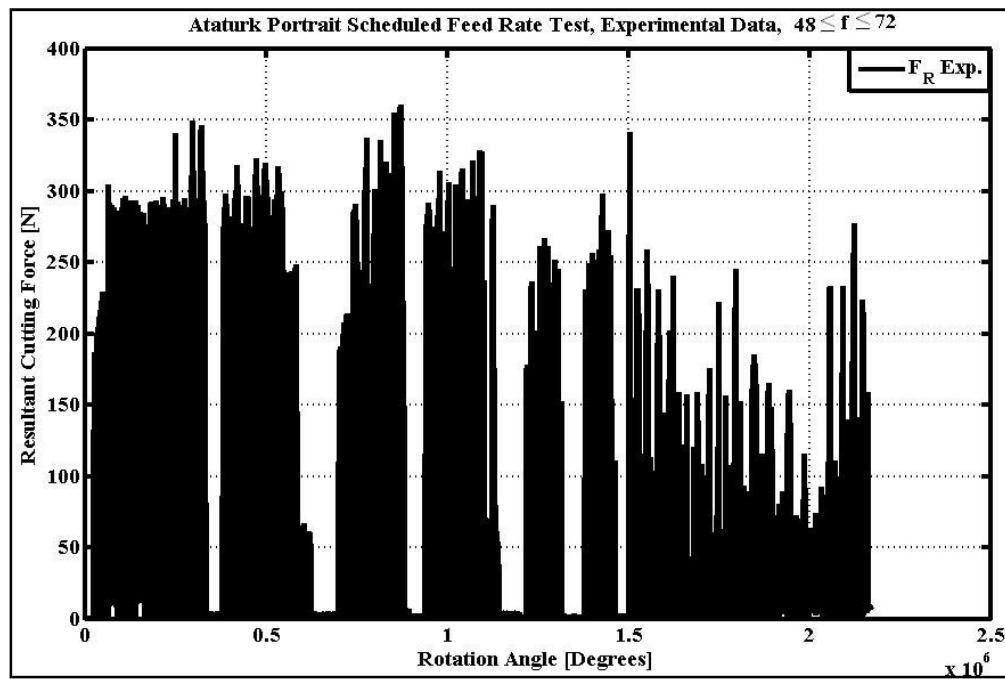


Figure 6.15: Experimental feed scheduled resultant cutting force for the Ataturk portrait.

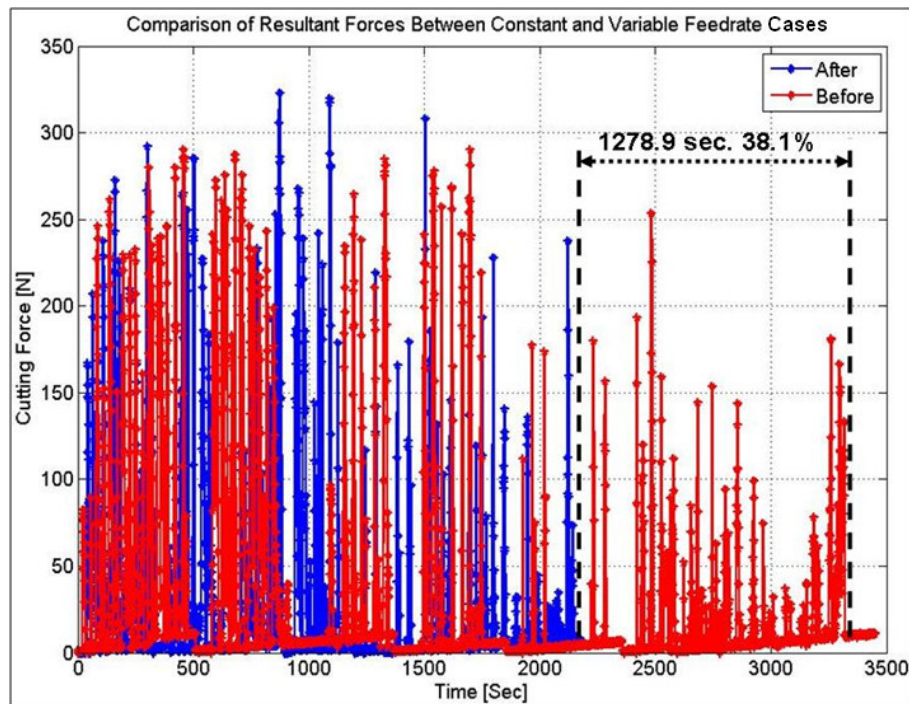


Figure 6.16: Comparison of cycle times of the Ataturk portrait.

6.6 Conclusions:

The tool has been moved through both convex and concave path in the x-y plane in all parts given in Sections 6.3, 6.4, and 6.5. Measured forces, force patterns and simulations for these parts showed very good agreement. Feed rate scheduling based on the mechanistic cutting force model was performed in three different free-form surfaces.

After validation experiments it can be concluded that cycle times in free-form surfaces can be decreased significantly as shown in Figure 6.6, Figure 6.11, and Figure 6.16. Cycle times before and after the feed rate scheduling was also given for all workpieces in Table 6.1. This decrease could be further improved by setting a larger reference value; however, this can cause excessive cutting forces, deflection and surface errors.

The only disadvantage of the feed rate scheduling strategy was the tooth marks on the machined workpiece surface, due to the high feed rate values. This may create some problems during finish milling. However, in the rough milling case, this problem can be tolerated. In this study, all parts were also machined with rough milling method. The purpose of roughing is to remove machining volume, leaving a relatively small offset for finishing operations.

Table 6-1: Cycle times before and after feed rate scheduling.

	Before Feed Rate Scheduling	After Feed Rate Scheduling		% Decrease in Cycle Time
Free – form Surface	Original Cycle time	Simulated Cycle time	Measured Cycle time	
Sinusoidal Surface	1543.8 sec.	703.2 sec.	688.0 sec.	% 51.3
Sine – Cosine Surface	1189.6 sec.	669.9 sec.	670.6 sec.	% 55.8
Ataturk Portrait	3356.7 sec.	1278.4 sec.	1278.9 sec.	% 38.1

Chapter 7

TOOL PATH COMPARISON AND TOOL DEFLECTIONS

7.1 Introduction:

Complex free-form surfaces, nowadays, are widely used in industry due to the advancements in CAD and CAM technology. There are several reasons for the popularity of free-form surfaces in industry. For example, free-form surfaces provide more efficient, ergonomic, and aesthetical designs for new products. As the demand for free-form surfaces in industry increases, CAD/CAM software companies develop different tool path strategies for machining of complex sculptured surfaces. Users can now use concentric or radial lines etc. instead of conventional zigzag cut. However, since there are different tool paths available to carry out the same process, a question arises that which tool path strategy is the best choice for a specific free-form surface. As it can be predicted, each tool path strategy offers different cutting time, cutting force magnitude and surface quality.

In the machining of free-form surfaces, ball-end milling is a versatile process and it is used in both rough and finish machining. Due to the complexity of ball-end milling, it is difficult to simulate the cutting forces occurred in the process. Moreover, precise prediction of surface finish and deviations from the CAD data is another complex process, because dynamic and static forces during machining make the prediction process difficult. This chapter focuses on evaluating different tool path strategies in terms of cutting forces, cutting time, and geometrical surface finish.

In this chapter, four different tool path strategies (0° zigzag, 45° zigzag, concentric arcs, and radial lines) were compared in terms of cycle time, cutting forces, and surface finish. Simulations and validations were performed and detailed results were presented.

7.2 Cutting Force Analysis:

Ball-end milling is an essential process in machining of complex sculptured surfaces. Therefore understanding the mechanics of this process is important for increasing the productivity and quality of the machining. Precise simulation of cutting forces in machining has many advantages; with cutting force predictions, it is possible to estimate the tool deflections thus surface form errors. Moreover, as presented in Chapter 6, by applying feed rate scheduling strategies, forces at each CL point can be predicted and feed rate can be modified in order to decrease the cycle time.

In this study, the same mechanistic cutting force model was used. All experiments were performed on Mazak FJV-200 UHS Vertical Machining Center using Al7039 workpiece material with dimensions of 40x40x14 mm. tool used in experiments was a Sandvik two fluted ball-end mill with a diameter of 12 mm, 30° nominal helix angle and 37 mm projection length. Kistler three-component dynamometer (Model 9257B) was used to measure the cutting forces. All experiments were performed with a spindle speed of 600 rpm and 48 mm/min feed rate. As stated before, sine – cosine surface was machined with 4 different tool paths, 0° zigzag, 45° zigzag, concentric arcs, and radial lines. Details of the sine – cosine surface are illustrated in Figure 5.10.

7.2.1 0° Zigzag Lines Tool Path:

Tool path of the 0° zigzag lines is shown in Figure 7.1. Simulation output of 0° zigzag lines tool path is presented in Figure 7.2. Figure 7.3 shows the experimental and simulation data for 0° zigzag lines tool path strategy. For simplicity, only peak envelopes were plotted. Detailed validation of the force model is presented in Chapter 5.

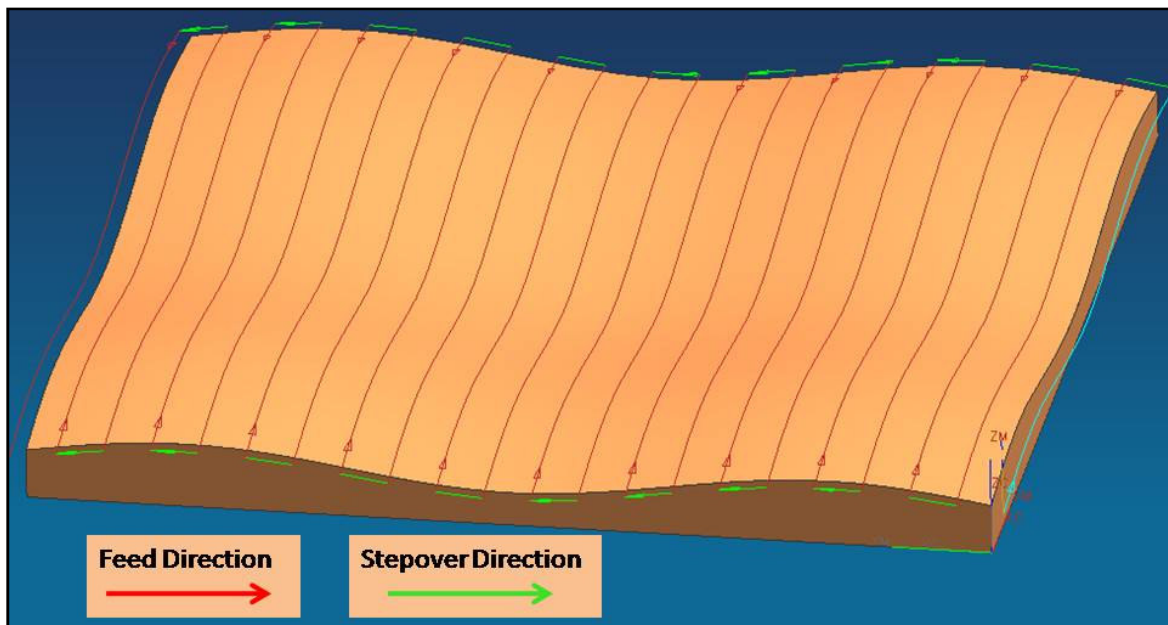


Figure 7.1: Illustration of 0° zigzag lines tool path on the sine – cosine surface.

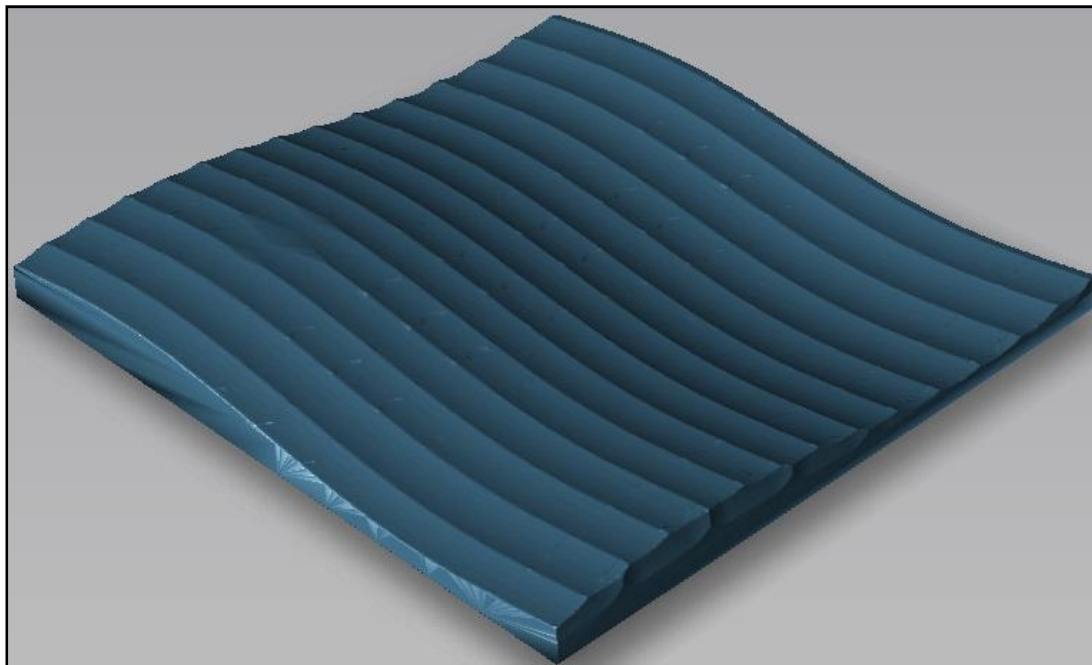


Figure 7.2: Simulation output of the 0° zigzag lines tool path for the sine – cosine surface.

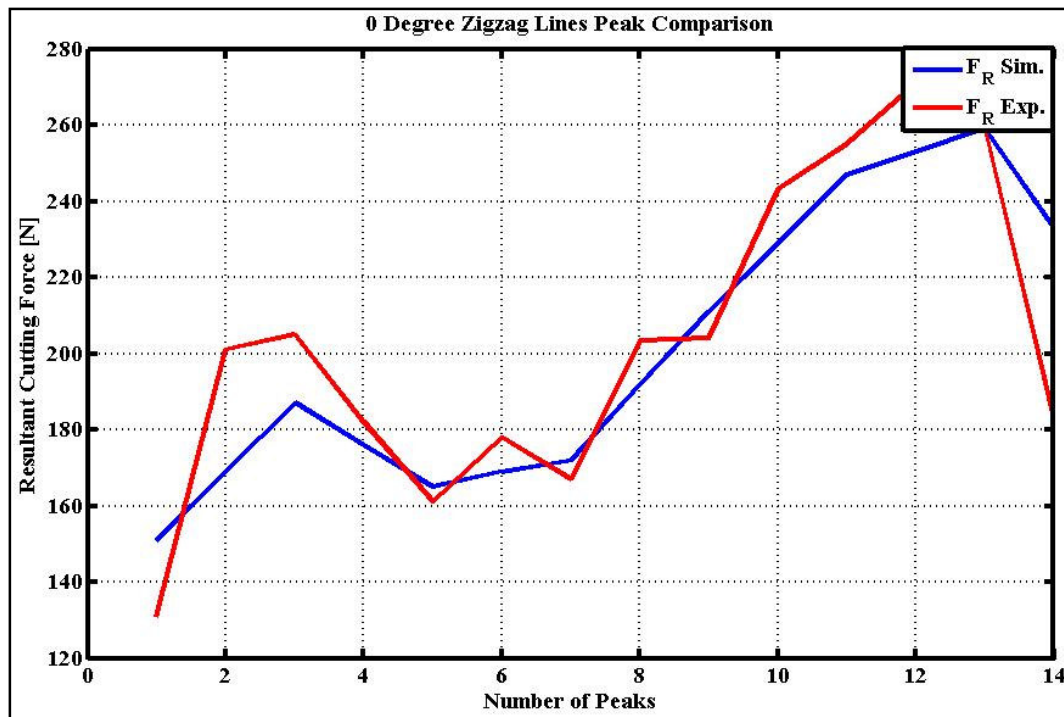


Figure 7.3: 0° zigzag lines tool path cutting force envelopes of simulation and experimental resultant cutting force components.

7.2.2 45° Zigzag Lines Tool Path:

Tool path of the 45° zigzag lines is shown in Figure 7.4. Simulation output of 45° zigzag lines tool path is presented in Figure 7.5. Figure 7.6 shows the experimental and simulation data for 45° zigzag lines tool path strategy.

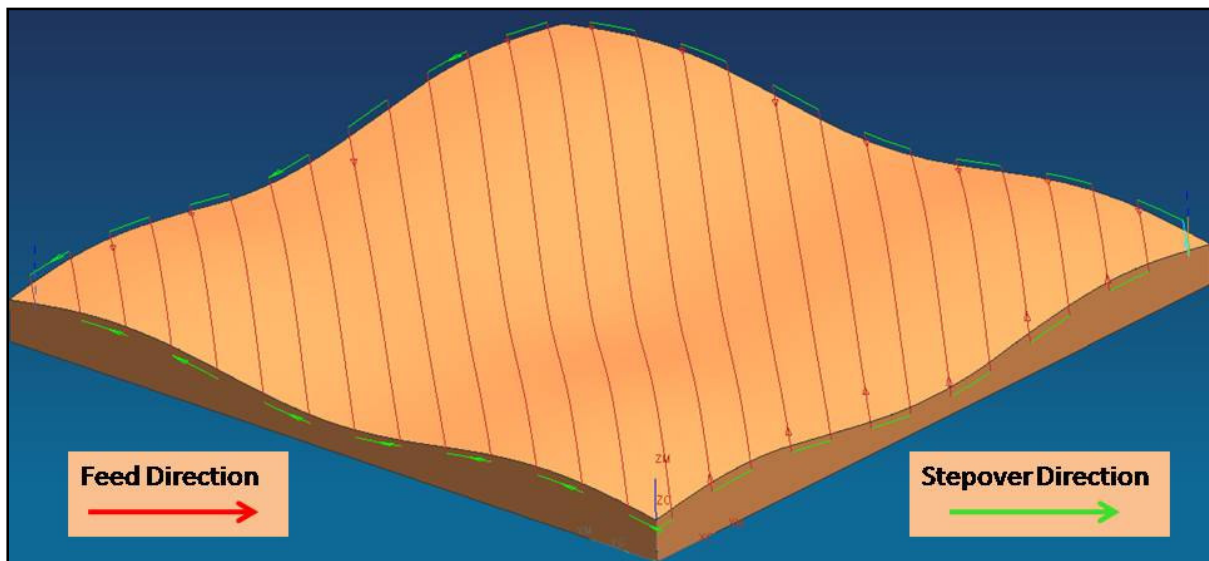


Figure 7.4: Illustration of 45° zigzag lines tool path on the sine – cosine surface.

