

15/3/15

Dynamic Forces and Hole Quality in Drilling Process

by

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15/3/15

**A Thesis Submitted to the
Graduate School of Engineering
in Partial Fulfillment of the Requirements for
the Degree of**

Master of Science

in

Mechanical Engineering

Koc University

July 2004

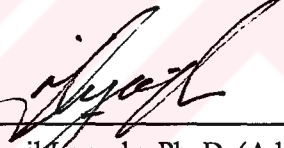
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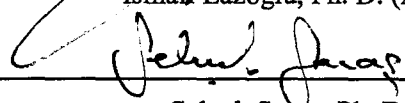
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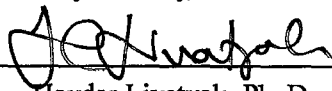
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and have found that it is complete and satisfactory in all respects,
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28.07.2004

ABSTRACT

Drilling is one of the most commonly used machining processes in various industries such as automotive, aircraft and aerospace, dies/molds, home appliance, medical and electronic equipment industries. Due to the increasing competitiveness in the market, cycle times of the drilling processes must be decreased. Moreover, tight geometric tolerance requirements in designs, drilled hole precisions must be increased in production. On the other hand, process engineers have to be conservative when selecting machining conditions with respect to metal removal rate in order to avoid undesirable cases such as drill breakage, excessive cutter deflection and undesirable hole profile problems.

In this research, a new mathematical model based on the mechanics and dynamics of the drilling process is developed for the predictions of cutting forces and hole qualities in advance. A novel method is also proposed in order to obtain cutting coefficients directly from a set of relatively simple calibration tests. The model is able to simulate the cutting forces for various cutting conditions in the process planning stage. In structural dynamics module, measured frequency response functions of the spindle and the tool system are integrated into the model in order to obtain drilled hole profiles. Therefore, in addition to predicting the forces, the new model allows to determine and visualize drilled hole profiles in 3D and to select parameters properly under the manufacturing and tolerance constraints. Extensive number of experiments is performed to validate the theoretical model outputs with the measured force and CMM hole profiles. It is observed that model predictions agree well with the force and CMM measurements.

ACKNOWLEDGEMENTS

I will always be grateful to my advisor, Dr. Ismail Lazoglu for the guidance and support in the research toward this thesis. Thank you for your willingness and enthusiasm for this thesis. I thank Dr. Selcuk Savas and Dr. Haydar Livatyali for being on my dissertation committee and providing me their insights and helping me make this a better thesis.

To my friends, Kivilcim Buyukhatipoglu, Isil Yildirim, Isilay Talay Degirmenci, Ertan Cetingul that made me feel at home. Thank you for your great emotional support, without you I can not achieve so far. To everyone here at the Koc University who made this a great place to be, my heartfelt thanks.

Arcelik A.S. was the firm that financially supported this research and provided tools, workpieces for the refrigerator compressor piston tests. To everyone at Arcelik A.S. that helped me and made my work so much easier; Fatih Ozkadi, Feriha Sertcelik, Tekin Tekkalmaz, Yusuf Sahin, Ahmet Arpaciglu, Ercan Kitirci, Irem Nur Duru, I express my deepest gratitude.

Last but not least, I thank my parents and my brother for always being there when I needed them most, and for supporting me through all these years.

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NOMENCLATURE

β_0	Helix angle
ψ_c	Chisel edge angle
κ	Total tip angle
β	Lag angle
θ	Angular rotation of drill
Ω	Rotation angle for each respective discrete disk
c	Feed per revolution
Δb	Differential chip width
dA	Differential chip load for flat surfaces
dS	Differential chip load for cylindrical surfaces
dz	Differential chip height
h	Chip thickness
w	Total chisel width
f	Feedrate
$K_{tc}, K_{rc}, K_{\psi c}$	Tangential, radial, zenith cutting coefficients
$K_{te}, K_{re}, K_{\psi e}$	Tangential, radial, zenith edge coefficients
N	Number of flutes
dF_r, dF_ψ, dF_t	Radial, zenith, tangential force components
ζ	Damping ratio
ω_n	Natural frequency
K	Stiffness of the system
R	Residue
ω_d	Damping frequency
k	Mode number
P	Pressure

R_p Radius of the compressor piston

f_s Sampling frequency



Chapter 1

INTRODUCTION

1.1 Background

Drilling is one of the most commonly used machining processes. A typical drill has several design parameters such as tip angle and helix angle, each affecting the cutting in a different way. From the metal cutting point of view, chip load is large and the chips may be trapped in the cutting zone causing various problems in drilling.

It is known that a drill consists of two cutting edges: the chisel edge and the cutting lips. The chisel edge extrudes into the workpiece material and contributes substantially to the thrust force but little to the torque. The cutting lips cut out the material and produce the majority of the drilling torque and thrust. During a drilling operation, the chips are formed along the cutting lip and moved up following the drill helix angle. The drill geometry has a complicated effect on the cutting forces. In addition to that, the cutting forces depend on the tool and workpiece material properties and machining conditions. The cutting forces are the reason of the problems related to drilling in manufacturing such as form and surface errors, vibration, tool wear etc.

In the past, in industry, the drill point geometry and machining conditions were selected without considering the cutting forces; therefore, drill manufactures introduce new point geometry and recommend each for specific application and certain performance requirements and these mean extensive experiments. A simulation predicted the cutting forces for arbitrary drill point geometry based on tool geometry parameters and machining conditions will be beneficial for designers.

As in this work, mechanistic approach is based on the geometry of the process and relates the forces to the chip load through the specific cutting forces which are related to fundamental machining parameters and the coefficients are determined from calibration experiments. The mechanistic force models for each machining process has a calibration algorithm that is unique to the process and calibration procedure is developed for drill geometry; however, it should be generalized and valid for

arbitrary point geometry. From this point, the model coefficients depend on the tool and workpiece material and should be independent of drill point geometry and machining process. Therefore, a lot of costly experiments can be eliminated when a new tool or workpiece material is used.

1.2 Objectives and Scope of the Thesis

In this study, the force model is based on a new calibration method that made it possible to obtain the cutting force coefficients directly from the tests performed with the drill tool prior to the actual cutting. The differential cutting forces are determined using a mechanistic approach for the discrete cutting edge sections and this approach takes into account the cutting force constants that are determined through calibration. These differential forces are transformed and summed into the total cutting force. After the prediction of the forces are predicted, measured frequency response functions of the tool and the spindle system are utilized for hole profile predictions. The model developed in this work has the flexibility of working for any workpiece and tool combination.

Chapter 2 provides necessary background with a state-of-the-art review on drilling analysis. The fundamentals of cutting mechanics, previous models for prediction of cutting forces and hole profiles in drilling are reviewed.

Chapter 3 describes the detailed illustration of the drill geometry for each cutting edge and modeling of drilling forces assuming the cutting edges are not identical. The force model also includes the chip load model for flat and cylindrical surfaces. In addition to these points, calculation of the cutting forces for each cutting edge and the resultant dynamometer forces are also included in this chapter.

Calibration process details are given in Chapter 4, where the methodology that is employed to determine the cutting constants for the force model is described. The proposed methodology for more accurate prediction of the cutting force in Z direction is explained in detail. The effect of the tip angle on the calibration coefficients is also investigated.

In Chapter 5, the dynamic model is enhanced to obtain displacement values in X and Y directions. A satisfactory prediction of the cutting forces in the X and Y direction has been made possible to be used in hole quality predictions in this model. The transfer function of the system is experimentally found and used in the dynamic model to predict the displacement and the hole profile. Measuring

some properties of the hole such as cylindricity, roundness and perpendicularity values are predicted by the model.

Validation tests under various conditions are described and their results given in Chapter 6, together with the discussion of these results.

Chapter 7 summarizes the research conducted in this study and includes the recommendations for the future.



Chapter 2

LITERATURE REVIEW

2.1 Overview

Drilling is one of the most commonly used metal cutting processes in manufacturing, and precisely drilled holes are important for producing high quality products. For example, more than a million holes may be drilled in one wing of a commercial passenger jet. Despite its wide usage, drilling remains scientifically a poorly understood manufacturing process where current difficulties include poor hole quality, early tool wear and breakage, burr formation, chip clogging, excessive heat generation, process stability, self excited vibration and regenerative chatter. In order to improve the performance and the capability of the process, it is necessary to understand the mechanics and dynamics of drilling.

2.2 Static and Dynamic Drilling Force Models

Previous researchers have developed mathematical models of drilling to estimate thrust and torque. Williams [1] showed that during cutting there are three identifiable zones of interest at the drill point, the main cutting edges, the secondary cutting edges at the chisel edge and an indentation zone about the drill center and he developed a theoretical method to predict the torque and thrust along the main cutting edge and chisel edge. Zhang *et al.*'s model was based on mechanics of vibration cutting analysis and the continuous distribution of thrust and torque along the lip and the chisel edge of the twist drill [2]. Wang *et al.* presented a method which involves the development of a dynamic uncut chip thickness for each vibration cutting element at the lips and chisel edge. The mean thrust and torque increased as feed increase under constant vibration parameters [3-4]. They

concluded that vibration drilling is different from conventional drilling and is a dynamic cutting process.

Another model was presented for drilling processes by Yang *et al.* [5]. The model has four parts: the force model for the cutting lip, the force model for the chisel edge, the dynamic model for the machine tool and the regenerative correlation between the force and machine tool vibration. Some of the results they observed in the vibration experiments are given as follows; the larger the feed and the point angle are, the larger the vibration is and the vibration is largest at the tip of the tool. Actually vibration may be started as the tool cuts and at hard area in the workpiece. If the radial forces are zero then the vibration will be zero. Elhachimi *et al.* assumes that the chisel edge model results are very small compared with where the cutting process takes place and they found that the thrust force is not sensitive to the variation of the spindle rotational speed. However, the effect of the spindle speed cannot be neglected on the torque. The power and the torque are proportional to the rotational speed. Moreover, thrust force, torque and power increase with the feed [6-7].

Rincon and Ulsoy [8] investigated the effects of gyroscopic moments and rotary inertia by a transverse vibration model for drill bits. The model used demonstrates the significance of these effects and complex drill geometries on the natural frequencies of the drill bit vibration. The most significant complex drill geometries were found to be the number of flutes rather than material properties, web taper etc.

Won and Dharan showed that the chisel edge in such drills is a major contributor to the thrust force that is the primary delamination when drilling composite materials. The experiments show a large reduction in the thrust force when a pilot hole is present which removes the chisel edge contribution and allows the use of much higher feed rates without the danger of delamination [9]. The diameter of the pilot hole is selected equal to the chisel length of drill in order to eliminate the disadvantage of the chisel-induced thrust force and avoids the threat of creating large delamination by large pre-drilled hole [10].

More recently, several researches have applied oblique machining theories to drilling by dividing the drill's cutting edges into small segments, performing calculations for each segment, and summing the results [11-12-16-17-18]. Unlike the other models, Stephenson and Agapiou's model is applicable to arbitrary point geometries and includes radial forces due to point asymmetry [11].