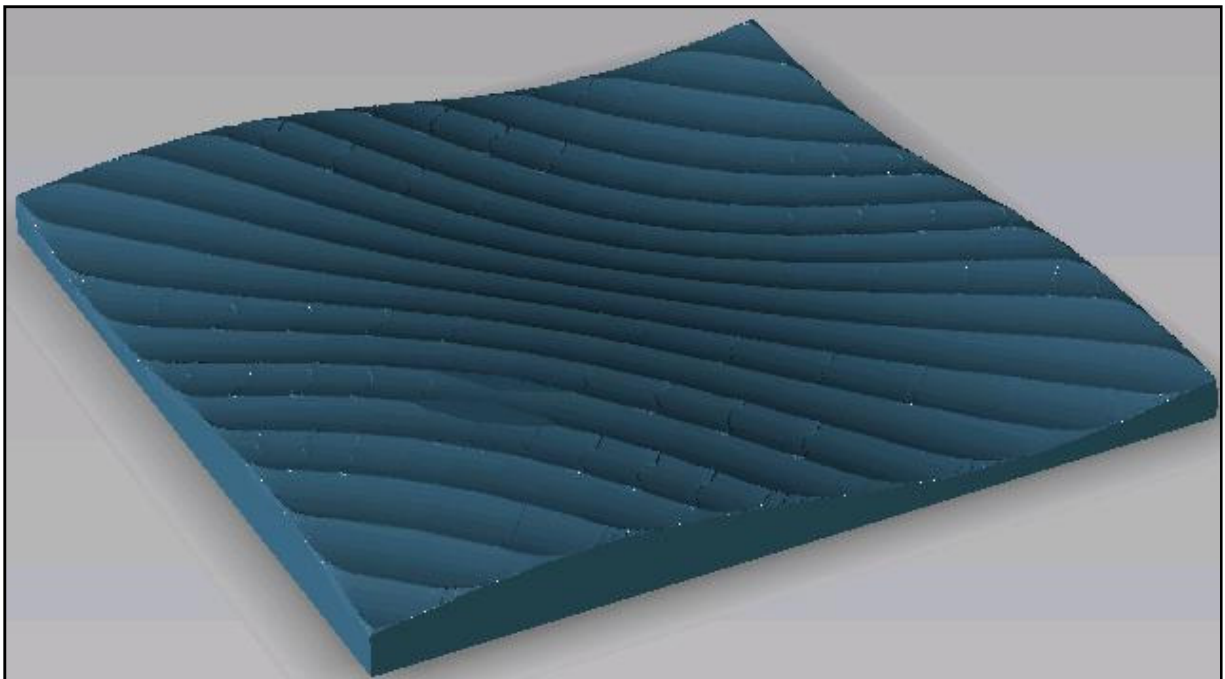


Figure 7.5: Simulation output of the 45° zigzag lines tool path for the sine – cosine surface.

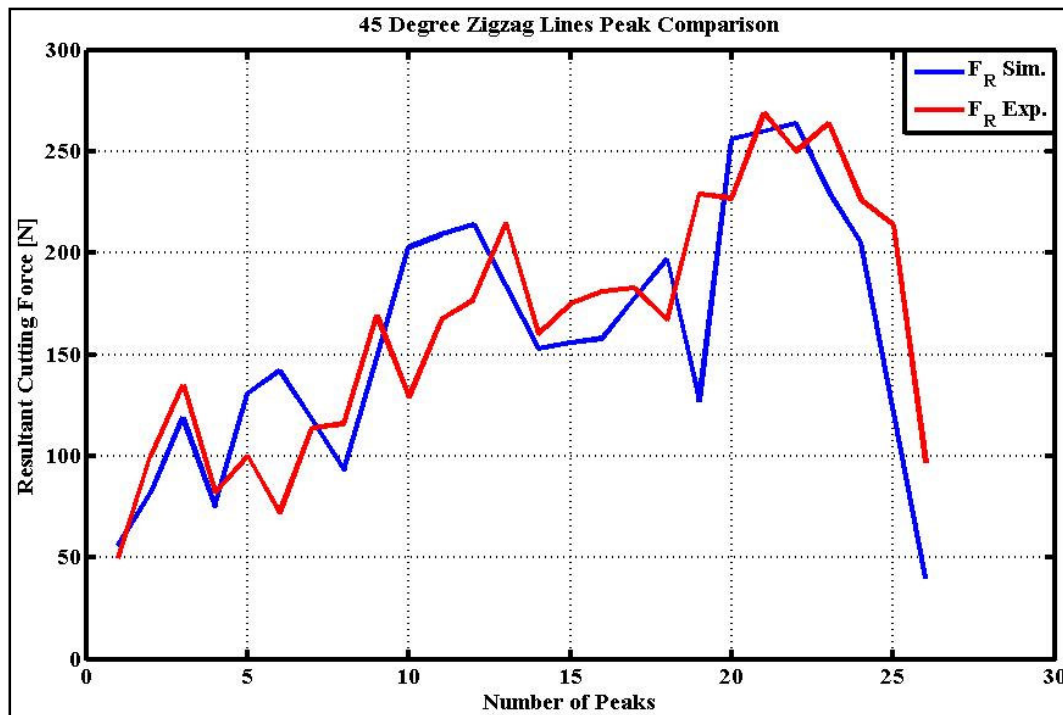


Figure 7.6: 45° zigzag lines tool path cutting force envelopes of simulation and experimental resultant cutting force components.

7.2.3 Concentric Arcs Tool Path:

Tool path of the concentric arcs is shown in Figure 7.7. Simulation output of concentric arcs tool path is presented in Figure 7.8. Figure 7.9 shows the experimental and simulation data for concentric arcs tool path strategy.

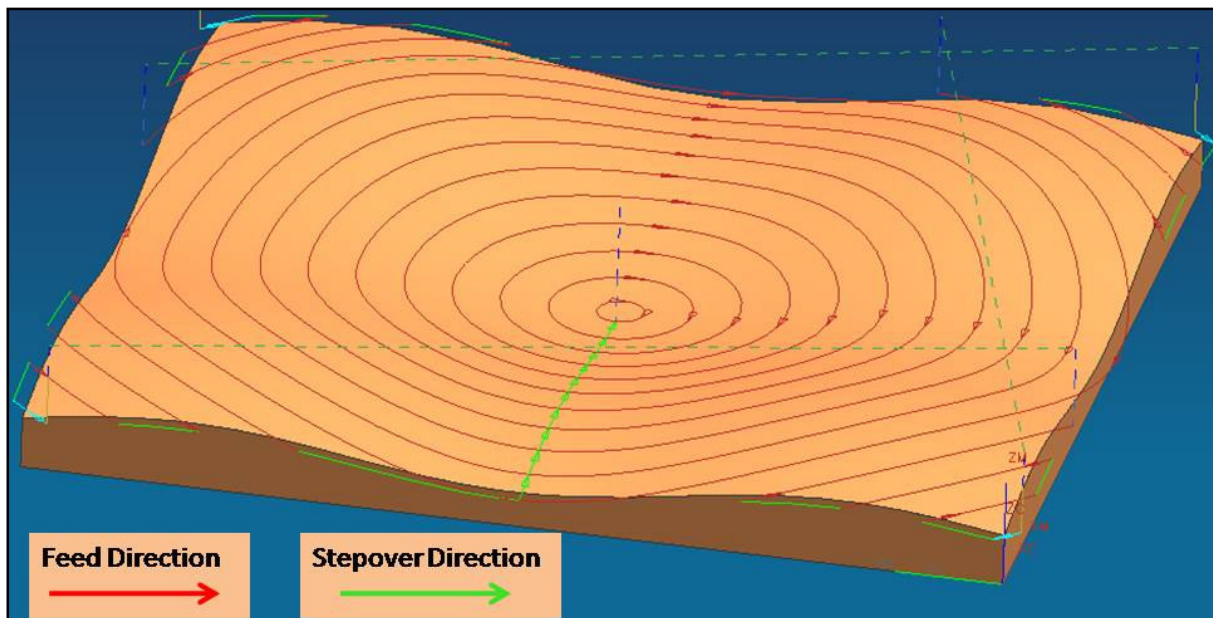


Figure 7.7: Illustration of concentric arcs tool path on the sine – cosine surface.

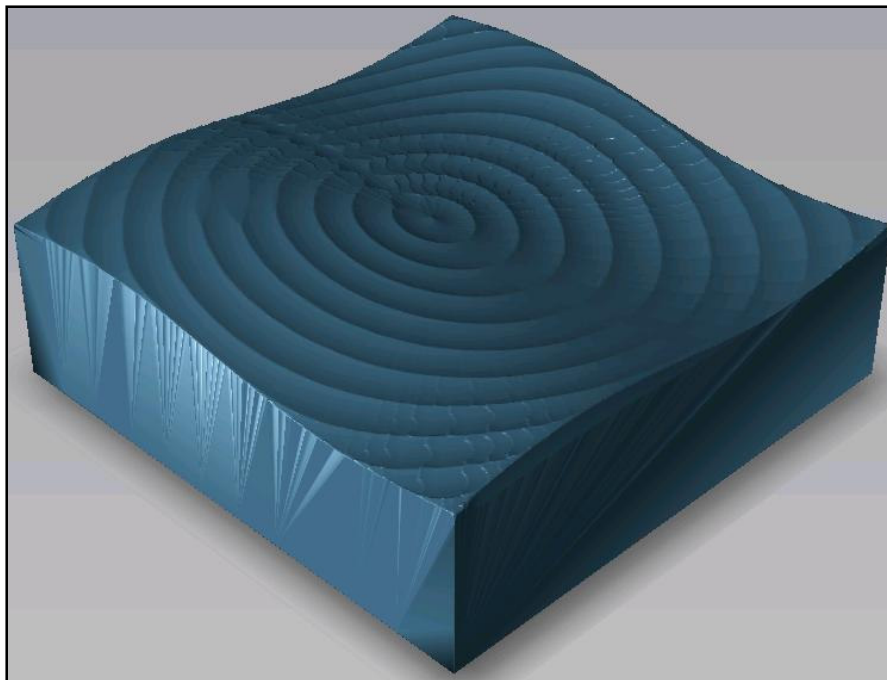


Figure 7.8: Simulation output of the concentric arcs tool path for the sine – cosine surface.

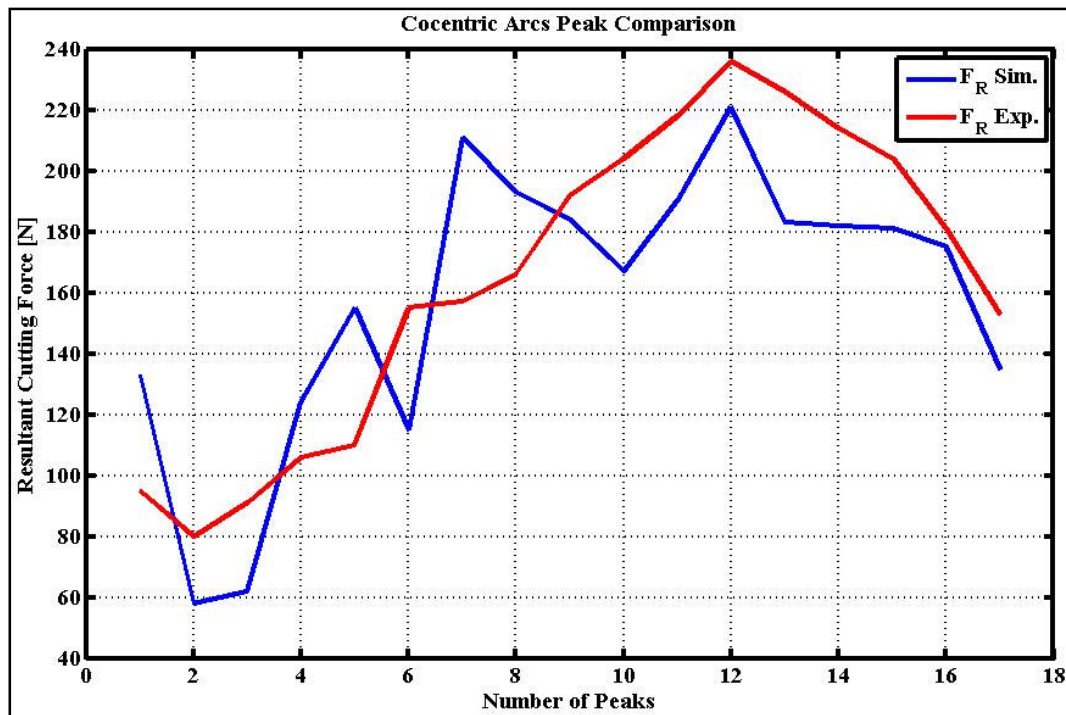


Figure 7.9: Concentric arcs tool path cutting force envelopes of simulation and experimental resultant cutting force components.

7.2.4 Radial Lines Tool Path:

Tool path of the radial lines is shown in Figure 7.10. Simulation output of radial lines tool path is presented in Figure 7.11. Figure 7.12 shows the experimental and simulation data for radial lines tool path strategy. Results of the cutting force analysis of different tool paths are summarized in Figure 7.13.

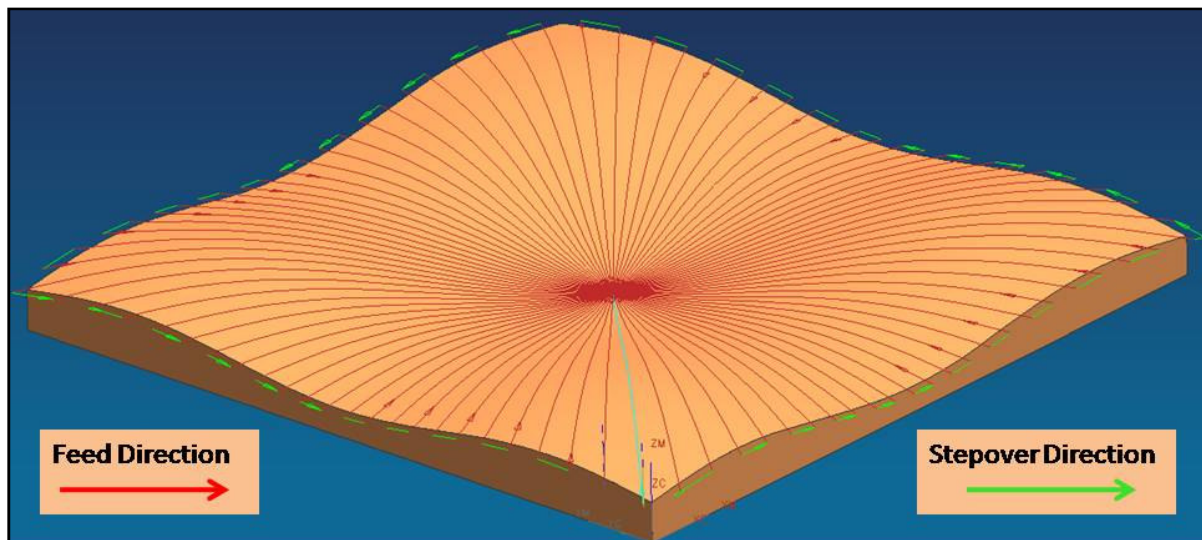


Figure 7.10: Illustration of radial lines tool path on the sine – cosine surface.

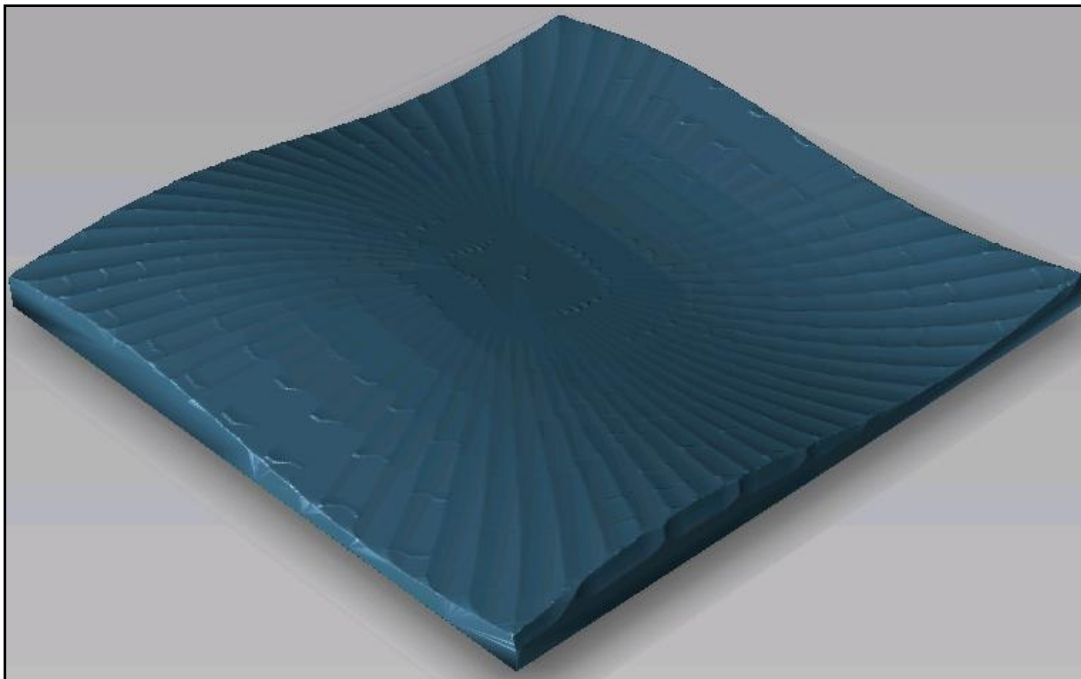


Figure 7.11: Simulation output of the radial lines tool path for the sine – cosine surface.

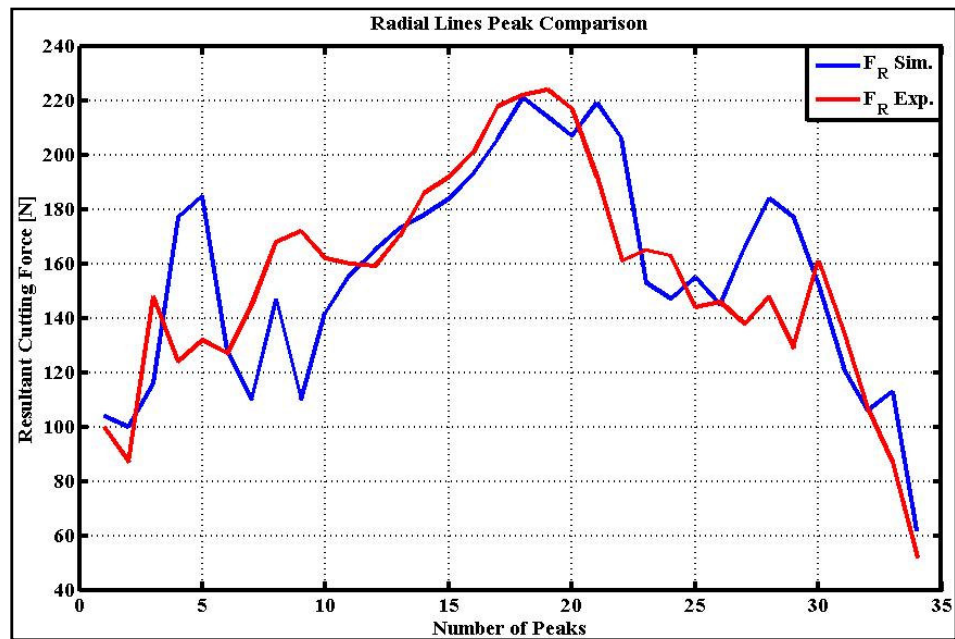


Figure 7.12: Radial lines tool path cutting force envelopes of simulation and experimental resultant cutting force components.

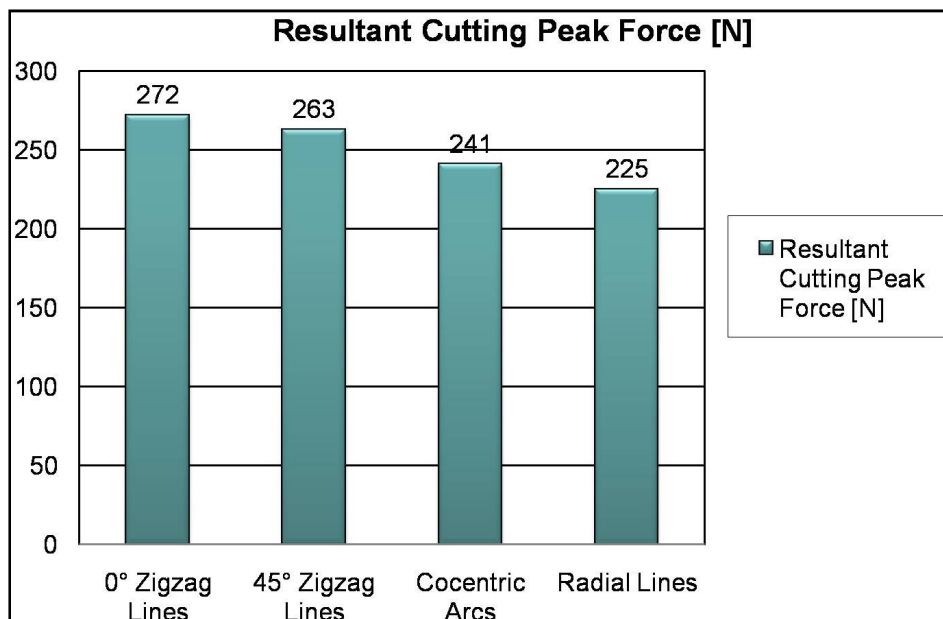


Figure 7.13: Comparison of different tool paths in terms of maximum resultant cutting force.

7.3 Cycle Time Analysis:

Tool path strategy has a significant effect on the cycle time in free-form machining. Different tool paths have different lengths, although they remove the same amount of material. Removing same amount of material in a shorter time increase the production by decreasing the cycle time, however, also increases the cutting forces. Figure 7.14 illustrates the cycle time of tool path strategies.

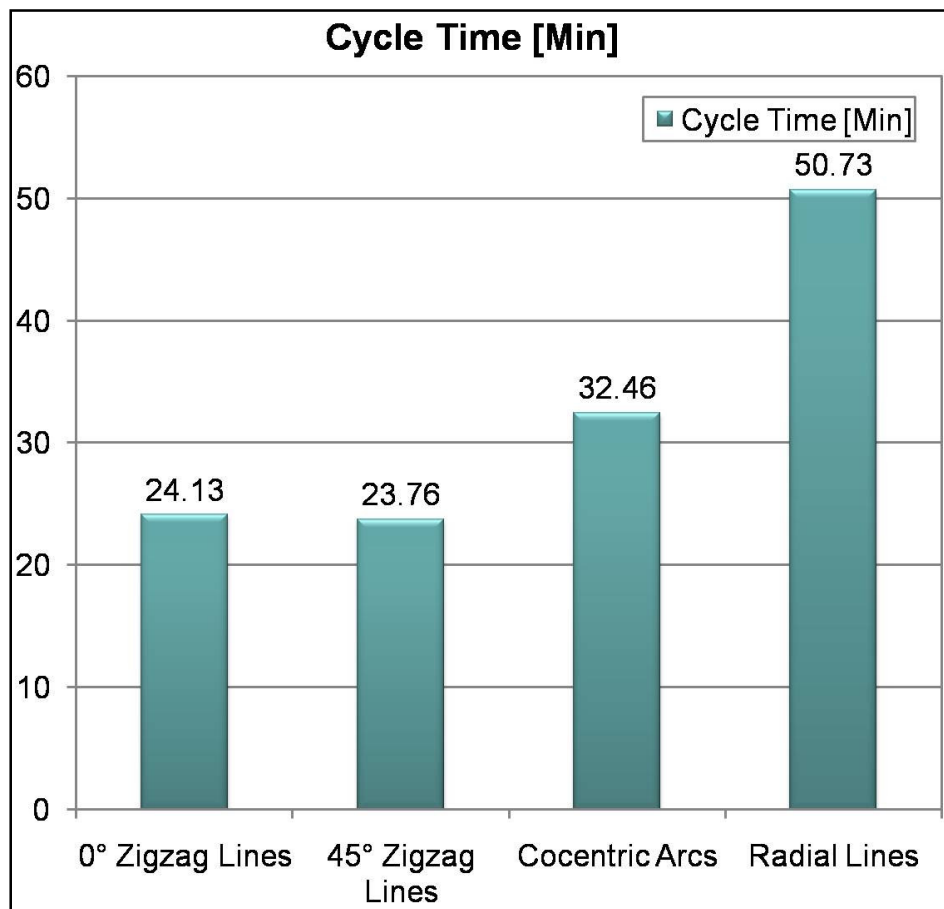


Figure 7.14: Cycle times of different tool path strategies.

7.4 Surface Finish Analysis:

Surface finish is another important criterion in complex sculptured machining. Sculptured surface machining is used in die and mold industry widely, thus any form errors occurred in machining influences the parts manufactured with these molds. In this section, surface finish predictions and validations of tool path strategies will be presented.

7.4.1 Surface Finish Simulations:

7.4.1.1 Tool Path Simulation Analysis

Surface finish simulations were performed in two steps. In the first step, both 3D solid model of the tool path simulation output obtained from the solid based engagement model and the desired CAD data were converted into stereolithography (STL) file which approximates the surfaces of CAD data with triangles. Then using a developed algorithm, these triangles were converted into 3D point cloud with a controllable resolution. Finally, subtracting the desired CAD data from the engagement output, it is possible to obtain the surface finish and error produced by CAM software.

In order to create a point grid cloud from STL data, first of all, a minimum bounding box created for the solid model. Bounding box was divided into controllable layers and for each layer, layer's cross-section vertices were found using triangle vertices and normal of the triangle plane. Next step is to create controllable parallel vectors which are in Y direction and bounded by the minimum and the maximum X points that form a line which is normal to the vectors. As the final step, for each Y vector, vector is intersected with line segments formed by consecutive vertices of a cross-section of the layer and the intersection points are recorded. Using these intersection points, it is possible to define the solid model as point grid cloud. Figure 7.15

illustrates STL to point grid conversion algorithm and Figure 7.17 represents the point grid cloud layer by layer. In Figure 7.16, grid distance is selected as 0.5 mm; however, calculations in study were performed with a grid distance of 0.04 mm. Figure 7.16 shows the STL data of the sine – cosine surface. It can be observed that in STL data surfaces are represented by triangles.

This algorithm only determines the location of the solid model in the point grid. In order to determine the dimensions of the form errors, number of the points at each (X, Y) coordinates along Z axis were counted and multiplied by grid distance. This algorithm applied for each tool path engagement simulation and outputs were subtracted from the desired CAD surface.

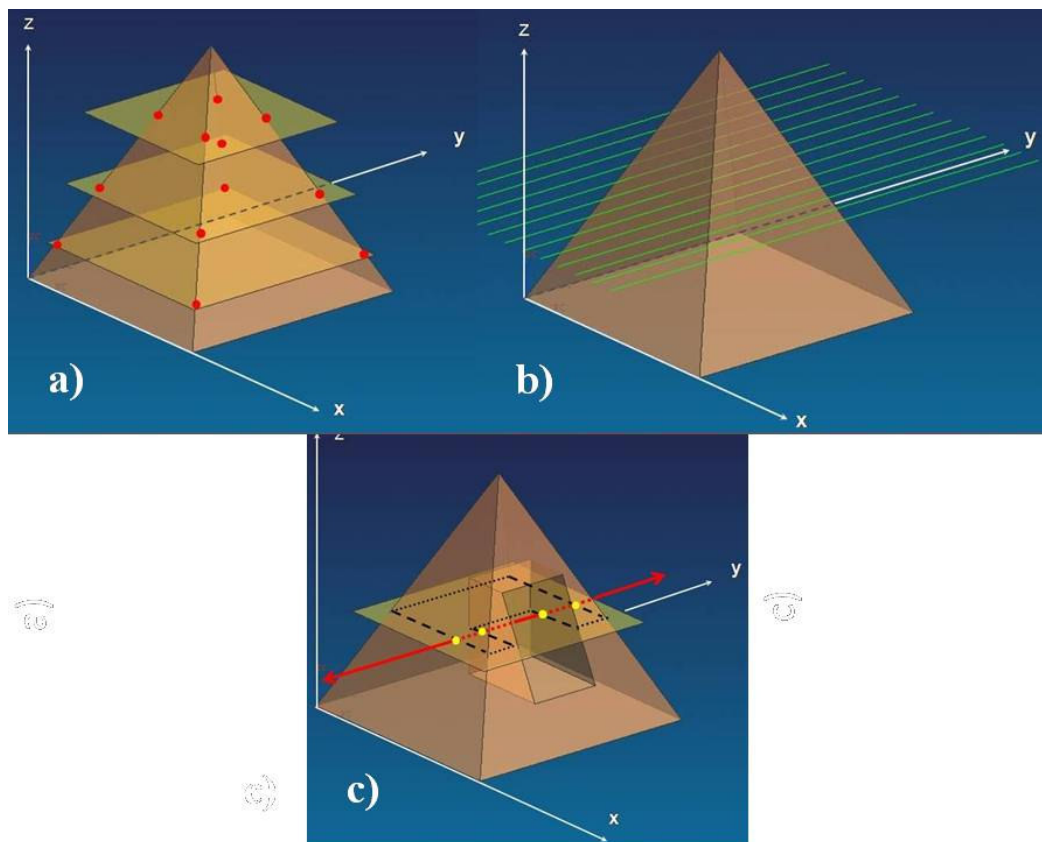


Figure 7.15: Illustration of STL to point grid cloud algorithm. a) Division of solid model into layers. b) Creation of Y vectors in each layer. c) Intersection of each vector with the layer and determination of grid points.

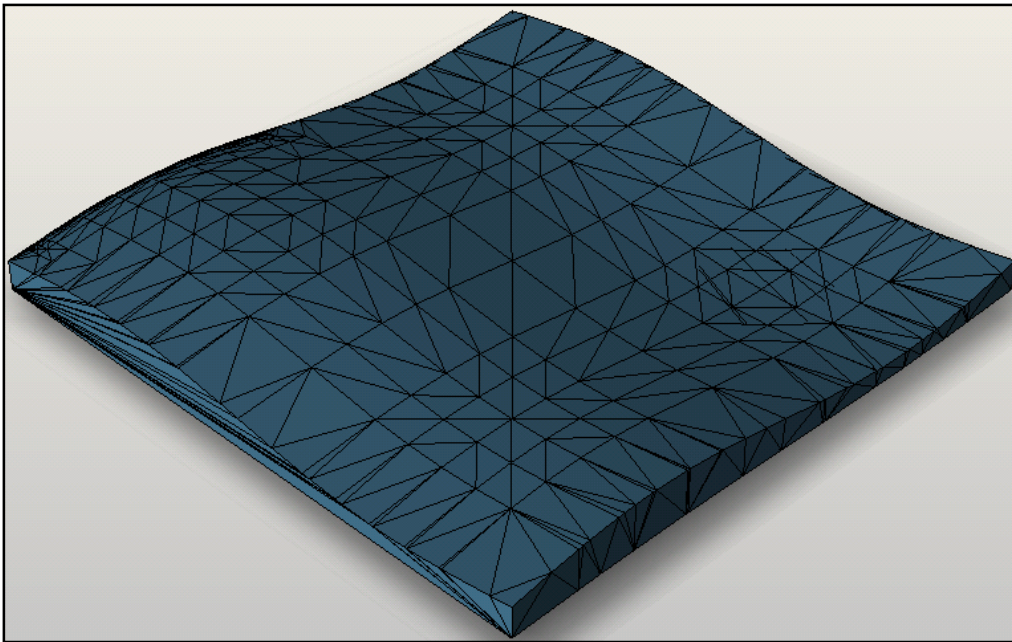


Figure 7.16: Triangulated STL data of the sine – cosine surface.

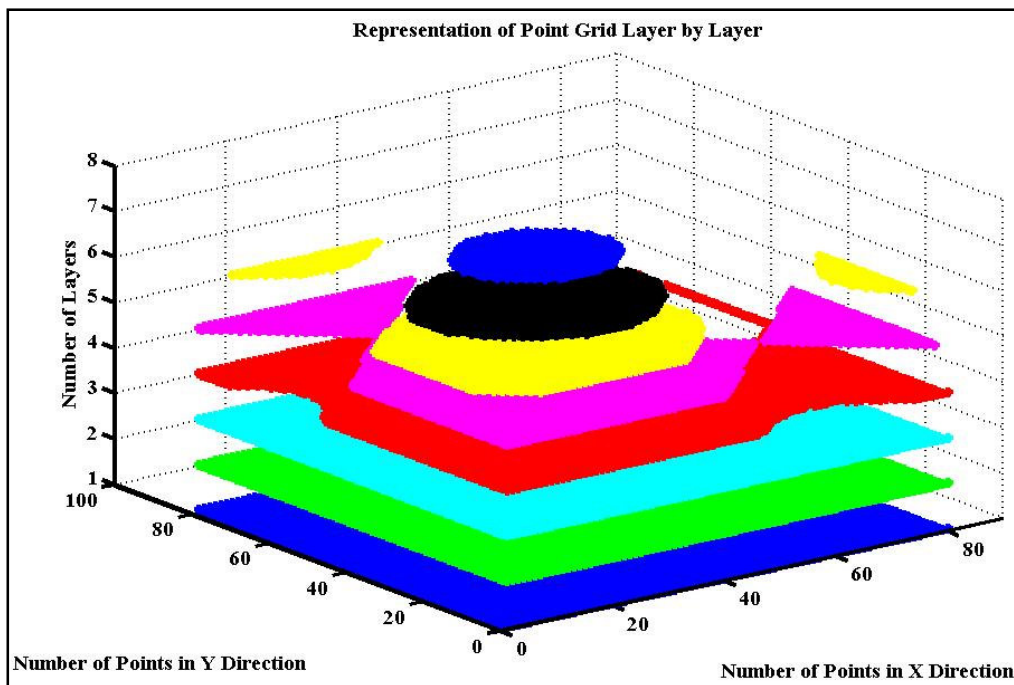


Figure 7.17: Representation of point grid cloud at each layer.

7.4.1.2 Deflection Analysis

Machining errors result from several factors, namely, tool wear thermal distortion and tool deflection of the machine tool fixture. Machine tool vibrations also play an important role in hindering productivity during machining. Excessive vibrations accelerate tool wear and chipping, cause poor surface finish, and may damage the spindle. Tool deflection is the most significant machining error.