Watson considered the integrity chip in his model and he assumed that there may be a variation in the thickness of the chip along the cutting lip, then predictions of the torque and thrust, when drilling with a pilot hole that removes the material that would be machined by the chisel edge, can be obtained that agree with experimental results [13]. It had been assumed that the material being removed by the various processes can be divided into a series of small elements along the chisel edge and the integral chip for the cutting lip necessary to constrain all of the elements on the cutting region of the chisel edge [14]. Watson considered the effects of the feed, speed, point and relief angles on the chisel edge. As the feed, point angle and relief angles increase, the thrust increases. On the other hand, as speed decreases the thrust increases [15].

Chandrasekharan *et al.* [16-17-18] developed a theoretical method to predict the torque and thrust along the lip and chisel edge. A mechanistic force model can be used to develop models for cutting force system and a calibration algorithm to extract the cutting model coefficients. A generalized calibration is developed to determine the coefficients from force data from drilling experiments. The models are calibrated to a particular material using the relationships between chip load and cutting forces, modified to take advantage of the characteristics of the drill point geometry.

2.3 Factors Affecting Hole Quality

Drill performance can be defined in terms of tool life and hole quality (hole location, angularity, roundness, surface, burr formation). Hole quality parameters for the drilling processes are determined from the hole profile. The hole profile depends on transverse vibrations of the drill and associated radial forces, both of which are affected by the alignment errors such as drill axis offset and tilt. James [19-20] carried out tests using high speed twist drills in order to understand the machinability of sintered steels and investigate the reproducibility of hole quality under drill conditions. In those workpiece material containing MnS, torque and thrust decrease with speed. Errors in the hole diameter increase with the speed and the feedrate so presence of MnS reduces the effects of the errors. He found that drill thrust forces increased with feedrate and both drill torque and thrust forces increased with rotational speed. Hayajneh investigated the effect of machining parameters on hole quality produced by the deep hole machining process and to develop a better understanding of the effect of these process parameters on the hole quality [21].

Another statistical analysis of hole quality was performed by Furness *et al.* [22]. They found that feed and speed have a relatively small effect on the measured hole quality features. With the expectation of hole location error, the hole quality was not predictably or significantly affected by the cutting conditions. Although the authors did not expect these results, they have the important positive implication that production rates may be increased without sacrificing hole quality. The drilling feeds and speeds would be constrained by factors other than hole quality, such as drill wear, drill breakage, or force, torque, and power limits.

Two different types of vibration can be distinguished in drilling, low frequency vibrations associated with lobed holes and chatter. One of the most common roundness problems in drilled holes is the existence of the spaced lobes. Bayly *et al.* found that lobed hole profiles exist even in the absence of chatter and at very low cutting speed. The low frequency vibration is significant for drilling because it directly affects the hole quality [23]. Batzer *et al.* suggested that to consider real stiffness of tool and workpiece, it is necessary to develop a mathematical model describing vibratory drilling process dynamics and to study the influence of system parameters on the vibratory drilling process [24]. The features of the vibratory cutting are periodic changes of cutting forces, dynamic conditions (feed, speed, forces, and tool angles) and decreased frictional forces between tool, chip and workpiece, increased cutting fluid application efficiency.

Rincon and Ulsoy [25] showed that the changes in the relative motion of the drill do affect the variations of the forces. An increase in the ranges of drill motion, results in an increase in the ranges of torque and thrust. They suggested that drill vibrations can have an effect on drilling performance because increasing vibration during entry can cause poor hole location accuracy and burr formulation. Increased vibration during steady state drilling conditions results in worst hole quality.

Khagendra *et al.* [26] modeled the drilling dynamics, including the drill vibrations and the drilling forces, in the presence of alignment errors. The drill vibrations and the radial forces depend strongly on the alignment errors. Alignment errors are defined as axial tilt, drill orientation angle and linear offset. It was found that the axial tilt, drill orientation angle and the feed rate significantly affects them. An increase in the feed rate causes the chip area and thus the radial forces and the drill vibrations to increase. They developed a hole profile model that considers alignment errors, effects of drill wandering and drill margin interaction with the hole wall [27].

Chip extraction in drilling machining causes great variations in cutting force, drill life and hole accuracy. Deyuan and Lijiang [28] analyzed the major cutting edge chip and the chisel edge chip formulation in vibration drilling.



Chapter 3

DRILL GEOMETRY AND CUTTING FORCE MODEL

3.1 Introduction

A large variety of drilling tools are available such as spiral point drills, split point drills, spade drills and multiflute drills but the twist drill is the most popular and often the only practical tool for boring holes. All the drills used in such experiments are the conventional drills with two cutting edges and two flutes. Each cutting edge on the tool is carefully designed to ensure maximum cutting performance while minimizing the resulting cutting forces, and therefore minimizing the error in displacements. A detailed analysis of the cutting edge geometry is necessary for the development of the force model. In order to form the model, all of the acting components in cutting must be represented mathematically first, and thereafter, the relationships between these components in the real process must be defined building upon these representations.

In this chapter, the nature of the cutting tool has been given firstly by determining the tip angle κ and secondly with the determination of cutting edges which are represented as a function of r , the vertical distance from a cutting point to the axis of cutter and the tip angle in Figure 3.1. This approach is applied for each cutting edge on the cutting tool.

Thereafter, a detailed description of the proposed force model is given. The utilized chip load model for flat and circular surfaces is introduced first, which is followed by the explanation of the mechanistic force model.

3.2 Tool Geometry

The important characteristics of drilling tools are the micro geometry (point angle, helix angle, chisel edge angle, drill diameter, web thickness etc.), the drill type (e.g. carbide, HSS), and coating material (e.g. TiN, TiAlN/ TiN).

The detailed geometry of a twist drill cutter is shown in Figure 3.1. A drill has a chisel edge at the bottom and two helical cutting lips with a tip angle κ that meet with the flutes with a helix angle of β_0 . The chisel has a width of w , and a chisel edge angle of ψ_c . Drill cutting edge geometry varies locally in the helical flutes part. Assuming that the drill is not identical, the point angle and chisel edge angle thus the cutting edge geometry should be evaluated for each helical flute.

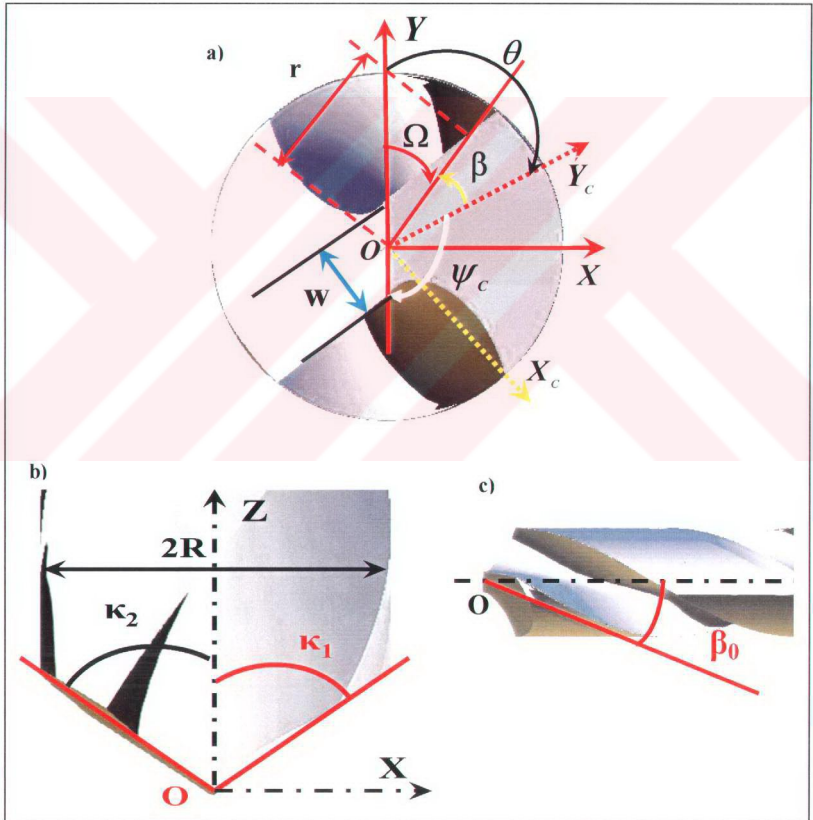


Figure 3.1: a) Illustration of the angular relationships
b) Illustration of the point angle
c) Illustration of the helix angle

The geometry of the cutting lip of a drill is important to evaluate chip load because the lips expand the hole by removing the material with a constant chip thickness of h as the drill is fed into the material at a feedrate of c . The drill axis is aligned with z and when the drill rotates an angular rotation angle of θ , the lip that having an offset from the drill axis due to chisel edges is made parallel to y_c , and the axis normal to the lip is parallel to x_c in a cartesian coordinate system with a center at the drill tip O .

The radial distance r in the x - y plane is

$$r^2 = x_c^2 + y_c^2 \quad (3.1)$$

and considering the bottom of the flute where the lips and chisel edge meet, the cutter radius is

$$r(0) = \frac{w}{\sin(\pi - \psi_c)} \quad (3.2)$$

The cutting edge geometries of a cutter in the model can be presented by using polynomial fitting of CMM data set. The cutting edge coordinates can be measured either using a coordinate measurement machine (CMM) or using a sufficiently magnified picture of the cutting edge. After the collection of the data points on the cutting edges, polynomial fitting can be performed on this data.

For this purpose a magnified view of the cutter (with 7.698 mm diameter, two-flute twist carbide drill), has been obtained using a optical microscope as seen in Figure 3.2. As mentioned before assuming that the cutting edges of the drill are not identical, cutting edge geometry is obtained for the two cutting edges. By using the obtained photo, both cutting edges of the cutter have been divided into grids and 12 distinct points have been taken on the cutting edges to resemble the cutting edges (Figure 3.3 a). The relative locations of these points have been entered to Matlab to obtain a third degree fitted polynomial that formed the cutting edge geometry for the mathematical model (Figure 3.3 b). The following equations have been obtained for the two cutting edges;

$$\beta_1 = -0.059382 \cdot r_1^3 + 0.60252 \cdot r_1^2 - 2.1645 \cdot r_1 + 3.0607 \quad (3.3.a)$$

$$\beta_2 = -0.029695 \cdot r_2^3 + 0.34285 \cdot r_2^2 - 1.4145 \cdot r_2 + 2.4455 \quad (3.3.b)$$

where r_1 and r_2 [mm] are the radius of points on the cutting edges on a plane perpendicular to the cutter longitudinal axis, and β_1 and β_2 [rad] are the angles between the lines which connect these points to the tip and the lines which are tangent to the cutting edges at the tip. Therefore, by varying r_1 and r_2 values from the tip to cutter radius (i.e., $0-R_d$), the full cutting edges profile can be determined from these equations.

After obtaining the cutting edge geometry, by using the same photo w and $r(0)$ can be measured for each cutting edge. Through the use of Equation (3.2) the chisel edge angle can be calculated for the two cutting edges. The total chisel width can be calculated as follows,

$$w = w_1 + w_2 \quad (3.4)$$

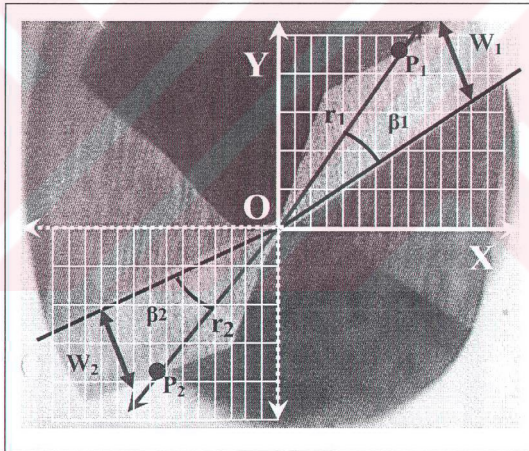


Figure 3.2: Ø7.698 mm carbide twist drill cutter

Afterwards in order to evaluate the total point angle, for each cutting edge, the angle between the drill center and the point where the radial distance is R_d , is measured by using CMM (Figure 3.4). The sum of these angles is the total tip angle of the drill (Equation 3.4).

$$\kappa = \kappa_1 + \kappa_2 \quad (3.5)$$

In Table 3.1 and 3.2, the edge tip angles for each cutting edge measured by CMM, the chisel edge angles and chisel edge widths for each cutting edge calculated from the photo and the drill diameter measured by using micrometer can be seen. The first drill is used for the calibration procedure (See Chapter 4 for detail) and the other drills are used to see the effects of the tip angle to the thrust and torque.

Table 3.1: Numerical values of drill diameter and tip angles for each cutting edge

Drill Number	Drill Diameter D (mm)	First Cutting Edge Tip Angle κ_1 (degree)	Second Cutting Edge Tip Angle κ_2 (degree)	Total Tip Angle κ (degree)	Number of Cutting Edge
1	7.698	46.983	47.112	94.095	One cutting edge
2	7.696	47.292	47.273	94.565	One cutting edge
3	7.697	52.546	54.779	107.325	One cutting edge
4	7.697	64.134	63.803	127.937	One cutting edge
5	7.698	47.313	47.430	94.743	Two cutting edge
6	7.7	47.326	47.306	94.632	Two cutting edge

Table 3.2: Numerical values of chisel edge angles and chisel edge widths for each cutting edge

Drill Number	First Cutting Edge Chisel Edge Angle ψ_{c1} (degree)	Second Cutting Edge Chisel Edge Angle ψ_{c2} (degree)	First Cutting Edge Chisel Edge Width W_1 (mm)	Second Cutting Edge Chisel Edge Width w_2 (mm)
1	133.5927	136.1781	1.0430	1.0888
2	139.7691	137.3577	0.8851	1.0920
3	136.1869	133.0491	0.9504	0.9879
4	137.0114	134.4153	0.9050	0.8640
5	134.456	132.263	0.9435	0.9873
6	136.572	133.856	0.8921	0.9249

The z coordinate of a point located on the cutting edges can be found by utilizing the κ_1, κ_2 angles as follows,

$$z = \frac{r}{\tan(\kappa_n)} \quad n = 1, 2 \quad (3.6)$$

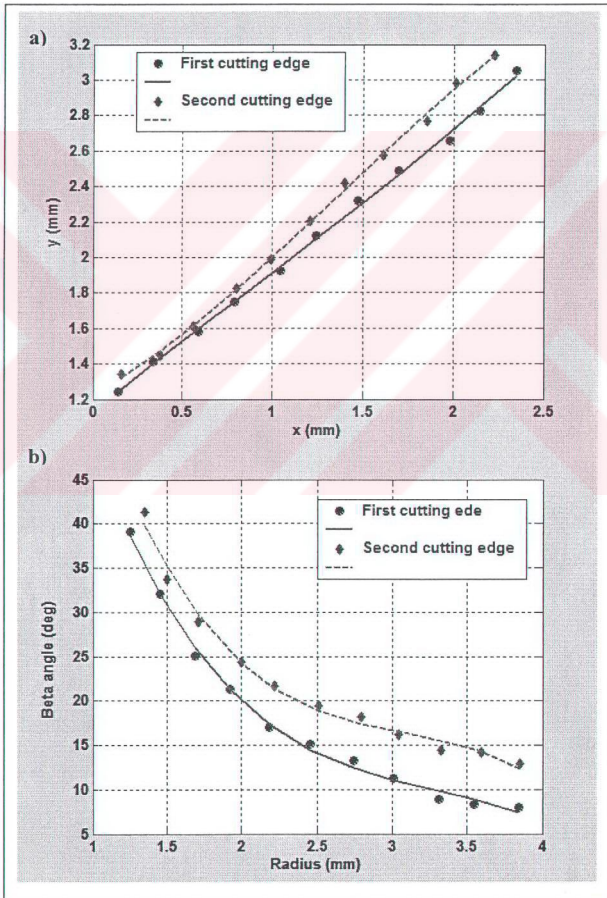


Figure 3.3: a) Measured data points for x-y planes
b) Third degree polynomial fit obtained for $\beta_1(r_1)$ and $\beta_2(r_2)$

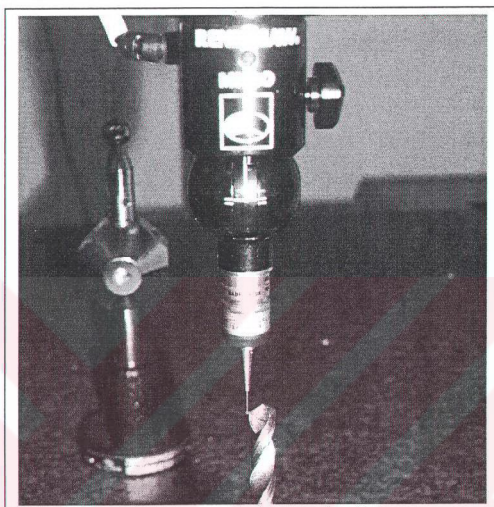


Figure 3.4: Measuring the tip angle for each cutting edge of drill

3.3 Modeling of Drilling Forces

3.3.1 Introduction

In the machining of complex and costly parts such as those involved in the automotive, aircraft and computer industries as well as fields such as home appliance industry, medical science and equipments, prior knowledge of the drilling forces help engineers in selecting appropriate cutting conditions to reduce tool deflection which affects the surface quality of the drilled holes and designing machine tools. For instance, if the chip load is selected to be too large, the forces cause chipping of the cutting edge or even tool breakage, while a small chip load will decrease productivity.

Many recent investigations have been made to understand the nature of the cutting forces during drilling. By utilization of the previously proposed methods, the motivation in this study is to form a

comprehensive and practical model that is validated through various cutting conditions. Since accurate predictions for the cutting forces are aimed, a mechanistic approach is employed. Calibration tests are required to be made for each material/tool combination in order to determine the specific cutting constants in the model; however the resulting model is supposed to be making satisfactory predictions for all drill types as long as cutter's properties of cutters are known.

In this chapter, the chip model is obtained for both flat surfaces and cylindrical surfaces. After explaining the details of the chip load model, the employed force model is described. In the model, the cutting forces for each cutting edge are calculated because the cutting edges are not identical. In order to calculate the total force, the cutting forces for each cutting edge are added up. At the end of this chapter, summary charts for the mechanistic approach and dynamic approach can be seen.

3.3.2 Chip Load Model

3.3.2.1 Flat Surfaces

In order to determine the differential cutting forces at any cutter point in the engagement point, the chip load is found as follows,

$$dA = \Delta b \cdot h \quad (3.7)$$

where Δb is the differential chip width and h is the chip thickness removed by one of the two flutes (Figure 3.5). Δb can be written as the following,

$$\Delta b = \frac{dz}{\cos(\kappa)} \quad (3.8.a)$$

$$h = \frac{c}{N} \cdot \sin(\kappa) \quad (3.8.b)$$

where dz represents differential chip height along the longitudinal cutter, c is the feedrate per revolution of the drill and N is the number of cutting edges.

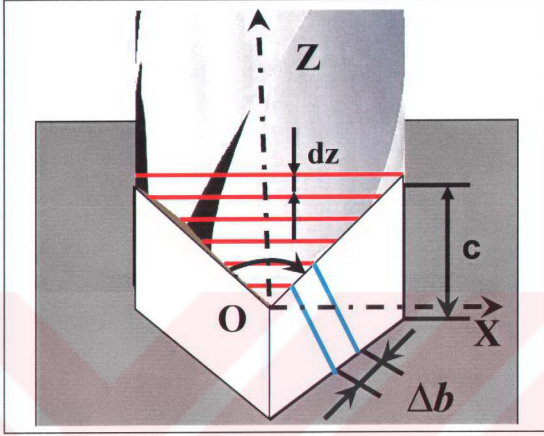


Figure 3.5: Illustration of the chip load for flat surfaces

3.3.2.2 Cylindrical Surfaces

In order to determine the chip load for circular surfaces, the chip load (dS) is divided into two regions S1 and S3. S3 is the area between S2 and S4. S1, S3 and S4 can be seen in Figure 3.6. dS can be calculated as the sum of S1 and S3 areas (Equation 3.13). S1 and S3 can be found as follows,

$$S1 = \frac{c \cdot dz \cdot \tan(\kappa)}{N} \quad (3.9)$$

$$S2 = \frac{\pi R_p^2}{360} \cdot \sin^{-1}\left(\frac{r_i}{R_p}\right) \quad i = 1 \dots K \quad (3.10)$$

$$S4 = r_i \cdot \left(\frac{\sqrt{R_p^2 - r_i^2}}{2} \right) \quad (3.11)$$

$$S3 = (S2 - S4) \quad (3.12)$$

$$dS = (S1 + S3) \quad (3.13)$$

where R_p is the radius of the circular surface and r_i is the radial distance of the cutting edge in x - y plane at the i^{th} term.

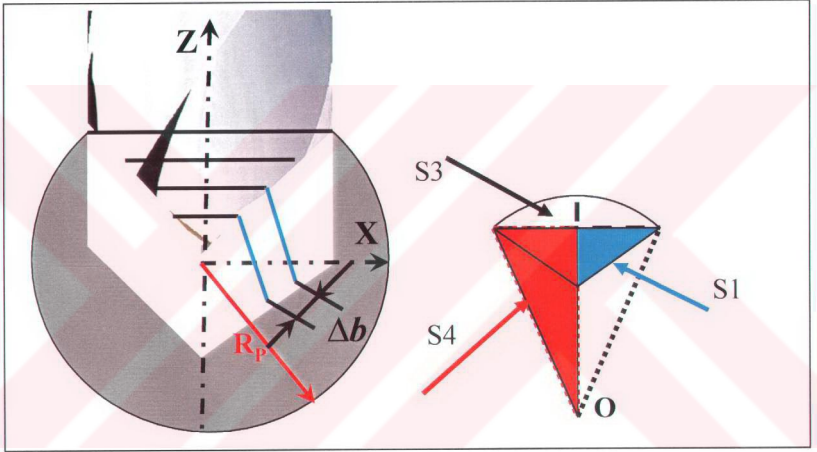


Figure 3.6: Illustration of the chip load for circular surfaces

3.3.3 Cutting Force Model

For a differential chip load dA in engagement domain, the differential radial dF_r , zenith dF_ψ and tangential dF_t cutting forces can be written as follows (Figure 3.7),

$$\begin{aligned} dF_t &= K_{tc} \cdot dA + K_{tc} \cdot \Delta b \\ dF_r &= K_{rc} \cdot dA + K_{rc} \cdot \Delta b \\ dF_\psi &= K_{\psi c} \cdot dA + K_{\psi c} \cdot \Delta b \end{aligned} \quad (3.14)$$

where K_{tc} , K_{rc} , $K_{\psi c}$ are the tangential, radial, zenith cutting coefficients and K_{te} , K_{re} , $K_{\psi e}$ are the related edge coefficients.