The tool is assumed as a cantilever beam loaded with a static force. This assumption is valid when the lowest natural frequency of an elastic structure is at least 10 times higher than the frequency of the applied load. In this study, spindle speed of the tool is taken as 600 rpm which is corresponding to frequency of the cutting force is 10 cycles/second. The natural frequencies of the tool can be identified by structural dynamics tests. As it is obvious, natural frequency is one of the most important parameter for transfer function, and it can be determined experimentally. An impact hammer instrumented with a piezoelectric force transducer was used to measure the transfer function of the system. Mass of the hammer and the impact tip material attached to the impact force sensor must be selected according to the mass, rigidity, and the material of the structure being excited. The resulting vibrations are measured with displacement sensors is more common in measuring vibrations. The mass and frequency range of the accelerometers must be selected depending on their mass and target mass ratio, because they are mounted on the structure, their mass may alter the natural frequencies of the system. Complete test environment can be seen in Figure 7.18. In this study, the natural frequency of the tool in X and Y directions were measured from transfer function data. Transfer function of the tool and spindle system in Laplace domain is given as;

$$G(s) = \frac{U(s)}{F(s)} = \frac{1/m}{s^2 + 2\xi\omega_n + \omega_n^2} \quad (7.1)$$

where $U(s)$ and $F(s)$ are representing the displacement and force respectively (either in X or Y direction), m is the modal mass, ξ is the damping ratio and ω_n is the natural frequency. In CutPro, from the plots of real and imaginary parts of the frequency response function, number of modes of the system can be utilized. After finding the mode number, for each mode, the damping ratio, stiffness and natural frequency can be exactly obtained. In Figure 7.19, a sample output screen of CutPro can be seen. Experimental results for the tip of the ball end mill are;

In X direction: $\omega_{nx_1} = 989.6$ Hz and $\omega_{nx_2} = 2171.4$ Hz

In Y direction: $\omega_{ny_1} = 961.2$ Hz and $\omega_{ny_2} = 2118.9$ Hz

First natural frequencies of the system in X and Y directions indicate that 10 times rule for static loading is satisfied.

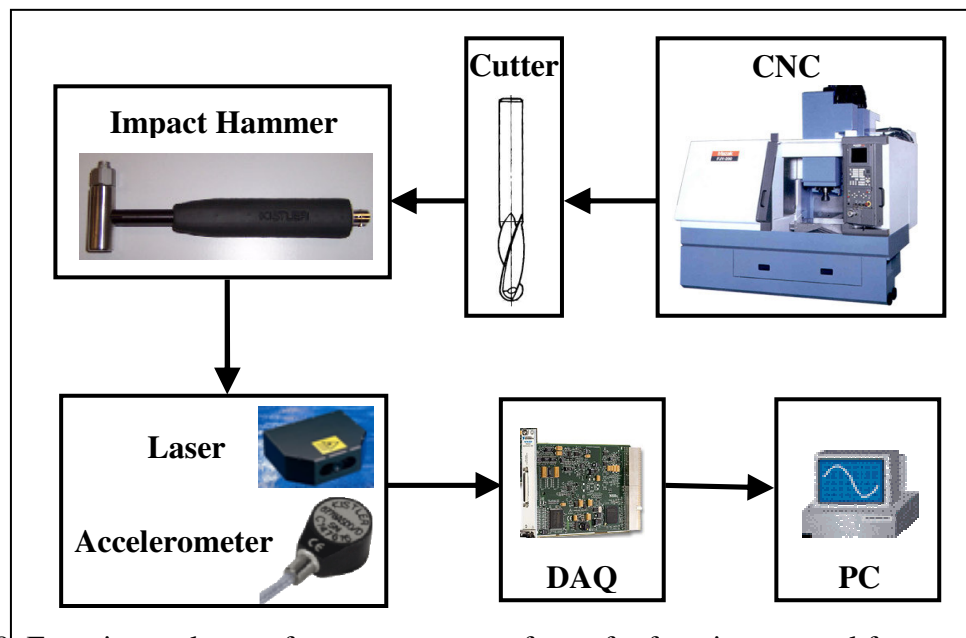


Figure 7.18: Experimental setup for measurement of transfer function, natural frequencies and stiffness.

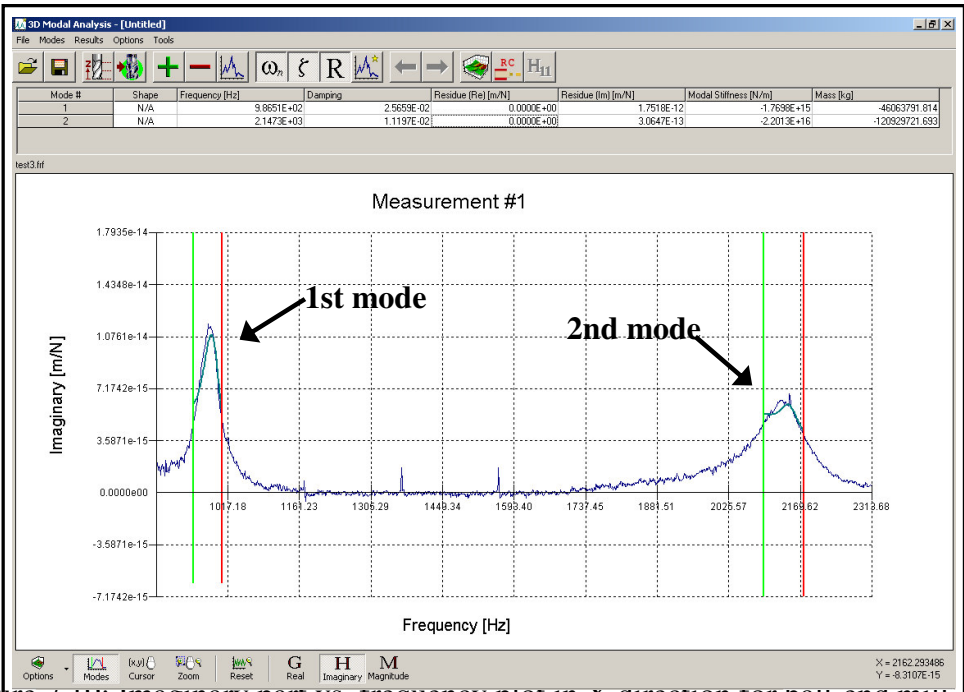


Figure 7.19: Imaginary part vs. frequency plot in X direction for ball end mill.

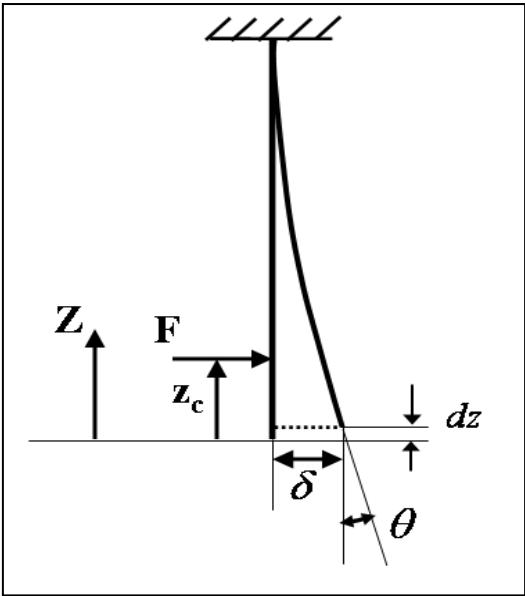


Figure 7.20: Deflection of a cantilever.

Horizontal component of the cutting force is the major reason of the tool deflection. The effect of the vertical component on the tool deflection is negligible, because the stiffness in the axial direction of the system is relatively high. It is assumed that the tool rigidly supported by the tool holder and the other end of the tool deflects due to the X and Y cutting forces. Figure 7.20 shows the simple deflection of a cantilever beam. Kline et al [37]. derived the tool bending deflection as;

$$\delta = \frac{F}{6 \times E \times I} [(z_c - z)^3 - (L - z)^3 + 3 \times (L - z)^2 \times (L - z_c)] \quad (7.2)$$

where δ is the tool deflection at point z , F is the cutting force, I is the are moment of inertia of tool, E is Young modulus, L is the overhang, z_c is the applied force center, and z is the position of deflection. These variables are also illustrated in Figure 7.21. The equation for area moment of inertia for the tool has been given by Altintas [35] as;

$$I = \frac{\pi \times d^4}{64} \quad (7.3)$$

where d is the effective diameter of the tool which can be found by scaling its outside diameter by 0.8 - 0.85 to take the effect of flutes into account. As shown in Figure 7.21, a ball-end mill consists of two parts, flute and shank. Tool is taken as a cantilever beam consisting of two step cylinders as shown in Figure 7.22. The resultant tool deflection is found by summing the individual deflections that are presented in Figure 7.23.

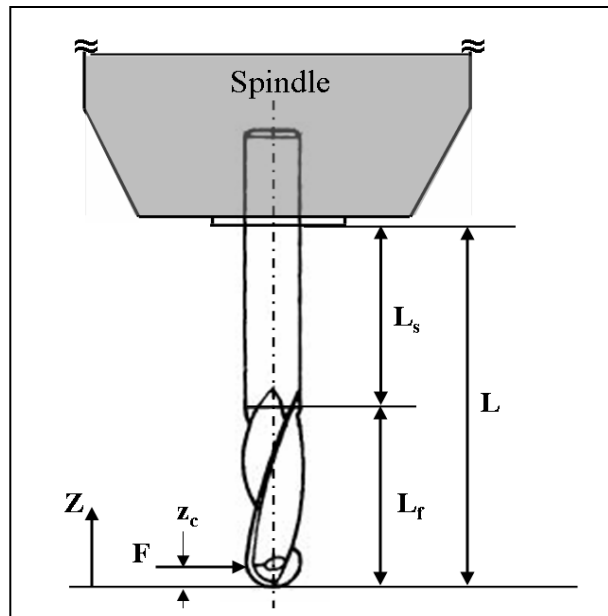


Figure 7.21: Tool deflection model.

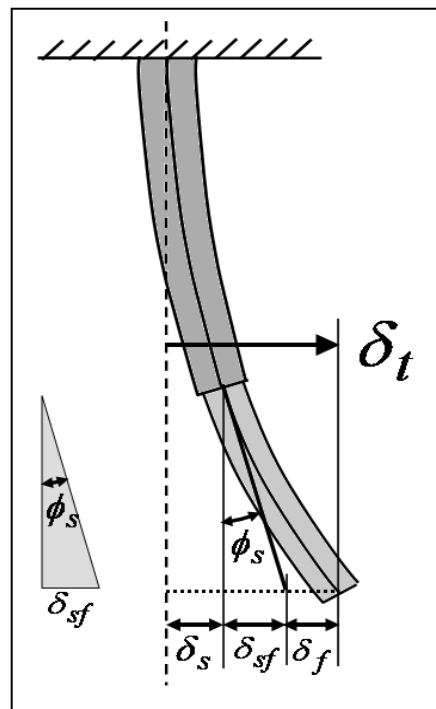


Figure 7.22: Individual tool deflections.

where δ_s is the deflection of shank, δ_f is the deflection of flute, δ_{sf} is the deflection of the shank due to the deflection angle ϕ_s , and δ_{st} is the deflection of the clamping part which is calculated from the stiffness of the clamping system experimentally, Gere and Timoshenko [38] derived the tool deflection angle as;

$$\theta = \frac{F}{2 \times E \times I} [2 \times (L - z_c) \times (L - z) - (L - z)^2] \quad (7.4)$$

where θ is the beam deflection angle which can also be seen in Figure 7.20. As stated, total tool deflection consists of shank and flute part of the tool. These individual parameters are given as follows;

$$\delta_s = \frac{F}{6 \times E \times I} [(z_c - L_f)^3 - (L - L_f)^3 + 3 \times (L - L_f)^2 \times (L - z_c)] \quad (7.5)$$

$$\delta_f = \frac{F}{6 \times E \times I_f} [(z_c - z)^3 - (L_f - z)^3 + 3 \times (L_f - z)^2 \times (L - z_c)] \quad (7.6)$$

$$\phi_s = \frac{F}{2 \times E \times I} [2 \times (L - z_c) \times (L - L_f) - (L - L_f)^2] \quad (7.7)$$

$$\delta_{st} = \frac{F}{K_s} \quad (7.8)$$

$$\delta_t = \delta_s + \delta_f + \delta_{sf} + \delta_{st} \quad (7.9)$$

where I_f is the moment of inertia of the flute, and δ_{sf} is the deflection of the shank due to deflection angle can be found from the right triangle shown in Figure 7.22.

$$\delta_{sf} = \tan(\phi_s) \times (L_f - z) \quad (7.10)$$

For small angle $\tan(\phi_s) \approx \phi_s$, then;

$$\delta_{sf} = \phi_s \times (L_f - z) = \frac{F}{2 \times E \times I} \left[2 \times (L - z_c) \times (L - L_f) - (L - L_f)^2 \right] \times (L_f - z) \quad (7.11)$$

In order to estimate the deflection of the clamping part, the stiffness of the spindle and tool system was found by using the experimental setup shown in Figure 7.18. The tool deflection in X (δ_{tx}) or Y (δ_{ty}) directions can be found by using Equation 7.9.

After determining the horizontal deflection of the tool in X and Y directions, they should be combined in a meaningful manner to obtain the surface error. The directions will be defined as feed and cross feed which will be corresponding to X and Y directions respectively in this study. From the calculated horizontal deflection, surface error in Z direction due to feed direction force can be calculated using Figure 7.23. Feed direction affects the total error formulation which becomes;

$$e_f = \pm \delta_t \times \tan(\alpha) + dz_f \quad (7.12)$$

If upward ramping occurs, the first term becomes positive, and if downward ramping occurs the first term turns out to be negative. α is the surface inclination angle and dz_f is the rise of the tip in feed direction. The deflection in feed direction is much more dominant than the deflection in cross feed direction; however, the cross feed direction deflection also plays an important role since the tip of the tool will rise such that it will cause the tool to cut with the right or left side of the tool mid-plane.

Details of the deflection in cross feed direction can be seen in Figure 7.24. δ_{tcf} is the total deflection in cross feed direction, dz_{cf} is the rise of the tip of the tool in cross feed direction, R_b is the radius of ball-end mill, θ is the deflection angle, and e_{cf} is the error due to cross feed force in z direction which will be added to final surface error. The error due to cross feed can be found as following;

$$e_{cf} = \sqrt{R_b^2 - (\delta_{tcf} - R_b \times \sin(\theta))^2} + (dz_{cf} + R_b \times \cos(\theta)) \quad (7.13)$$

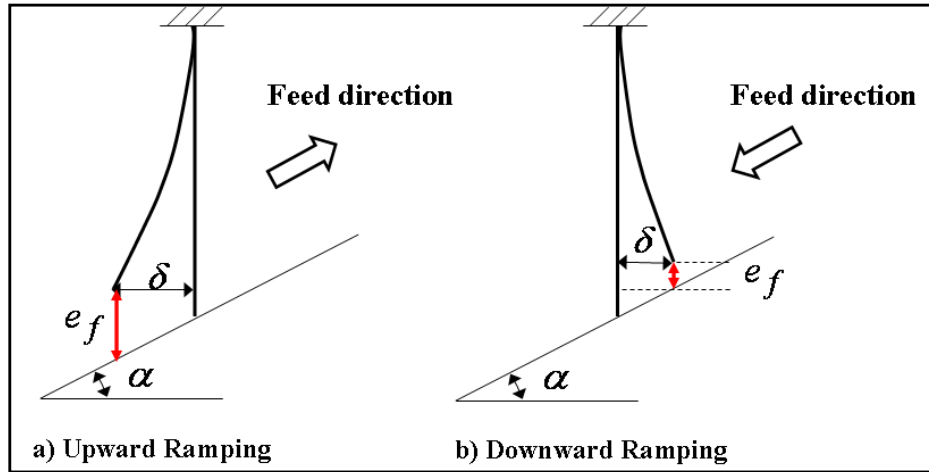


Figure 7.23: Feed direction surface error.

After determining errors due to feed and cross feed directions, total error is found by summing them as the following;

$$e_{total} = e_f + e_{cf} \quad (7.14)$$

Combining errors created by CAM software and deflection caused by cutting forces gives the final form error.

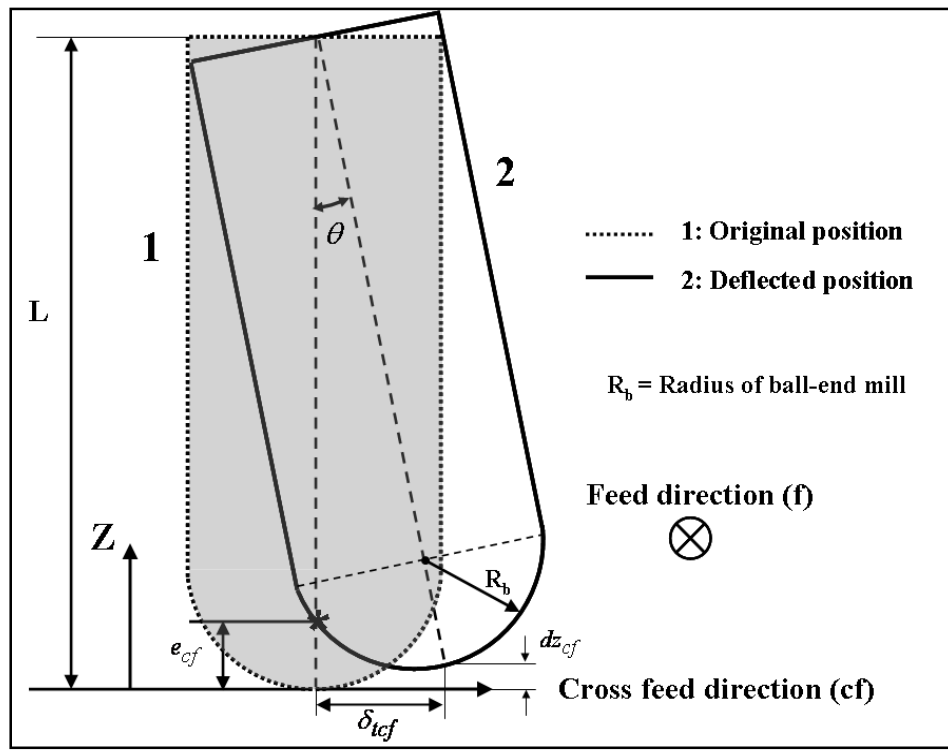


Figure 7.24: Cross feed direction surface error.