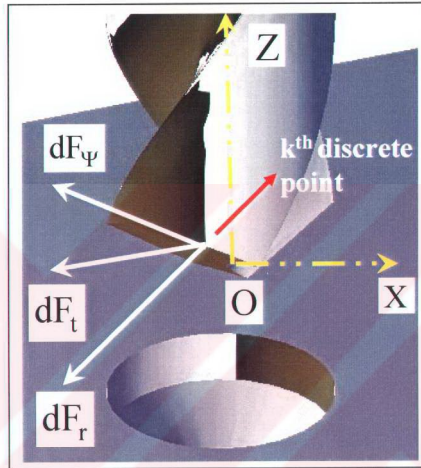


Figure 3.7: Illustration of the cutting forces

In order to determine these coefficients, calibration tests were performed with the single cutting edge drill cutter and an Al7039 workpiece material, which was also used in the model validation tests. The 7.698 mm diameter cutter that has one cutting edge has been divided into 5 separate disks and cutting constants were individually evaluated for each region by performing incremental drilling with different feeds at the calibration phase (Figure 3.5).

Once dF_r , dF_{ψ} , dF_t were obtained through use of Equation (3.14), these cutting force components can be transformed into X-Y-Z global coordinate system as the following:

$$\begin{bmatrix} dF_x \\ dF_y \\ dF_z \end{bmatrix} = A \cdot \begin{bmatrix} dF_r \\ dF_{\psi} \\ dF_t \end{bmatrix} \quad (3.15)$$

$$A = \begin{bmatrix} \sin \Omega \cdot \cos \kappa & \cos \Omega \cdot \cos \kappa & \cos \Omega \\ \sin \Omega \cdot \sin \kappa & \cos \Omega \cdot \sin \kappa & \sin \Omega \\ \sin \kappa & \cos \kappa & 0 \end{bmatrix}$$

$$\Omega = \theta + \frac{(n-1) \cdot 2\pi}{N_f} - \beta; \quad n = 1 \dots N_f \quad (3.15)$$

$$\begin{bmatrix} F_X \\ F_Y \\ F_Z \end{bmatrix} = \sum_{n=1}^N \sum_{k=1}^K \begin{bmatrix} dF_X \\ dF_Y \\ dF_Z + dF_P \end{bmatrix} \bigg|_{k,n}$$

where Ω is the drill rotation angle, θ is the instantaneous angular position of the discrete point on the cutting edge in concern (Figure 3.1) and N is the number of flutes, k is the discrete point on n^{th} cutting edge (Figure 3.7).

One important aspect of the model to mention here is the additional dF_P force that is added to dF_Z . This force is assumed to result from a constant pressure value existing over the workpiece as long as the cutter moved down into the workpiece in the z direction. Its amplitude equals this constant pressure times the area of the cutter/workpiece contact region. Additional tests have been performed in the calibration phase to detect the constant pressure $P(f)$ [MPa] as a function of feedrate (f) [mm/min].

$$P(f) = -0.00088548.f^2 + 1.5364.f - 103.06 \quad (3.16)$$

The next step after prediction of cutting forces is to validate these predictions by performing various validation tests. Validation tests and their results are explained in Chapter 6. A summary chart of the proposed mechanistic approach is supplied in Figure 3.8 and the dynamic approach is supplied in Figure 3.9.

3.3.4 Measured Dynamometer Forces

As mentioned before, calibration procedure was performed on the drill with one cutting edge. The reason for this is explained in Chapter 4 thoroughly. Shortly, the dynamometer measures the vector quantity of total forces at both lips and the forces on each lip act in opposite directions and would be in equal magnitude and sum to zero if two flutes are identical. However, the cutting edges used in those experiments were not identical. The dynamometer measures the error forces between the cutting edges. In order to measure the cutting forces in the X and Y direction, first cutting edge of the drill is grinded and calibration experiments were performed by using this drill. First cutting edge of the drill is grinded and its properties can be seen in Table 3.1 and 3.2.

As long as knowing the tip angle, chisel edge angle and the chisel edge width of each cutting edge, simulations of the cutting force model run for each cutting edge. The main difference in the model is the drill rotation angle and it can be calculated using Equation 3.14. The difference of rotation angle between the two cutting edges is 180 degrees. At the end of the model, the cutting forces found for each cutting edge are added vectorally to calculate the dynamometer forces.

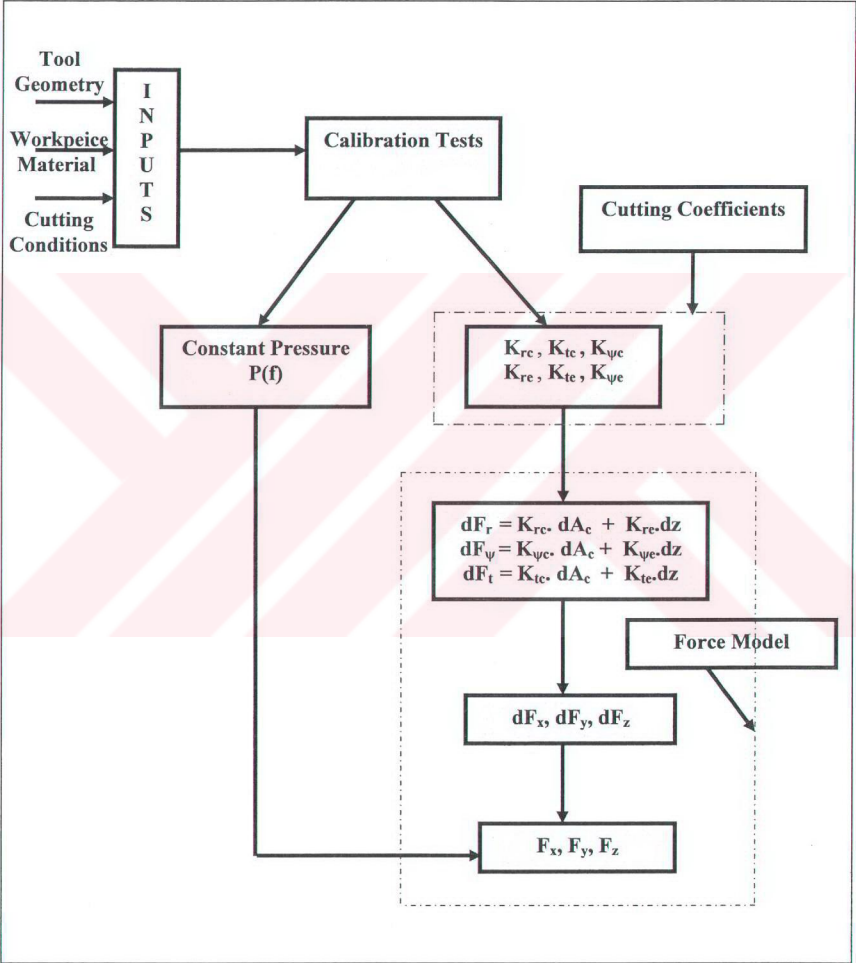


Figure 3.8: A summary chart of the proposed mechanistic approach

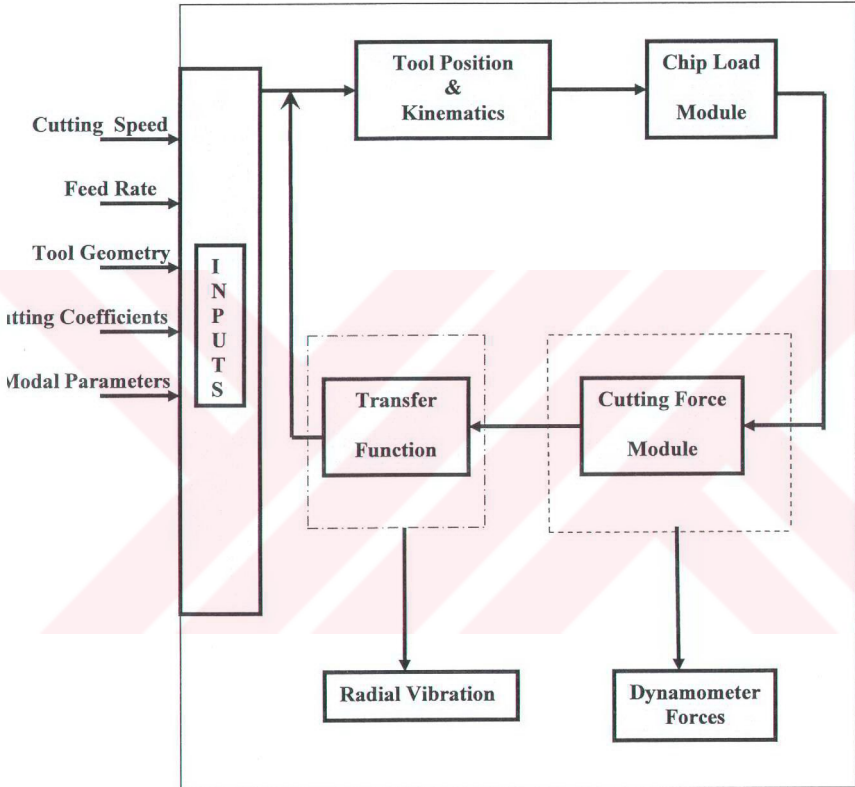


Figure 3.9: A summary chart of the proposed dynamic approach

Chapter 4

CALIBRATION PROCESS

4.1 Determining the Cutting Coefficients

A calibration algorithm is developed to determine the oblique-cutting model coefficients used in computing the specific forces.

The experiments for calibration were performed on Mazak FJV-200 UHS Vertical Machining Center (VMC). The cutter was uncoated drill cutter with 7.698 mm diameter, 94.095 degrees total tip angle. The drill (drill number 1) properties can be seen in Table 3.1 and Table 3.2. The workpiece materials were aluminum blocks (A17039) of size 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. (Figure 4.1)

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 later taken by the charge amplifier and converted into voltage output. The sensitivity values for the three channels (X, Y and Z) in the amplifier were -7.87, -7.90, and -3.69 pC/N, respectively. Amplifier gain for the device was set to 100 N/V for X, and Y channels and was set to 300 N/V for channel Z. Subsequently, through use of a proper data acquisition card and software, the voltage is displayed and recorded as cutting forces in Newton. A data acquisition program, MALDAQ module of CutPro, records and displays the measured data (See Figure 4.4 for a sample output screen of CutPro). The complete testing environment is shown in Figure 4.3 and the details of the experimental setup can be seen in Figure 4.5.