7.4.1.3 Simulation and Experimental Results

Using stated surface finish analysis, form errors of tool path strategies were calculated and compared with experimental data. Experimental measurements of surface error performed on Coordinate Measuring Machine (CMM) Dia Status 7.5.5 with a probe of 1 mm. The CMM measurements were performed with selection of longitudinal increment of 0.5 mm. Simulations were also performed with an increment of 0.04 mm. Figure 7.25 shows the experimental setup. Following figures are the simulations and validations of tool path strategies. Illustrations of the tool path can be seen in Section 7.2.

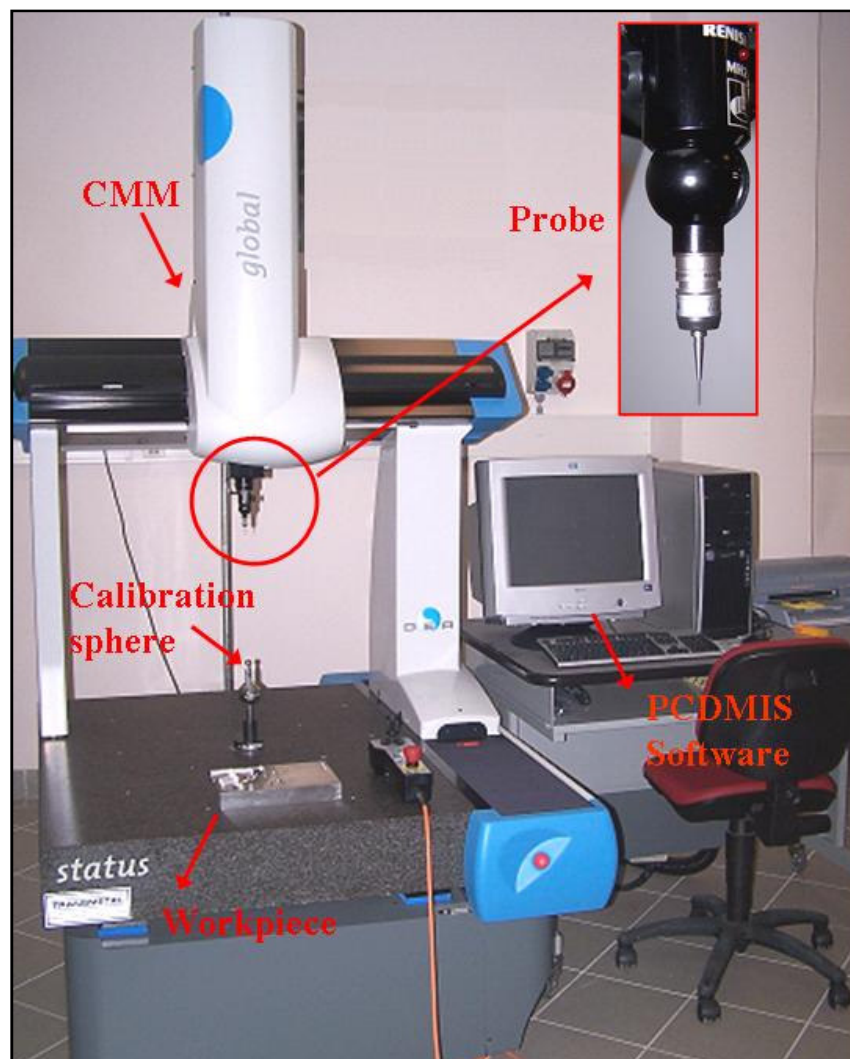


Figure 7.25: CMM setup for the measurement of surface finish.

7.4.1.3.1 0° Zigzag Lines Tool Path

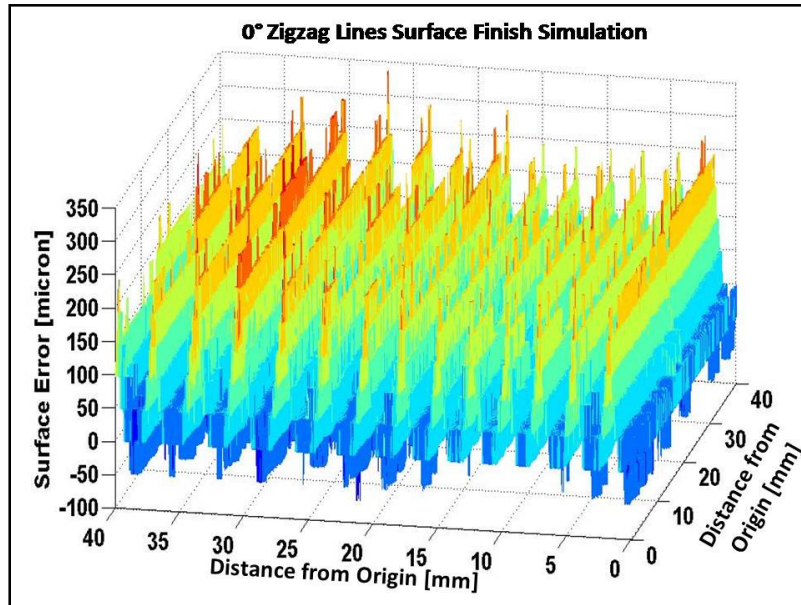


Figure 7.26: Surface error simulation for 0° zigzag tool path.

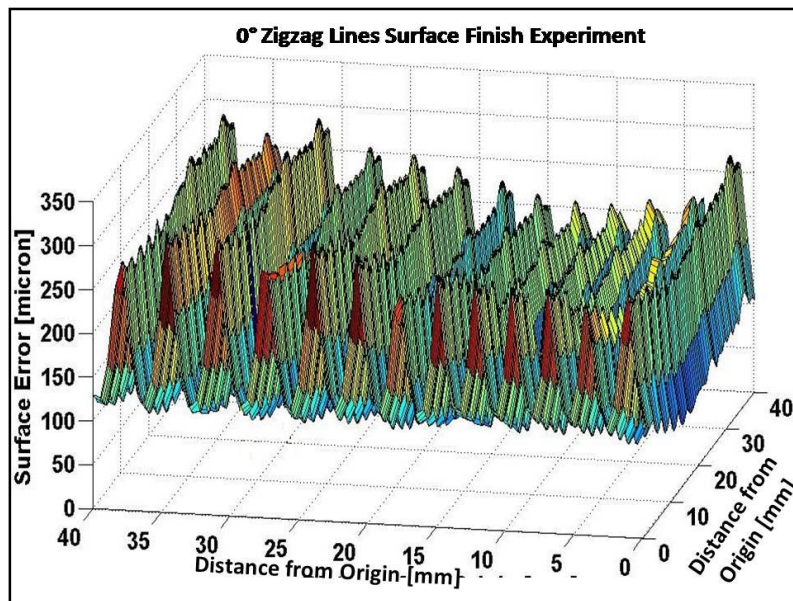


Figure 7.27: Surface error experiment for 0° zigzag tool path.

7.4.1.3.2 45° Zigzag Lines Tool Path

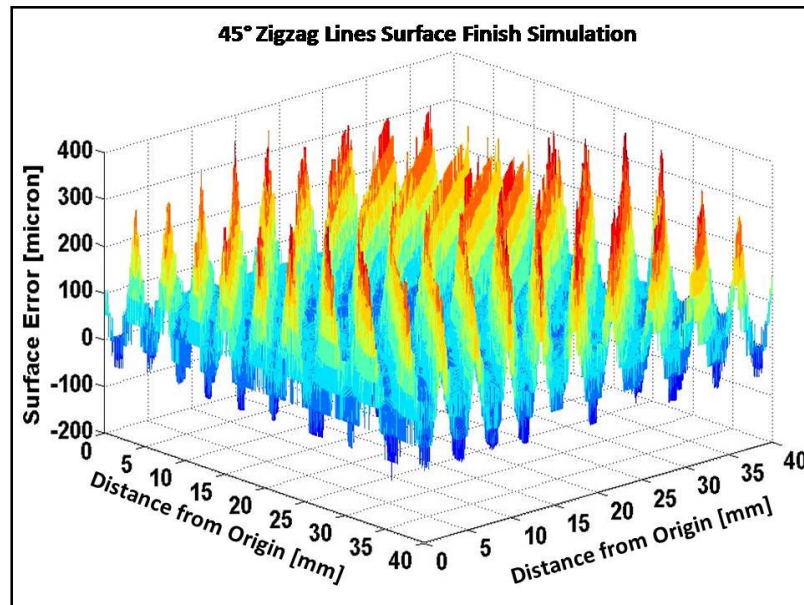


Figure 7.28: Surface error simulation for 45° zigzag tool path.

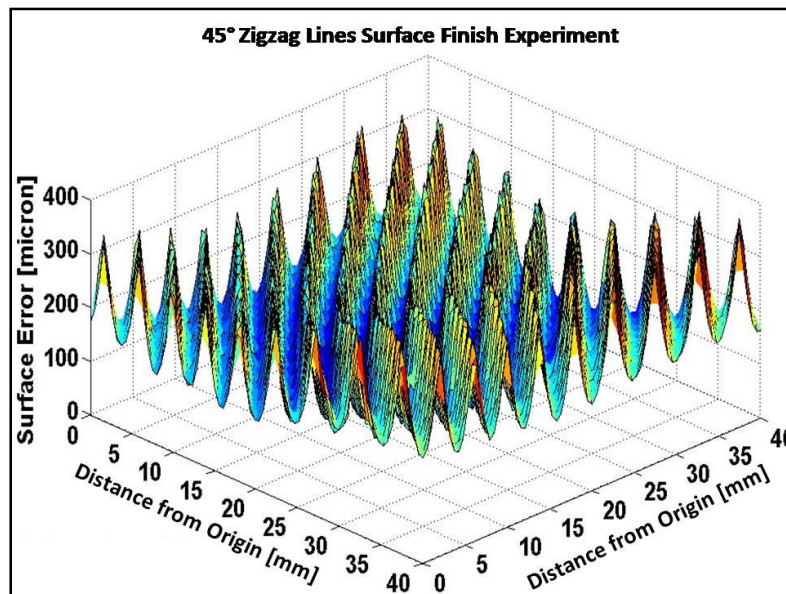


Figure 7.29: Surface error experiment for 45° zigzag tool path.

7.4.1.3.3 Concentric Arcs Tool Path

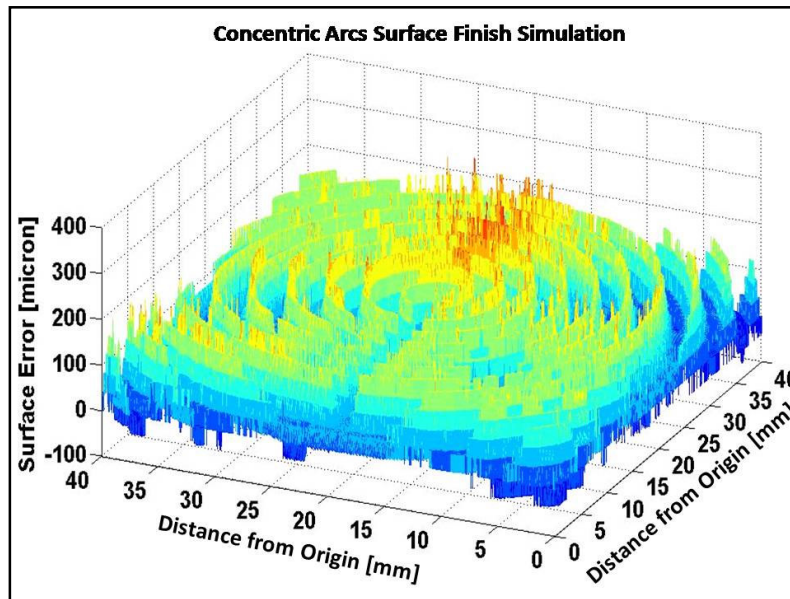


Figure 7.30: Surface error simulation for concentric arcs tool path.

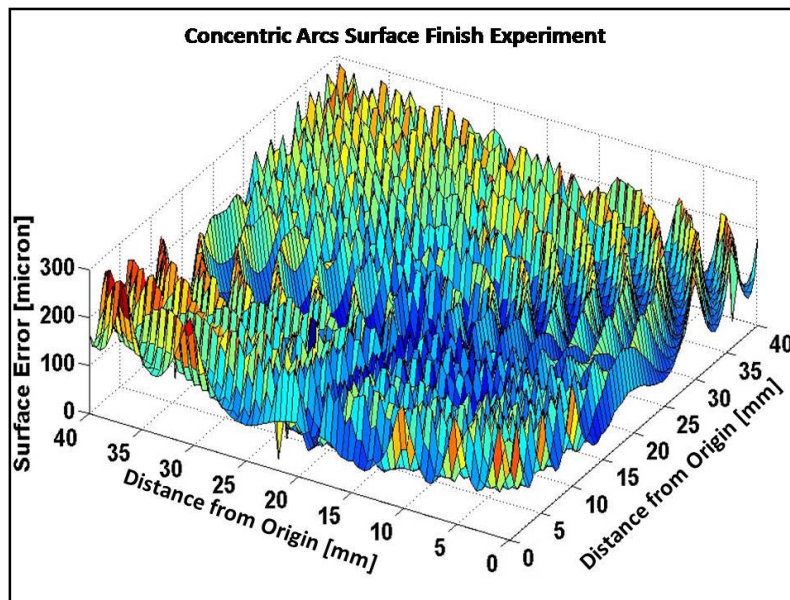


Figure 7.31: Surface error experiment for concentric arcs tool path.

7.4.1.3.4 Radial Lines Tool Path

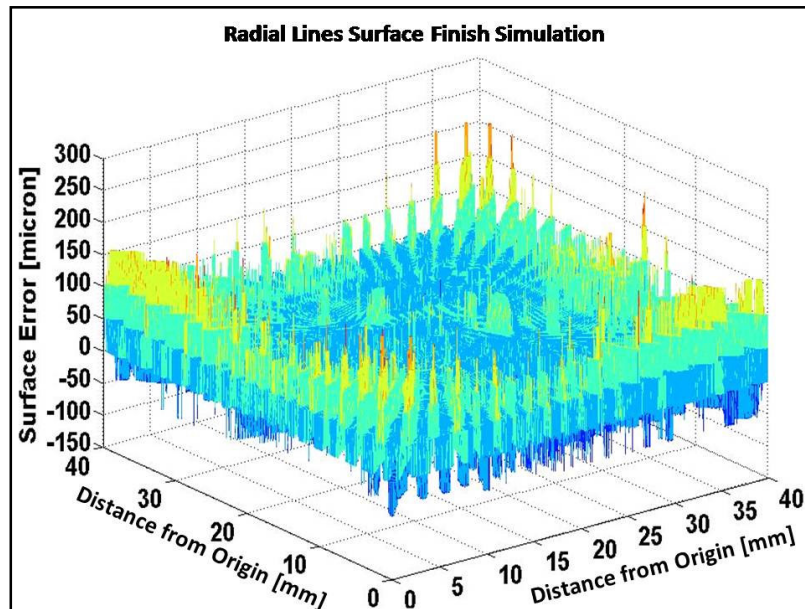


Figure 7.32: Surface error simulation for radial lines tool path.

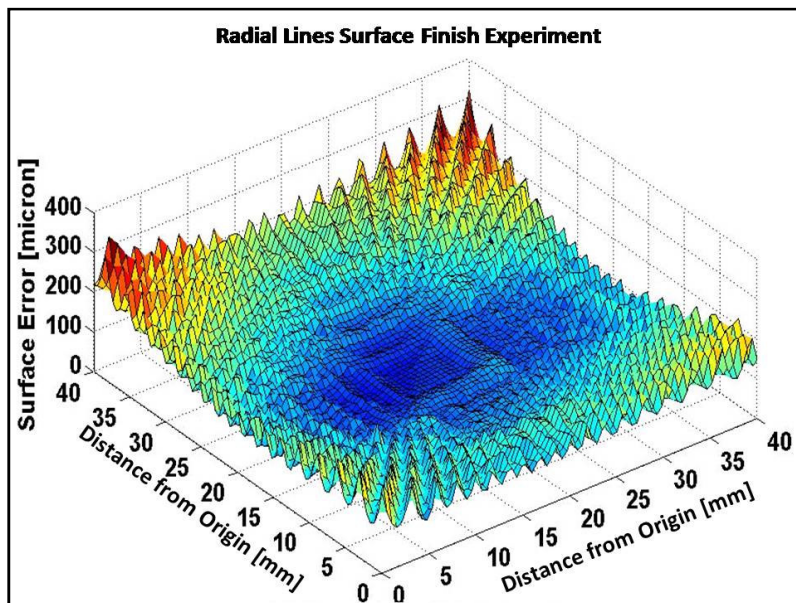


Figure 7.33: Surface error experiment for radial lines tool path.

7.5 Discussions:

This study summarized the influence of different tool path strategies in terms of cutting forces, cycle time, and surface finish. Simulations and measurements were presented. It can be concluded from the results that, radial lines has minimum cutting forces, 45° zigzag lines has minimum cycle time, and concentric arcs has minimum surface error. These results show that tool path selection depends on the aim of the user, because there is a trade-off criterion; for example, lower cutting forces result in longer cycle times. Following Table summarizes the maximum values of analyses.

Table 7-1: Analyses of maximum values.

	0° Zigzag Paths	45° Zigzag Paths	Concentric Arcs	Radial Paths
Maximum Resultant Cutting Force [N]	272	263	234	221
Cycle Time [min.]	24.13	23.76	32.46	50.73
Maximum Surface Error [micron]	317	372	294	321

Chapter 8

MECHANISTIC CUTTING FORCE MODELLING IN 5-AXIS MACHINING

8.1 Introduction:

The development in CAD/CAM technology provides much more complex geometries for dies and molds. Moreover, due to the advancements in aerospace and automobile industry, parts desired for manufacturing are more challenging and complex. There are some dies/molds and parts in industry that cannot be machined with 3-axis CNC's. Recently, due to the increased demand for more advanced milling machines, multi-axis machining technology is offered to industry. The conventional method of machining free-form surfaces is by using a 3-axis machine with ball-end mill. 3-axis machine tools cannot change the tool orientation, so a 5-axis machine tool is introduced to set the cutting tool in an appropriate orientation for efficient machining. With the rapidly advancing computer technology, commercial CAD/CAM systems can design free-form surfaces and generate either the 3-axis or 5-axis tool path.

In free-form surface machining, as stated before, the cutting geometry is changing and it is very difficult to model the cutting process. 5-axis free-form machining makes the modeling process much more difficult, because not only cutting geometry changes, but also tool orientation is changing at each CL point by two rotary axes. As a result, mechanistic modeling of 5-axis free-form surface machining is a challenging process.

8.2 Cutting Force Simulation in 5-Axis Ball-End Milling:

In the prediction of cutting forces in 5-axis ball-end milling process, the mechanistic cutting force model presented in Chapter 3 can be used with some certain modifications. Since the solid based engagement model presented in Chapter 4 is capable of calculating the engagement domain for 5-axis machining, the engagement domain can be used to predict the rotated cutting forces and then these forces are rotated to absolute coordinates by the help of lead and tilt angles presented in Figure 8.1. This rotation procedure is valid for a stationary dynamometer presented in Chapter 5. In this study a rotary dynamometer attached to the tool holder is used to measure the cutting forces. In 5-axis machining, the tool or workpiece is in rotation while in linear motion, Martelotti's [3] approach needs to be modified by including the rotational phenomenon of tool/workpiece to the translational model. The rotation of tool/workpiece must be taken into account and a kinematic analysis of the point on the tool must be performed for an accurate modeling of cutting forces in 5-axis machining.

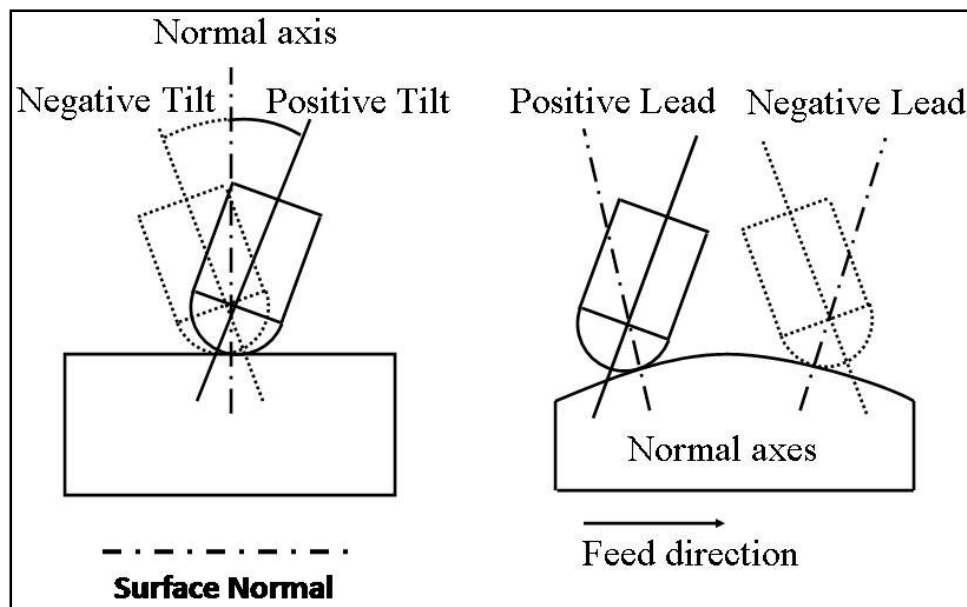


Figure 8.1: Representation of lead and tilt angles in 5-axis ball-end milling.

8.3 Experimental Setup:

The experiments for validation were performed on DECKEL MAHO DMU 50 eVolution 5-axis Machining Center with 15000 rpm spindle motor. The tool was a carbide ball-end mill cutter from CoroMill Plura series of Sandvik with 12 mm diameter, 37 mm projection length and 30° helix angle. The workpiece material was aluminum blocks (Al7039) with dimensions of 250x170x38 mm. Kistler rotary dynamometer (Model 9123C1111) and a charge amplifier have been used to measure the cutting forces. The rotary dynamometer has been fixed to the spindle and the aluminum block was attached to the rotary tables as seen in Figure 8.2.

The cutting forces are sensed by the piezoelectric transducer in the dynamometer and an electric charge output is the outcome of this process. This electric charge is sent to the charge amplifier and converted into voltage output. Displaying and recording of the measured data was performed with data acquisition software, MALDAQ module of CutPro 8.0.

Various tests were performed for validation of 5-axis cutting forces. Differential chip height and the differential rotation angle in simulations were selected to be 0.1 mm and 3.6° respectively which adequately resembled the actual cutting conditions for the mathematical force model. Cutting conditions were summarized in Table 8.1.

Table 8-1: 5-axis validation experiments cutting conditions.

Feed Rate	144 mm/min
Axial Depth of Cut	Up to 6 mm
Spindle Speed	600 rpm
Sampling Frequency	1000 Hz
Workpiece Material	AL 7039

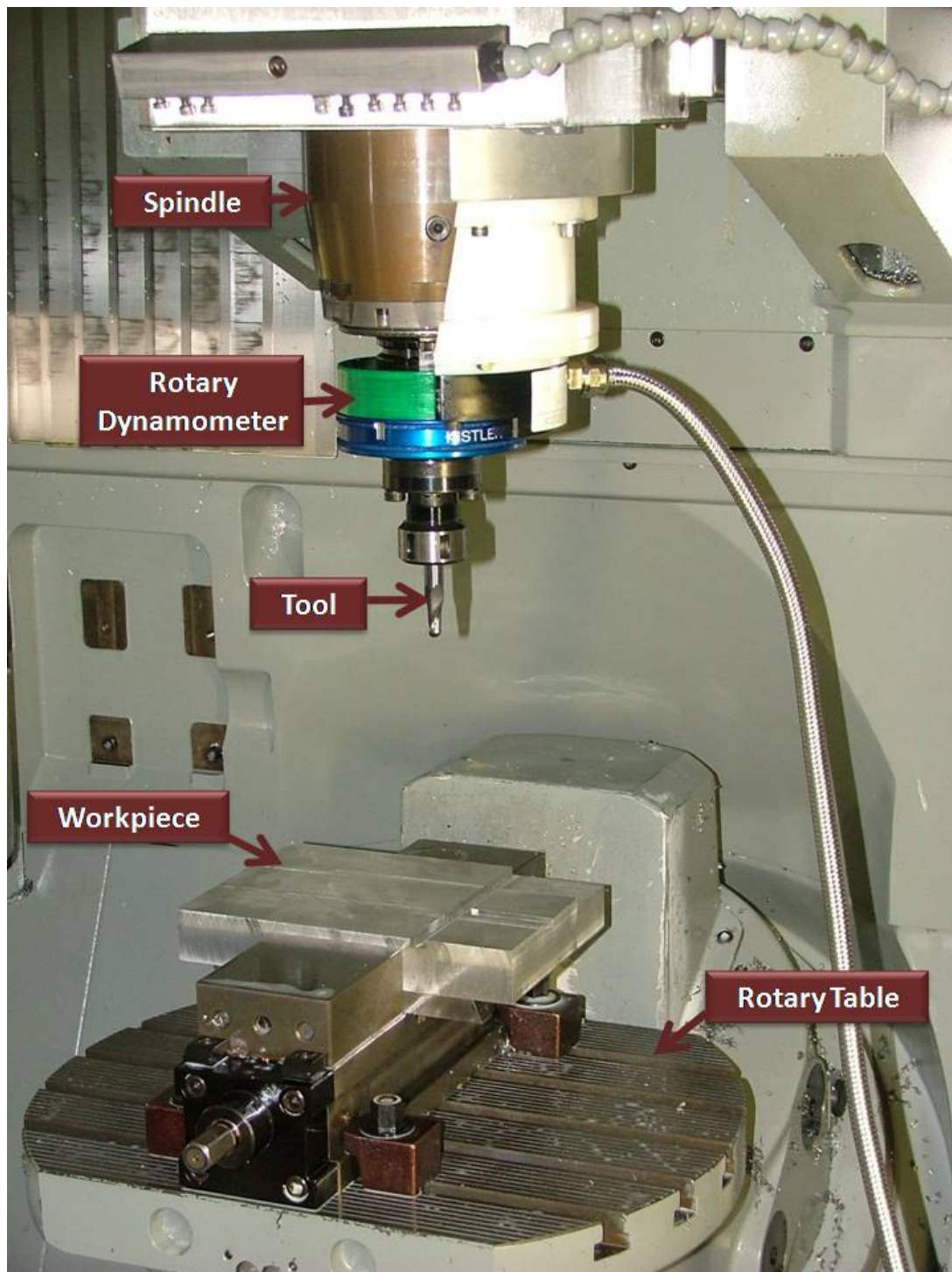


Figure 8.2: The experimental setup for measurement of cutting forces.

8.4 Simulations and Validations:

For the validation of the mechanistic cutting force model in 5-axis machining, various tests with different lead and tilt angles were performed on sine – cosine surface. The details of the sine – cosine surface can be seen in Figure 5.15. A total number of 6 tests were performed with lead and tilt angles of 20° and 30° and the combination of both lead and tilt angles were used. In order to avoid the engagement of the tip of the tool, tilt angles were determined as -20° and -30° . Table 8.2 summarizes the lead and tilt angles for each test. Since the orientation of the tool changes at each CL point, the simulations were performed up to 12 mm axial depth of cut due to the possibility of the cylindrical part of the tool is engaged with the workpiece.

The tool moved through a post-processed CAM file obtained from Unigraphics NX 4 Manufacturing application. The step-over of 2 mm/track was used to create on 50x50 mm blank workpiece. A two fluted ball-end mill with a diameter of 12 mm, nominal helix angle of 30° , and a projection length of 37 mm was used in experiments.

Table 8-2: Lead and tilt angles used in the tests.

	Lead Angle	Tilt Angle
Test 1	20°	0°
Test 2	0°	-20°
Test 3	20°	-20°
Test 4	30°	0°
Test 5	0°	-30°
Test 6	30°	-30°

8.4.1 20° Lead Angle:

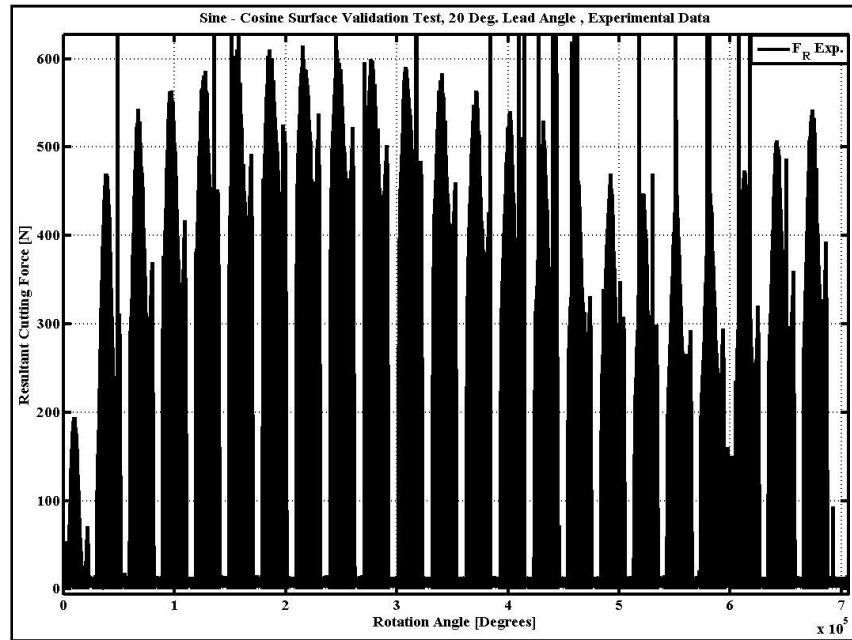


Figure 8.3: Resultant experimental cutting forces with 20° lead angle on sine – cosine surface.

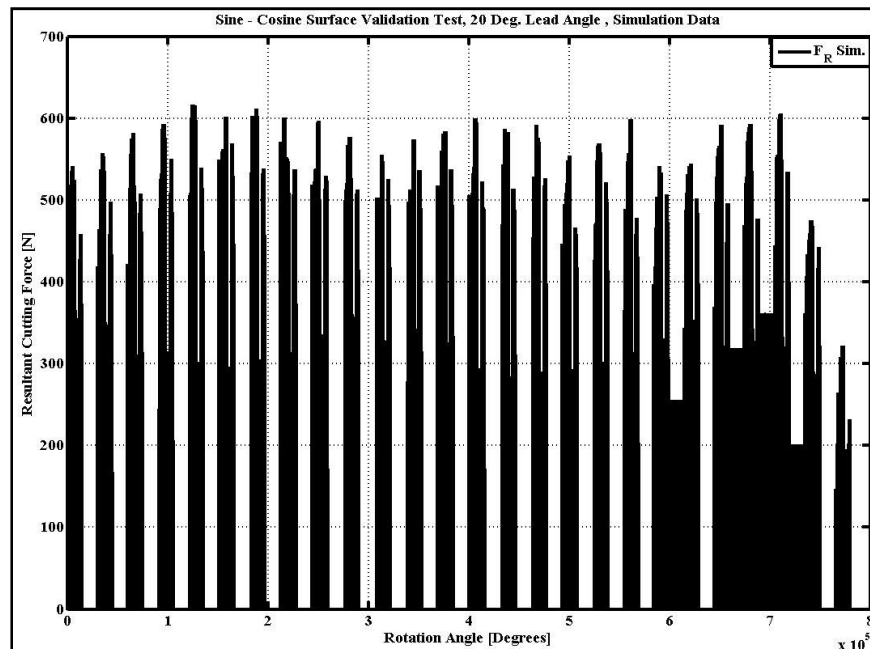


Figure 8.4: Resultant simulation cutting forces with 20° lead angle on sine – cosine surface.

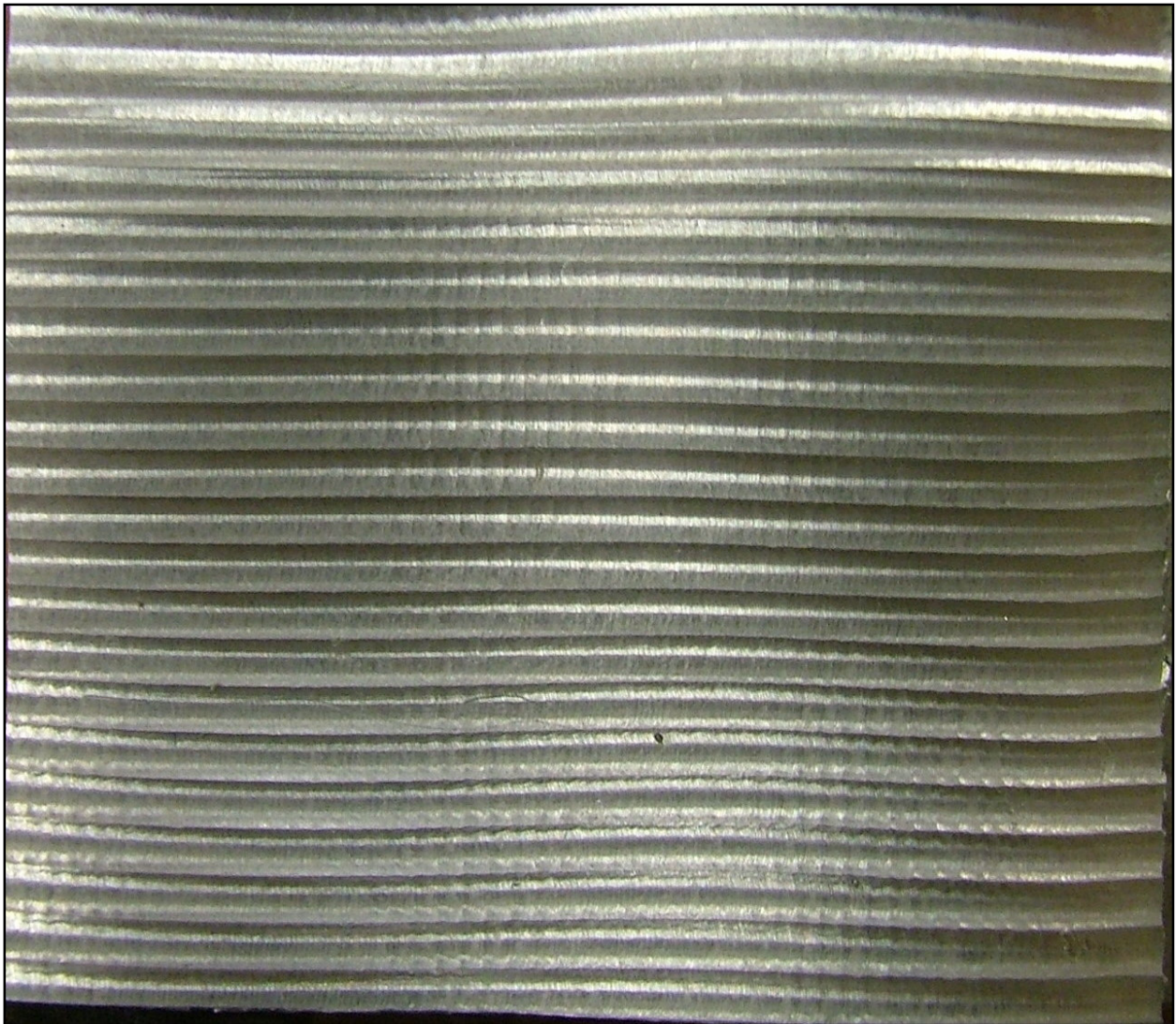


Figure 8.5: Surface quality of 20° lead angle sine – cosine surface.