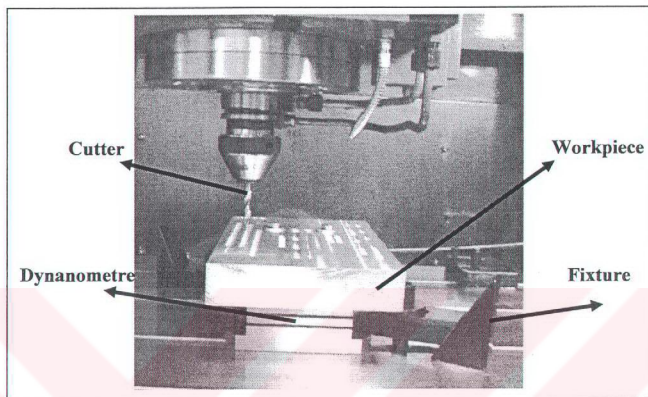


Figure 4.1: Workpiece and 3-component dynamometer fixed to VMC machine table for cutting tests

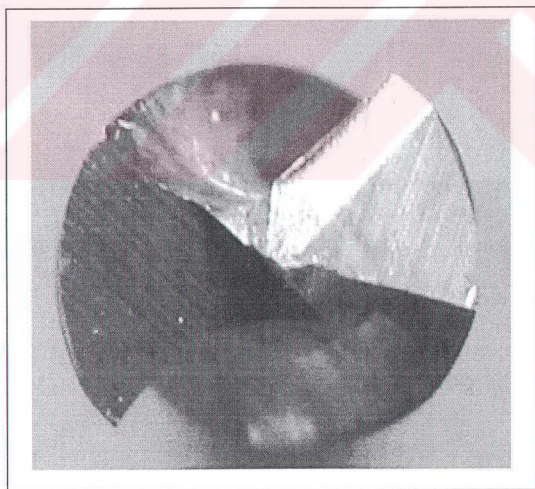


Figure 4.2: Top view of the grinded drill

First step to be taken is to obtain the cutting forces by conducting a set of drilling experiments at different feed rates. The 44-198 mm/min feed rate interval has been tested in this study. The cutting lip of the drill has been divided into 5 regions to accurately predict the distribution of the cutting forces. Assuming the tip to be at zero level, these intervals were subsequently at 0-0.3, 0.3-0.7, 0.7-1.2, 1.2-1.7, 1.7-2.2 mm distance from tip. Each interval has been tested for five different feed rates; 110, 132, 154, 176 and 198 mm/min. The spindle speed (ω) was kept constant at 1100 rpm. Data has been collected for 1 second and with sampling frequency rate (f_s) of 1000 Hz at all tests. Two sets of experimental runs have been performed in order to increase reliability of results. The force collection of data is performed at every 6.6 degrees of cutter rotation ($\Delta\theta$).

$$\Delta\theta = \frac{2\pi \cdot \frac{\omega}{60}}{f_s} \quad (4.1)$$

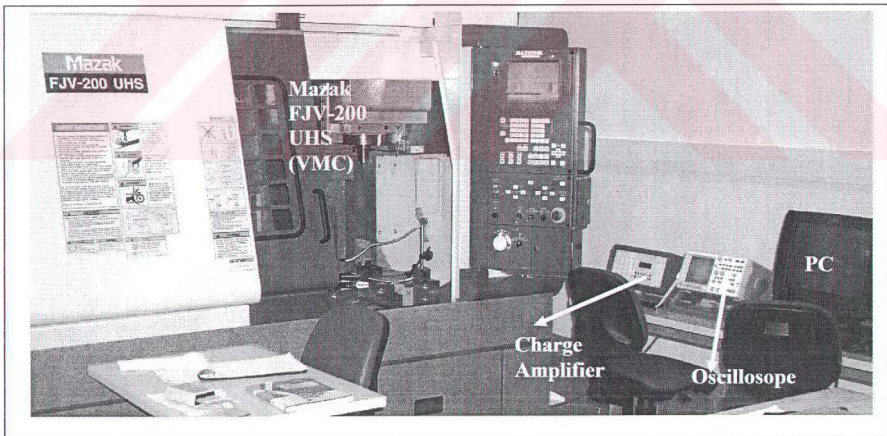


Figure 4.3: The experimental setup for measurement of cutting forces

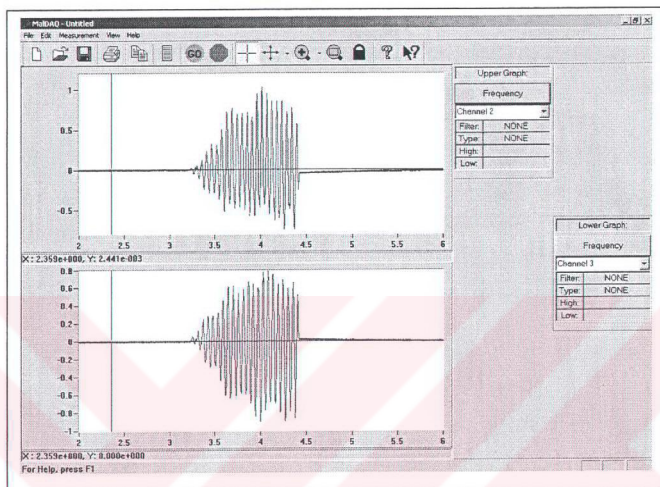
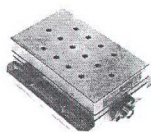


Figure 4.4: Sample output screen in CutPro for cutting forces

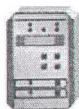
Cutting forces form a pressure on the workpiece which leads to occurrence of an electric charge output from the piezoelectric sensors on the dynamometer

Voltage output from the charge amplifier is displayed in analog form for validation

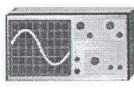
Cutting forces are displayed and recorded once voltage output from the charge amplifier is transformed into appropriate digital form



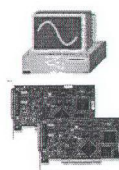
VMC Dynamometer



Charge Amplifier



Oscilloscope



DAQ+PC

Figure 4.5: The details of testing environment for measurement of cutting forces

All the cutting forces of the first set of experiments along the cutting edge height, 2.2 mm, can be seen in Figures 4.6 and 4.7. In order to obtain the cutting coefficients for a certain interval, the following procedure has been applied step by step:

1. The angular phase differences have been detected for all the collected data and by accounting for these differences all experimental force data have been equally aligned.

2. Using the inverse of the transformation matrix given in Equation 3.9; collected force components (F_x , F_y , F_z) have been transformed into radial, zenith and tangential components (F_r , F_ψ , F_t).

3. The peak points (maximum values) of all three components (r - ψ - t) of the cutting force for each depth of cut have been found for spindle revolution (ω) of 1100 rpm and sampling frequency (f_s) of 1000 Hz and have been averaged. At the end of this step, averaged values for each depth of cut have been obtained.

4. The differences between the averaged force values have been obtained for each depth of cut (e.g., for the 0.7-1.2 mm interval, the cutting forces will equal the difference between 1.2 mm depth of cut and 0.7 mm depth of cut tests).

5. Once the F_r , F_ψ , F_t values have been obtained for each depth of cut interval, these have been plotted versus chip thickness in order to obtain the cutting coefficients (Figure 4.9 to 4.11). The determination of cutting constants from experimental data is summarized in Figure 4.8. Calibration is performed only considering one single cutting edge. One cutting edge of the drill is grinded along its length (Figure 4.2). The reason for grinding is that the dynamometer measures the vector quantity of total forces at both lips and the forces on each lip act in opposite directions and would be in equal magnitude and sum to zero if two flutes are identical. However, the presence of point grinding creates unequal forces on each lip. For this reason, measured dynamometer cutting forces are the errors between the cutting edges. Finally, to measure the forces in the X and Y direction, one cutting edge of the drill is grinded and calibration experiments are performed by using this drill.

The numerical values of the cutting coefficients determined with the calibration process for the Aluminum material (Al7039) are summarized in Table 4.1.

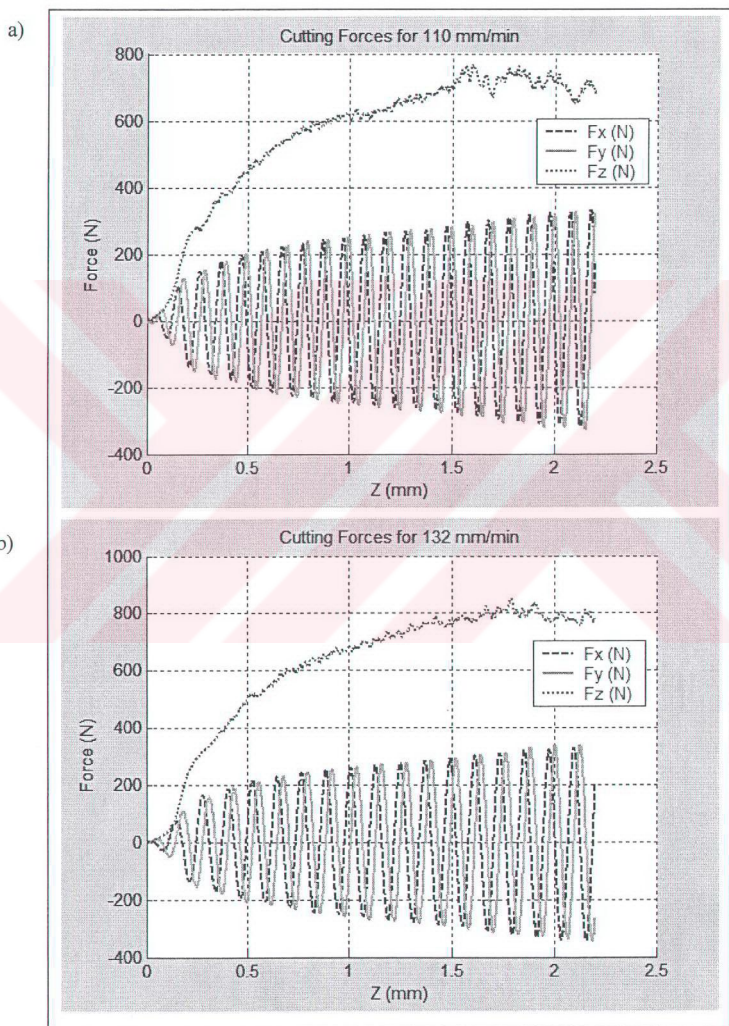
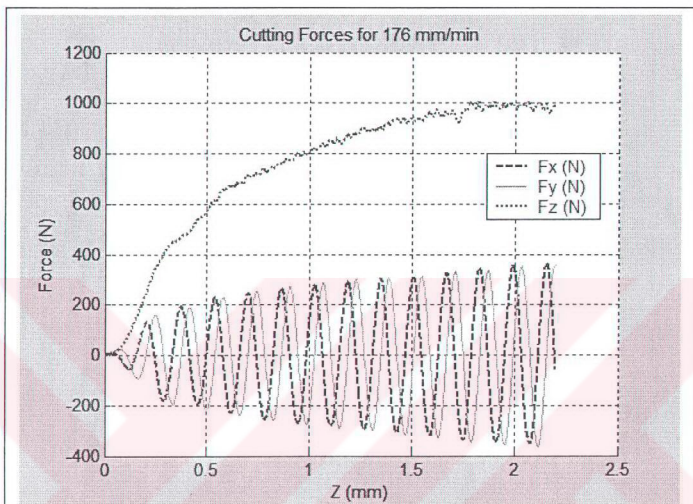