8.4.2 20° Tilt Angle:

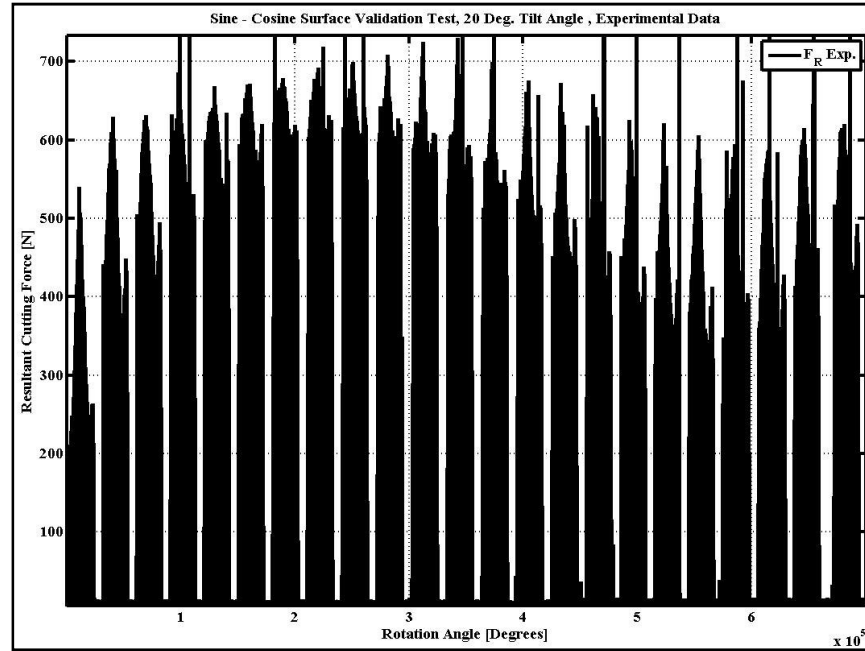


Figure 8.6: Resultant experimental cutting forces with -20° tilt angle on sine – cosine surface.

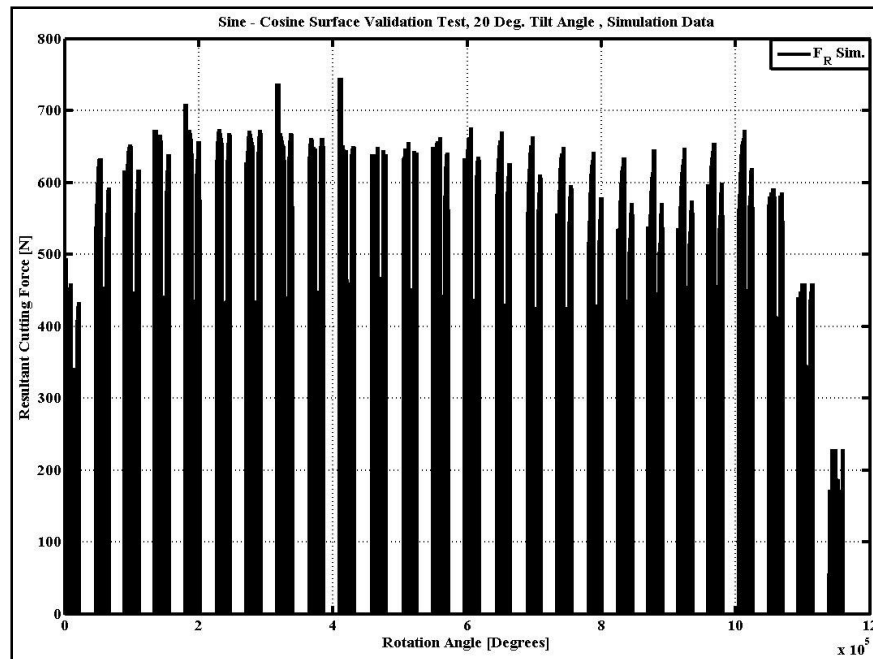


Figure 8.7: Resultant simulation cutting forces with -20° tilt angle on sine – cosine surface.

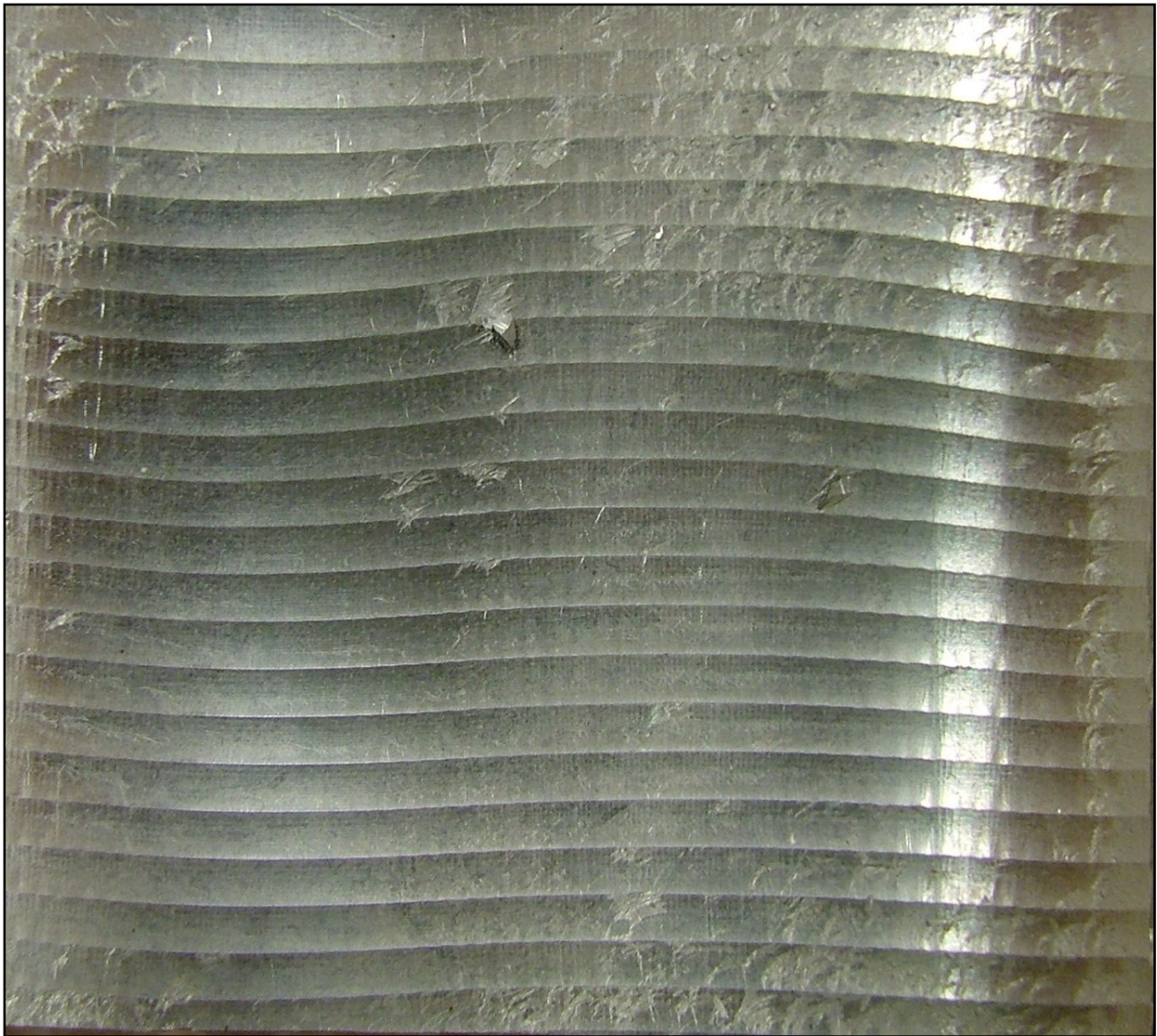


Figure 8.8: Surface quality of -20° tilt angle sine – cosine surface.

8.4.3 20° Lead and Tilt Angle:

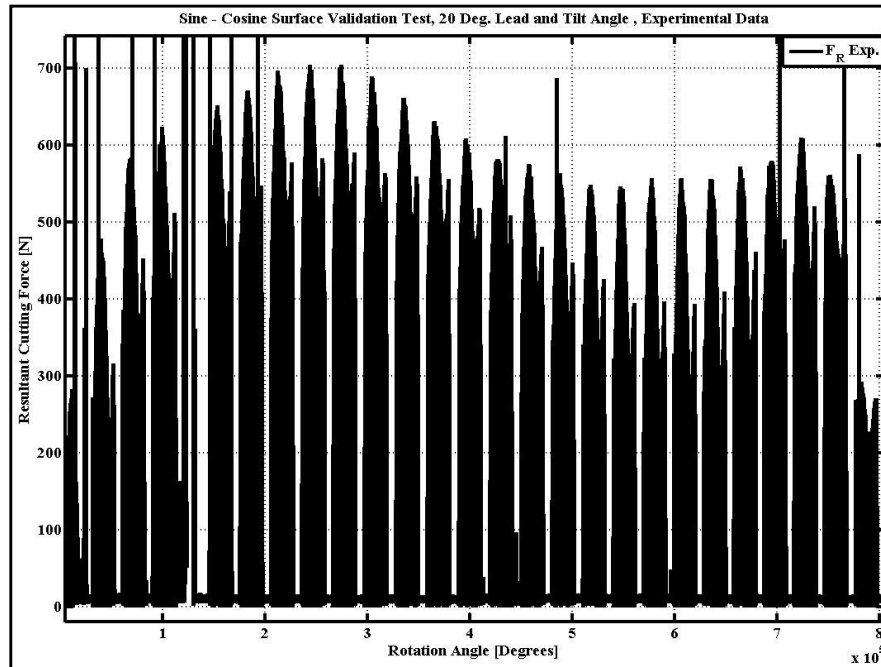


Figure 8.9: Resultant experimental forces with 20° lead and tilt angle on sine – cosine surface.

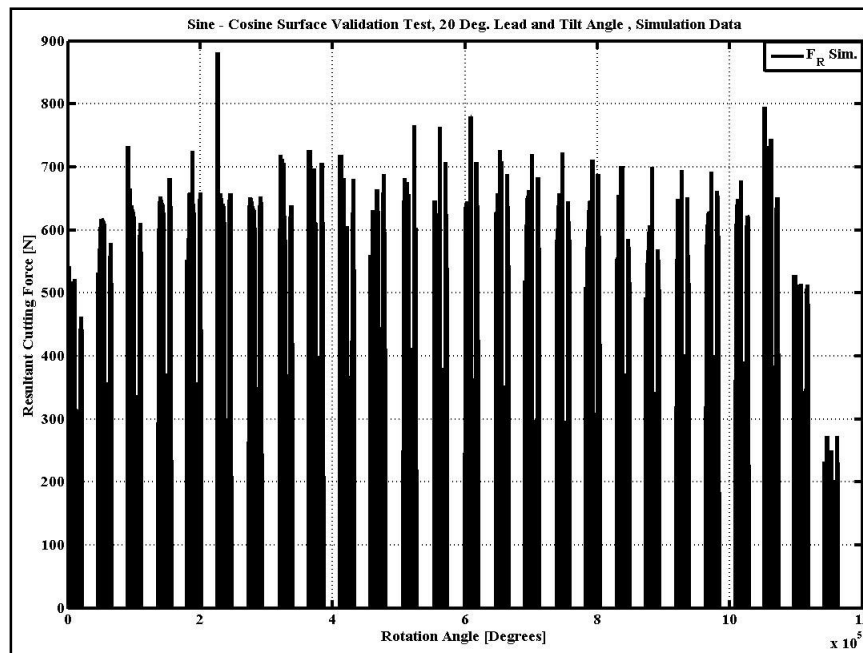


Figure 8.10: Resultant simulation forces with 20° lead and tilt angle on sine – cosine surface.

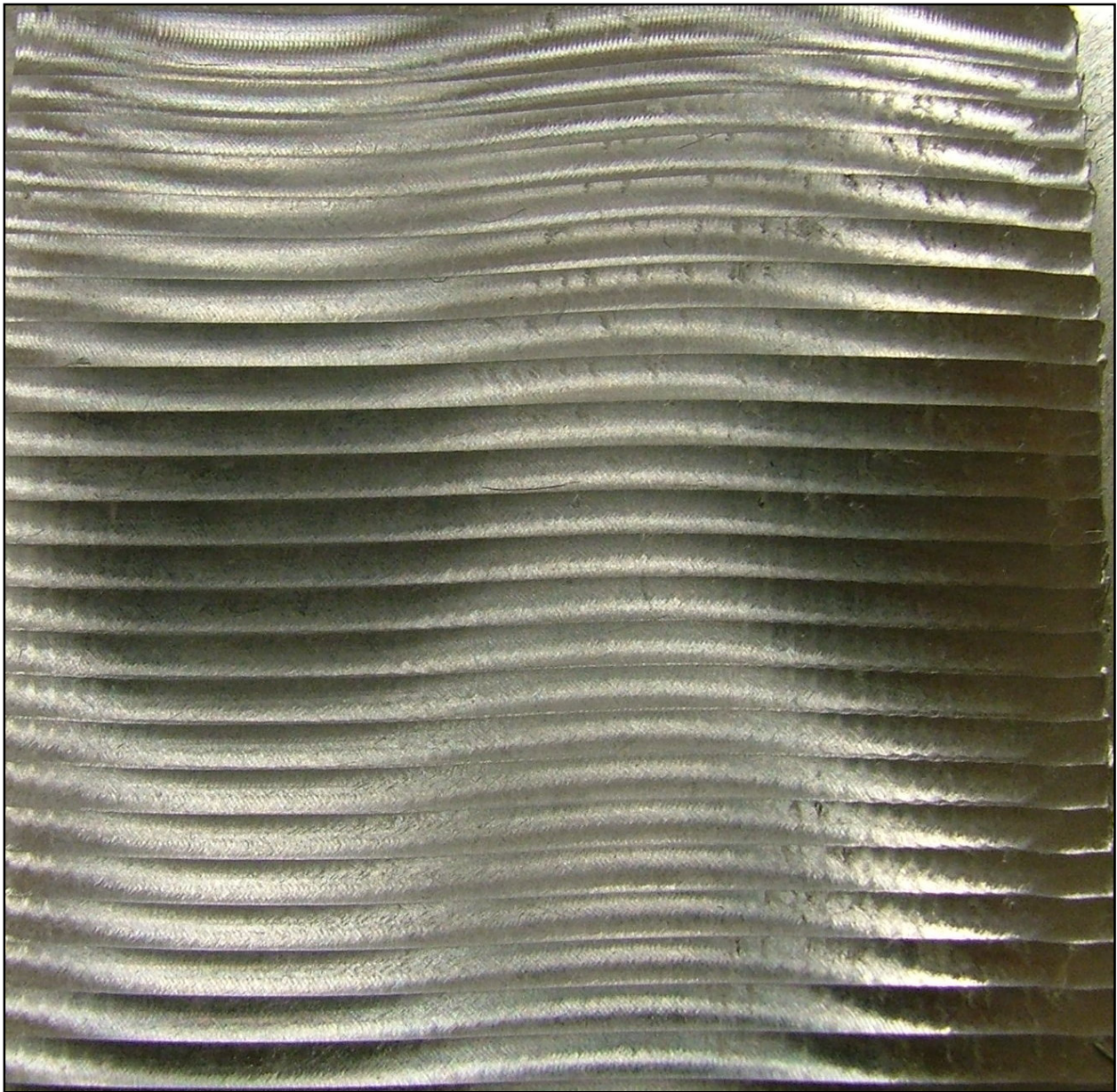


Figure 8.11: Surface quality of 20° lead and tilt angle sine – cosine surface.

8.4.4 30° Lead Angle:

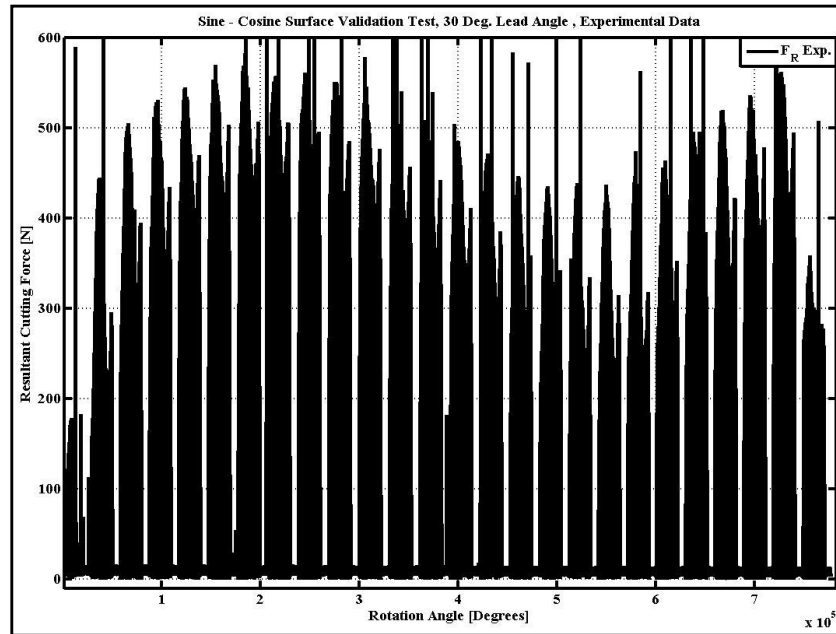


Figure 8.12: Resultant experimental cutting forces with 30° lead angle on sine – cosine surface.