Figure 4.6: Cutting forces at 1100 rpm and 2.2 mm depth of cut;
a) 110 mm/min, b) 132 mm/min

a)



b)

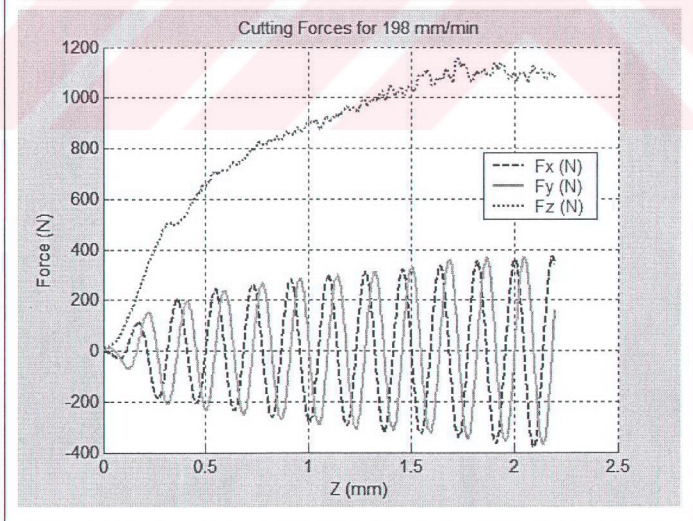


Figure 4.7: Cutting forces at 1100 rpm and 2.2 mm depth of cut;
a) 176 mm/min , b) 198 mm/min

Table 4.1: Numerical values of cutting and edge coefficients for the intervals from the drill tip.

interval from tip coefficients	0 - 0.3 [mm]	0.3-0.7 [mm]	0.7 - 1.2 [mm]	1.2 -1.7 [mm]	1.7 - 2.2 [mm]
$K_{\psi c}$ [N/mm ²]	27134	7235	4632	3744	2254
K_{tc} [N/mm ²]	15226	5462	3984	3063	2326
K_{rc} [N/mm ²]	24635	7428	4283	3315.6	2146.9
$K_{\psi e}$ [N/mm]	230.78	51.23	44.28	25.75	16.24
K_{te} [N/mm]	73.13	16.83	9.356	7.491	6.663
K_{re} [N/mm]	252.33	43.68	34.85	24.59	18.35

The change in cutting coefficients along the cutting edge is displayed in Figure 4.12. It is observed in these plots that the cutting and edge coefficients sharply fall until 0.5 mm distance from the tip.

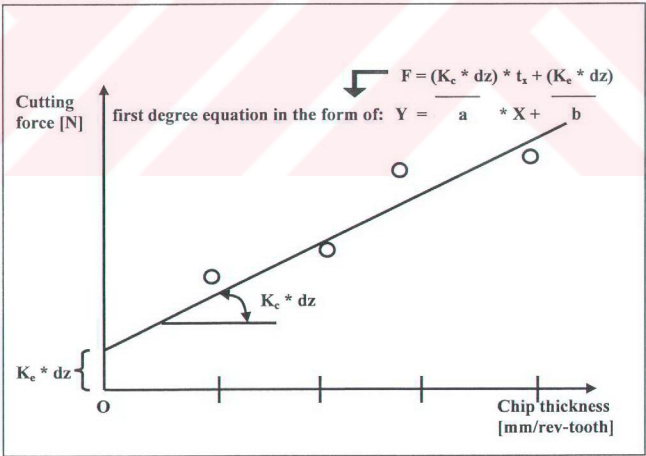


Figure 4.8: Determination of the cutting coefficients from experimental data

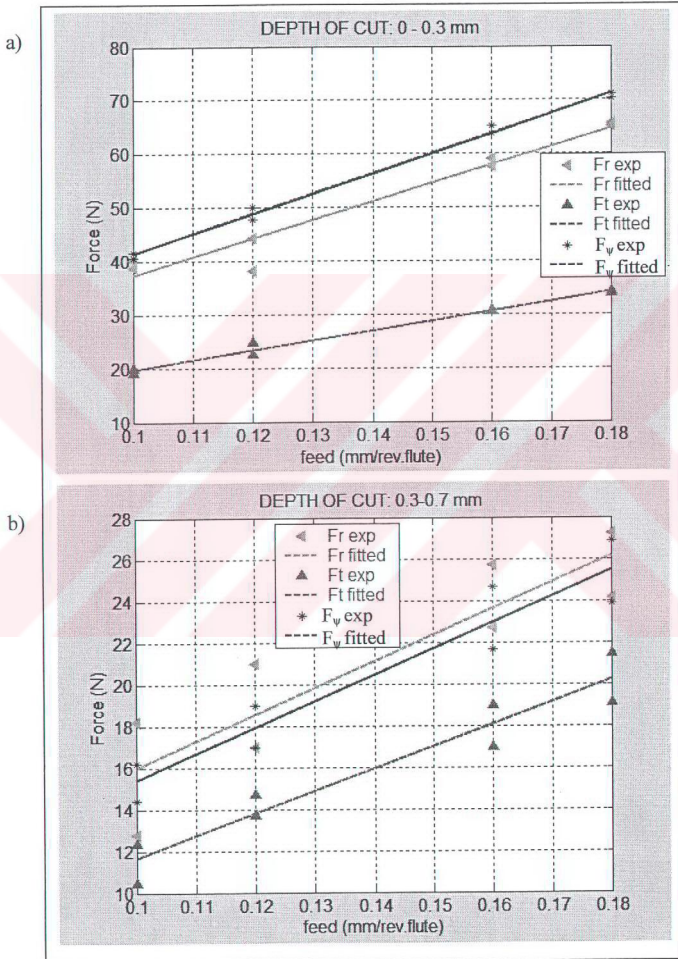
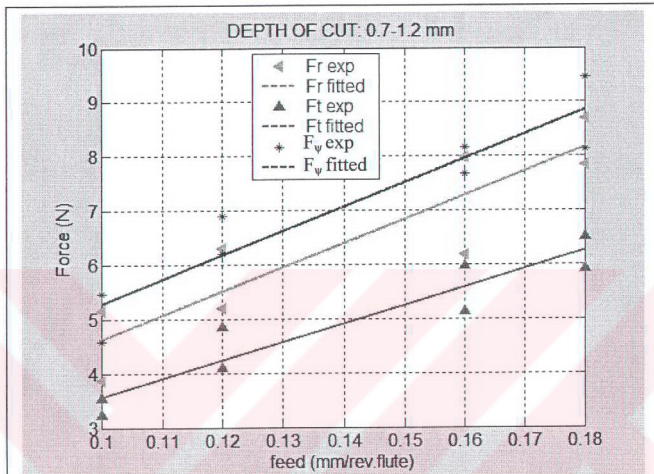
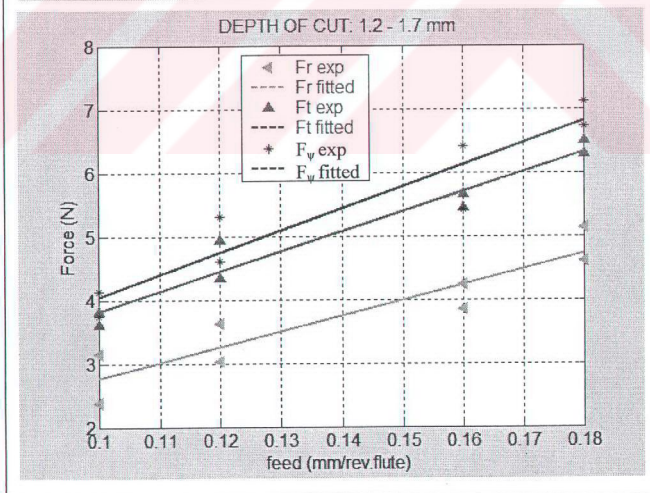


Figure 4.9: Cutting forces vs. chip thickness for different regions of the cutting edge;
a) 1100 rpm 0.0 – 0.3 mm, b) 1100 rpm 0.3 – 0.7 mm

a)



b)



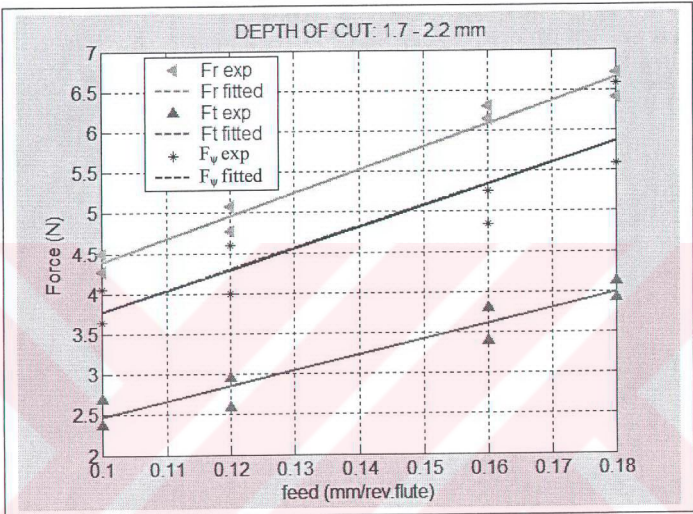


Figure 4.11: Cutting forces vs. chip thickness for different regions of the cutting edge, 1100 rpm 1.7 – 2.2 mm

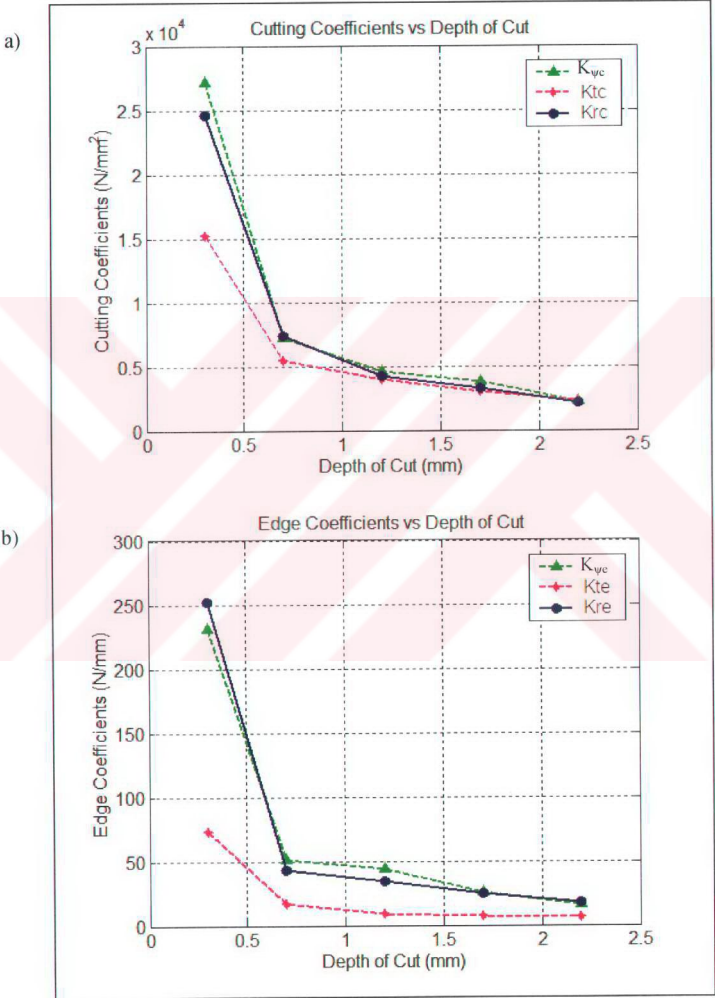


Figure 4.12: The change of coefficients along the cutting edge;
a) cutting coefficients, b) edge coefficients

4.2 Determining the Constant Pressure

Initial validation tests indicated a difference between force model outputs and the measured forces in thrust. This led to the assumption that the spindle was applying a constant pressure on the workpiece surface through the cutter which is proportional to the vertical feed rate into the workpiece. Thorough investigations proved that this assumption, indeed, was true.

The experimental setup in calibration tests has been used for these investigation runs. Vertical feed has been given the values; 110, 132, 154, 176, 198 mm/min. In order to determine the exerted constant pressure on the workpiece surface, the pressure formula:

$$P = F_z / A \quad (4.2)$$

has been used where F_z is the force in vertical direction and A is the contacting area of the cutter at an instant. The area contacting with the workpiece changes, as the cutter penetrates into the workpiece. This area is calculated numerically using a Matlab code for a certain feed rate. Since the penetration time is discretized for analysis, each incremental increase in the contacting area for a time interval is found and added in order to find the total contacting area at an instant.

The change of the contacting region with respect to time is given in Figure 4.13.a for the feed 198 mm/min. The cutting force F_z , changing with time is given in Figure 4.13.b and Figure 4.14 together with the resulting constant pressure.

The constant pressure values have been found for all tested feed rates and plotted in order to obtain a third degree fitted polynomial for pressure as a function of feed rate (Equation 3.15). The calculated values for the constant pressure can be seen in Figure 4.15 together with the fitted function for constant pressure. F_p is the pressure force that added to the simulated force F_z in the model to calculate the measured vertical force.

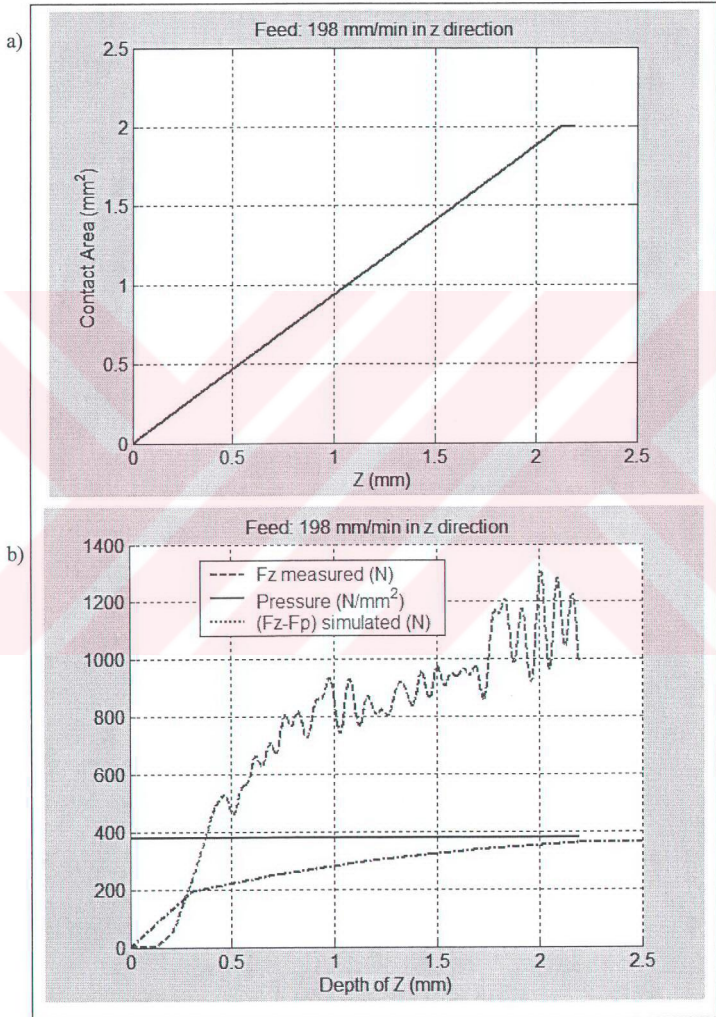


Figure 4.13: a) The change of contact area with feed 198 mm/min
b) The change of cutting forces with feed 198 mm/min and the observed constant pressure

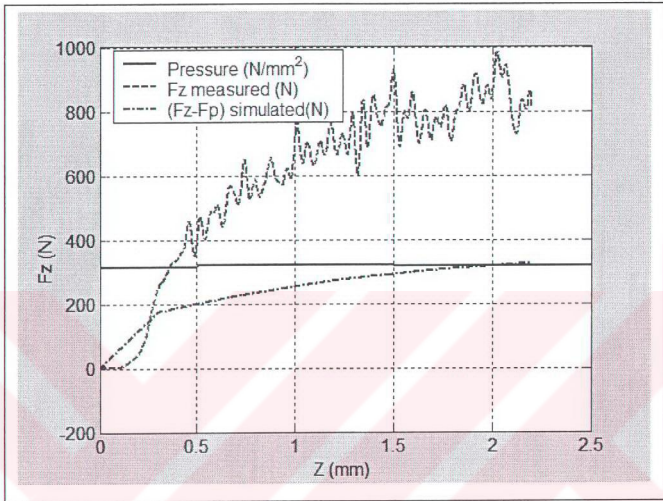


Figure 4.14: The change of cutting forces with feed 132 mm/min and the observed constant pressure

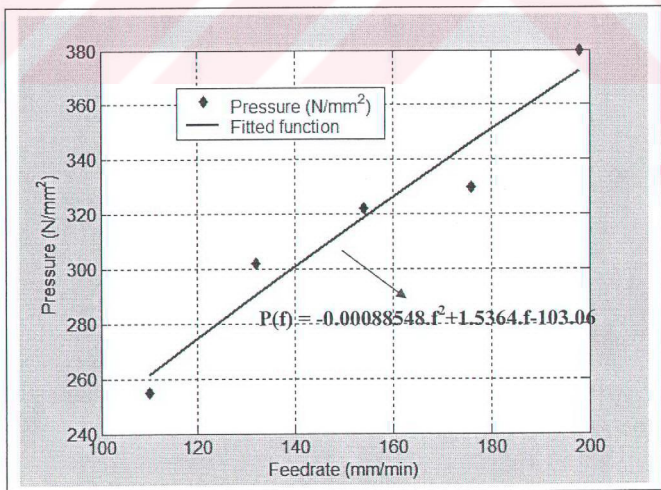


Figure 4.15: The change of pressure with feed rate

4.3 Determining the Cutting Coefficients for Lower Feedrates

In section 4.1, the cutting coefficients for aluminum alloy for feed rates of 110-132-154-176-198 mm/min were found but the lower feed rates such as 44-66-88 mm/min were investigated in this section because of the inconsistency of the simulated cutting forces between experimental cutting forces when the cutting coefficients used in the force model for the lower feedrates. The simulated forces overpredict the experimental forces. For that reason, for lower feedrates new calibration coefficients were found. The experimental setup was the same as the first setup. The experiments were performed on Mazak FJV-200 UHS Vertical Machining Center (VMC) and the workpiece materials were aluminum blocks (Al7039) of size 250x170x38 [mm]. The cutter was similar to the first drill (drill number 1). It was uncoated drill cutter with 7.696 mm diameter, 94.565 degrees total tip angle. The drill (drill number 2) properties can be seen in Table 3.1 and Table 3.2.

The calibration steps were performed and the calibration coefficients were obtained for the lower feed rates in aluminum material. The cutting coefficients can be seen in Table 4.2.

Table 4.2: Numerical values of cutting and edge coefficients for the intervals from the drill tip.

interval from coefficients tip	0 - 0.3 [mm]	0.3-0.7 [mm]	0.7 - 1.2 [mm]	1.2 -1.7 [mm]	1.7 – 2.2 [mm]
$K_{\psi c}$ [N/mm ²]	15205	7357	4251	3283	2054
K_{tc} [N/mm]	4369	3543	2577	2074	1526
K_{rc} [N/mm ²]	17858	6547	4039	3021	2146
$K_{\psi e}$ [N/mm]	132.52	43.86	31.85	20.64	12.24
K_{te} [N/mm ²]	64.44	17.03	12.73	7.163	6.663
K_{re} [N/mm]	178.10	35.78	20.91	18.48	10.35

4.4 Effects of Tip Angle on Calibration Coefficients and Cutting Forces

In order to determine the effect of tip angle on the calibration coefficients, three drills (drill number 2 – 3 – 4) with different tip angles were chosen for the calibration process (Table 4.3). Calibration steps are performed on the powder steel that has flat surfaces for these drills to obtain cutting and edge coefficients. In Figure 4.16, 4.17 and 4.18 calibration coefficients can be seen for the drills.