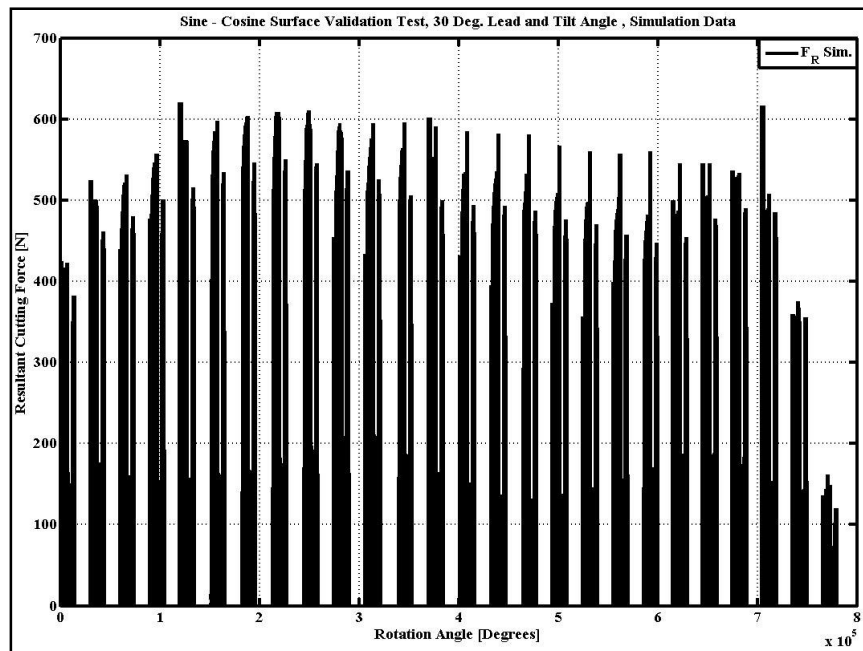


Figure 8.13: Resultant simulation cutting forces with 30° lead angle on sine – cosine surface.



Figure 8.14: Surface quality of 30° lead angle sine – cosine surface.

8.4.5 30° Tilt Angle:

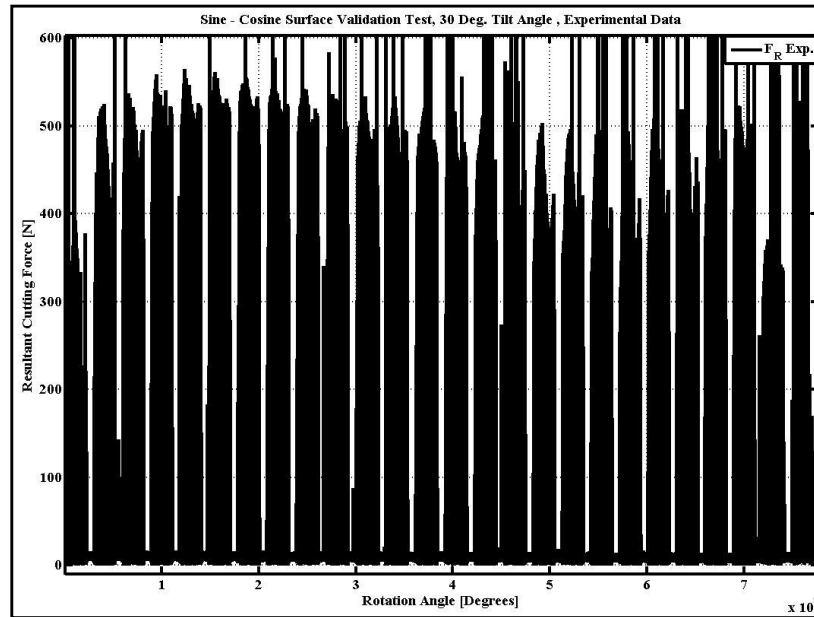


Figure 8.15: Resultant experimental cutting forces with -30° tilt angle on sine – cosine surface.

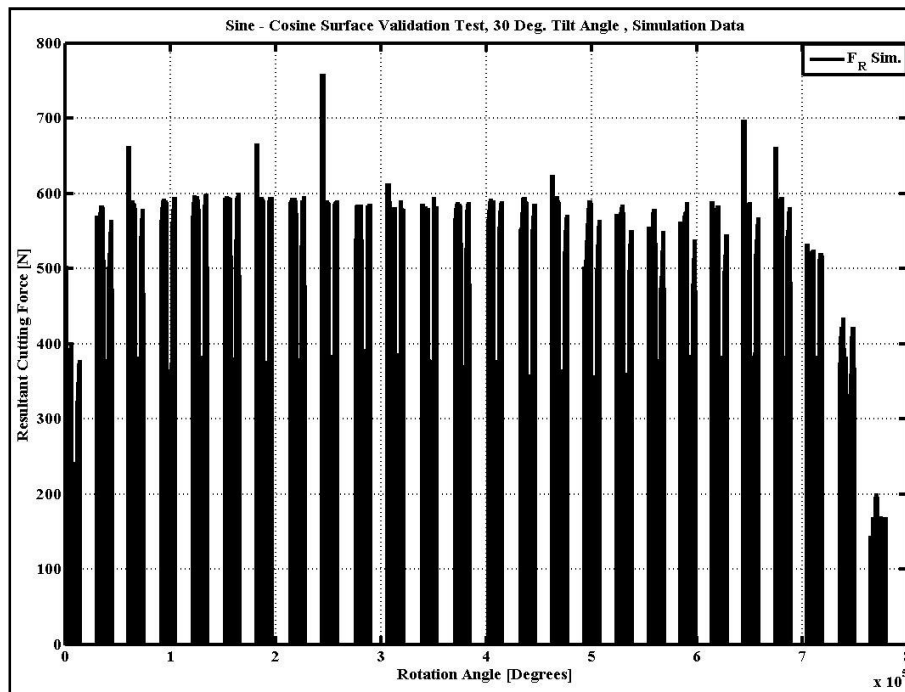


Figure 8.16: Resultant simulation cutting forces with -30° tilt angle on sine – cosine surface.



Figure 8.17: Surface quality of -30° tilt angle sine – cosine surface.

8.4.6 30° Lead and Tilt Angle:

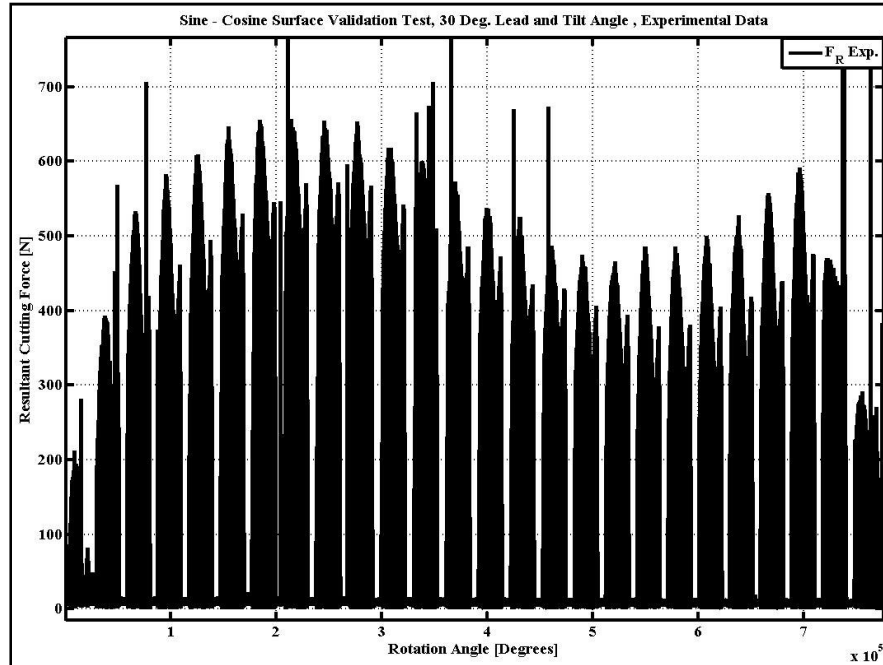


Figure 8.18: Resultant experimental forces with 30° lead and tilt angle on sine – cosine surface.

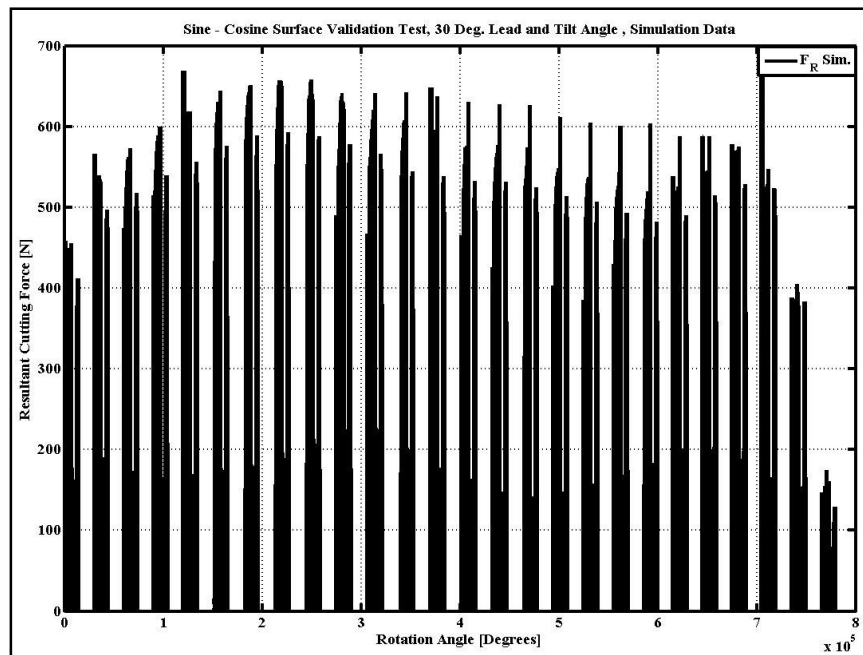


Figure 8.19: Resultant simulation forces with 30° lead and tilt angle on sine – cosine surface.

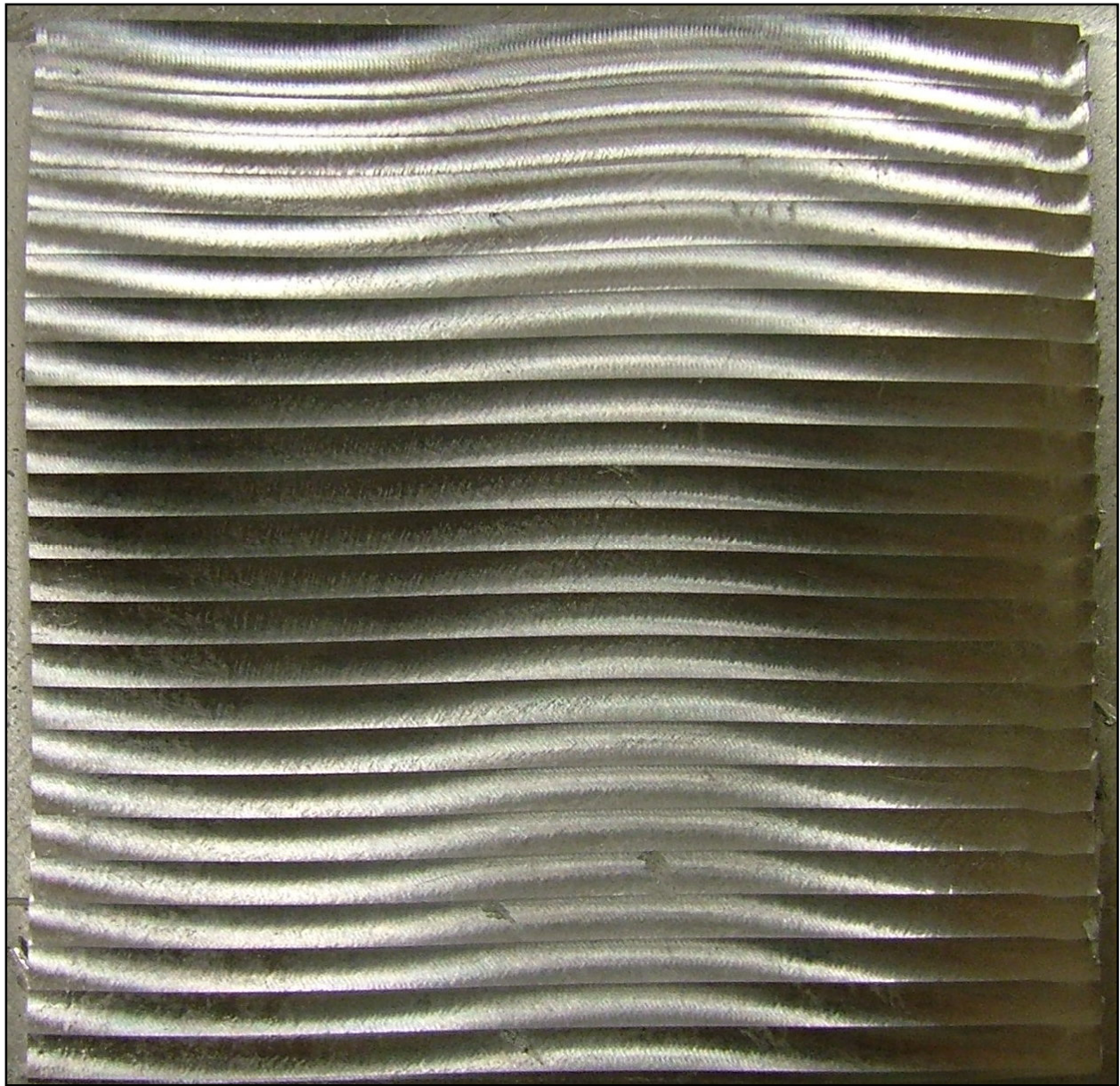


Figure 8.20: Surface quality of 30° lead and tilt angle sine – cosine surface.

8.5 Discussions:

Various tests were performed for validation of the proposed mechanistic cutting force model on 5-axis machining. Different lead and tilt angles and their combinations were applied. This study is a preliminary research on mechanistic modeling of 5-axis machining; therefore validation results are not as good as in the 3-axis cases. However, this study precisely identifies the effects of lead and tilt angles on 5-axis machining.

The surface speed of the tool decreases along the tip of the tool, because of the reduction of the radius along the tip. This results in poor surface finish. Therefore, engagement of the tip of the tool with the workpiece is strictly avoided. Since it is possible to use different lead and tilt angles on machining a free-form surface, the determination of optimum lead and tilt angles are important for productivity and surface quality.

From the experiments it can be concluded that each tool orientation option results in different cutting force and surface quality. For the sine – cosine surface using tilt angles results in poor surface quality due to the rubbing effect, although tilt angles decreases the scallop heights. Using only lead angles leaves tooth marks on the surface, thus it is more convenient to use the combinations of lead and tilt angles to achieve maximum surface quality.

Maximum resultant cutting force is also different at each tool orientation. However, it can be claimed that increasing lead or tilt angle decrease the maximum cutting forces.

Chapter 9

CONCLUSION

The aim of this study has been to develop an accurate and precise modeling of machining with ball-end milling of complex sculptured free-form surfaces and applying various methods to improve the productivity and part quality. Special importance was given to the mechanistic modeling of non-monotonic free-form surfaces, which are very difficult to model using widely used methods such as analytical engagement calculation. Free-form sculptured surfaces are very popular in many industries and in machining of dies, molds, automobile and aerospace parts. Therefore, accurate prediction of cutting forces during machining allows to improve productivity by applying feed rate scheduling strategy or to provide better surface finish by calculating deflections. As a result, knowledge gained from this thesis can be used to select appropriate cutting conditions which result in better part quality in a shorter cycle time.

The geometry of the ball-end mill used in this study was defined according to the previous studies of Guzel and Lazoglu [1], and Erdim [2]. Solid based approach [36] to the tool-workpiece engagement region is developed and used for 3D complex sculptured free-form surfaces with ball-end milling. Since other engagement domain calculation approaches (analytical, discretization, Boolean) do not cover non-monotonic surfaces or they are computationally expensive and slow, solid based engagement can be used for every kind of surface and is comparably faster and quite accurate than any other approaches. Another important aspect of the solid based engagement model is that it can also calculate engagement domain for any type of surface in five-axis machining.

Other than simulating and validating the force predictions, free-form surfaces are selected to improve the productivity by decreasing the production time. Conservative constant feedrate values have been mostly preferred up to now since there was a lack of physical models and

optimization tools for free-form surfaces. In this study, using the mechanistic cutting force model, the resultant cutting force is kept constant by applying force based feed rate scheduling strategy under a pre-determined threshold value. Feed rate scheduling was accomplished by adjusting the feed rate at each CL point. Measured forces, force patterns and simulations for these parts showed very good agreement. Feed rate scheduling based on the mechanistic cutting force model was performed in three different free-form surfaces. After validation experiments, it can be concluded that cycle times in free-form surfaces can be decreased significantly up to 55% compared to constant feed rate cases.

As stated before, as the demand for free-form surfaces in industry increases, CAD/CAM software companies develop different tool path strategies for machining of complex sculptured surfaces. Users can now use concentric or radial lines etc. instead of conventional zigzag cut. However, since there are different tool paths available to carry out the same process, a question arises that which tool path strategy is the best choice for a specific free-form surface. As it can be predicted, each tool path strategy offers different cutting time, cutting force magnitude and surface quality. In this study, four different tool path strategies were compared in terms of cycle time, cutting forces, and surface finish. Results showed that tool path selection depends on the aim of the user, because there is a trade-off criterion; for example, lower cutting forces result in longer cycle times.

As the preliminary study, mechanistic modeling of 5-axis machining was studied. Simulations and experimental validations for different lead and tilt angles on a free-form surface were presented. Simulations and experimental results are not in a good agreement in terms of force patterns compared to other 3 axis validations. The error in resultant cutting force magnitudes can be studied as a future subject, and mechanistic cutting force model for 5-axis machining can be improved. Accurate modeling of cutting forces in 5-axis machining can be used in feed rate scheduling and tool path optimization as in this study.

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