Table 4.3 Cutting conditions for drilling in powder metal

Feed rates	110 – 132 – 154 – 176 - 198 mm/min
Depth of cut	5 mm
Spindle Speed	1100 rpm
Drill Number	2 – 3 – 4 (single cutting edge)
Amplifier gain (Channel)	100 (X) – 100 (Y) – 300 (Z)
Sampling frequency	1000
Sampling time	1 s

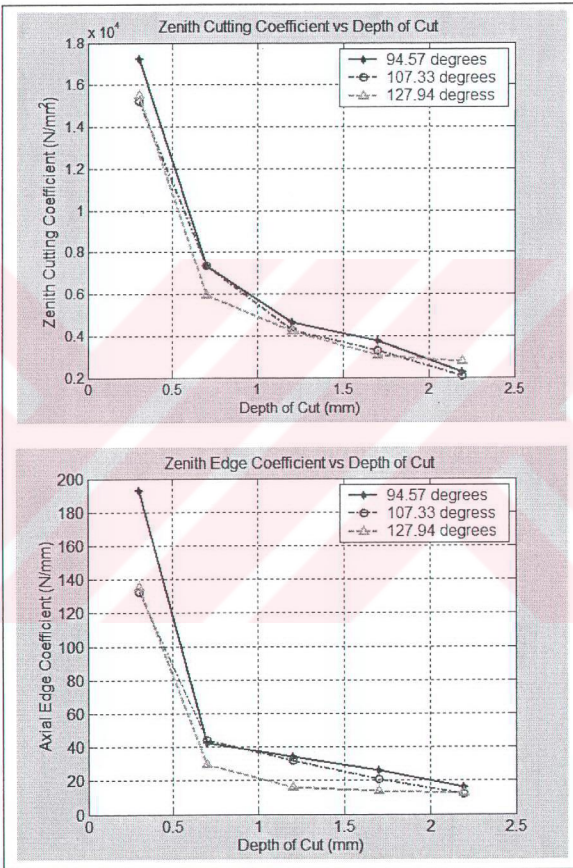


Figure 4.16 : The change of zenith coefficients with tip angle

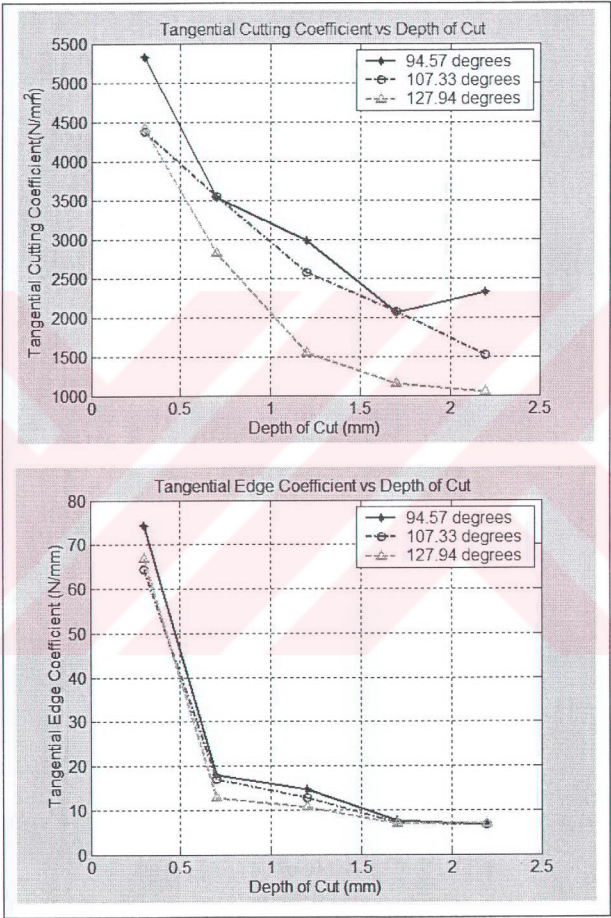


Figure 4.17 : The change of tangential coefficients with tip angle

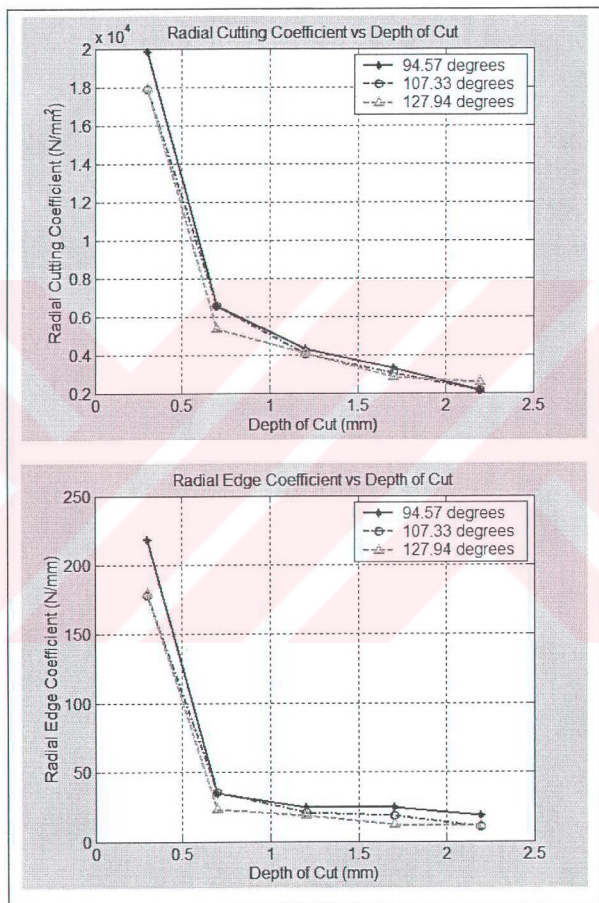


Figure 4.18: The change of radial coefficients with tip angle

From the calibration plots, as the tip angle decreases, the calibration coefficient increases. Especially this result is dominant in the tangential cutting coefficient. This may be proved that F_X and F_Y increase because the calibration coefficients increase. Using this assumption, the expectation is the increase of F_Z but F_Z decreases because the tip angle increases. This may be proved by the Equation 3.15. F_Z depends on the sinus and cosine of tip angle, and as the tips angle increases the sum of sinus and cosine of the tip angle decreases. dF_Z forces can be written as follows and dF_p is the differential pressure force. These forces are added to find F_Z .

$$dF_Z = \sin \kappa \cdot dF_R + \cos \kappa \cdot dF_\psi + dF_p \quad (4.3)$$

The effects of tip angle on the cutting forces can be seen in Chapter 6 with figures. These figures are the evidence of the effect of the tip angle on the cutting forces as mentioned above.

DYNAMIC MODEL OF DRILLING PROCESS FOR HOLE QUALITY PREDICTIONS

5.1 Introduction

Consider the three most fundamental chip-making processes: milling, drilling and turning. In milling and turning, cutting takes place in the open, making it possible to learn a great deal about the behavior of the cut through observation alone. But in drilling and in related hole-making processes, the action is hidden. No one can see what happens in the cut, and no unaided eye can see the machined surface unless the hole is cut open. This invisibility, as much as any other factor, probably accounts for why the mechanics of hole making have been so poorly understood. One particularly important missing piece has been an applied understanding of self-excited or "regenerative" vibrations in hole machining. These are vibrations such as chatter that feed themselves simply as a result of the dynamics of the cut and occurs near the system's natural frequency. A second form of regenerative vibration in hole making is the low frequency vibration that produces lobed holes. While the tool is chattering in and out at some high frequency, it may also be swaying back and forth at a much lower frequency of the system. This low-frequency vibration is also regenerative in that it creates waves in the resulting form that tend to exaggerate the severity of the vibration itself. However, this vibration is not chatter, because it has nothing to do with the natural frequency. Instead, the frequency of this vibration tends to be a multiple of the rotation speed, whatever that speed may be. This direct link to the spindle speed makes low-frequency vibration particularly insidious, Bayly [23] notes. With this type of vibration, adjusting the spindle speed is not going to help. The swaying motion from low-frequency vibration shapes the roundness of the hole. Holes that result from this vibration feature out-of-round lobes occurring in odd numbers.

The literature includes numerous efforts for mechanistic modeling of the thrust and torque in drilling process [12-18]. Although thrust and torque have a considerable effect, the radial forces play the dominant role in determining the dynamics behavior of a drill and hole quality. The radial forces

may cause the machine tool to vibrate, the vibration will affect the chip thickness and chip area, which in turn causes undulation of the cutting forces and this will decrease positional accuracy and cause the lobed patterns.

In fact, the interactions between the hole and the tool are rather complicated but some researches simplify their model by making some assumptions. Some of them neglect the vibration in workpiece, some of them consider only the axial vibration, the torsional or the radial vibration [5, 24, 26].

In ideal drilling, the vector sum of the cutting forces in X and Y directions are equal to zero. However, if there are non-ideal cases such as non-identical cutting lips etc., then there will be residual forces in the X and Y directions. In this study, low frequency of vibration is considered. Transfer function of all the system containing the spindle, the tool and the workpiece material is taken into account and modal mass, damping ratio and stiffness of the system are experimentally found. Later, using the dynamic model, displacement in X and Y directions are calculated for every cutter rotation angle. By knowing the displacements, the hole profile can be obtained for every drilling operation.

5.2 Determining Transfer Function

Transfer functions of the existing multi degree of freedom (MDOF) system are identified by structural dynamic tests. An impact hammer instrumented with a piezoelectric force transducer can be used to measure transfer function. The mass of the hammer and the impact tip material attached to the impact force sensor must be selected according to the mass, rigidity and material of the structure being excited. The resulting vibrations are measured with displacement, velocity or acceleration of sensors. The use of accelerometers or laser 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 added mass may alter the natural frequencies. The complete testing environment can be seen in Figure 5.1.

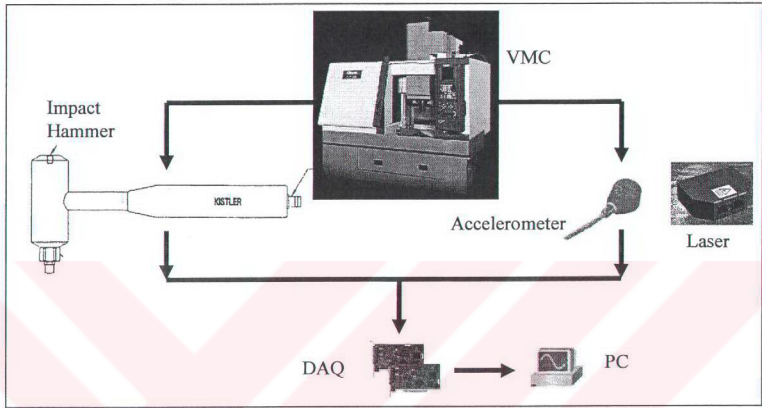


Figure 5.1: The experimental setup for measurement of transfer function

Transfer function of the tool & spindle system in Laplace domain is given as,

$$G(s) = \frac{U(s)}{F(s)} = \frac{1/m}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (5.1)$$

where $U(s)$ and $F(s)$ are representing the displacement and force, respectively (either in X or Y direction), m is modal mass, ζ is the damping ratio, ω_n is the natural frequency. $s^2 + 2\zeta\omega_n s + \omega_n^2$ is the characteristic equation of the system that has two complex conjugate roots,

$$s_1 = -\zeta\omega_n + j\omega_d \quad s_2 = -\zeta\omega_n - j\omega_d \quad (5.2)$$

The transfer function (Equation 5.1) can be expressed by its partial fraction explanation as follows,

$$G(s) = \frac{R}{s - s_1} + \frac{R^*}{s - s_2} \quad R = \frac{1/m}{2j\omega_d}, \quad R^* = -\frac{1/m}{2j\omega_d} \quad (5.3)$$

where ω_d is the damped frequency, R and R^* are the residues. In general form, for multi degree freedom of system transfer function can be written as the following,

$$G(s) = \frac{U(s)}{F(s)} = \sum_{k=1}^n \frac{R_k}{s^2 + 2\zeta_k \omega_{n,k} s + \omega_{n,k}^2} \quad (5.4)$$

where k is the mode number of the system.

Transfer function can be separated into real $H(\omega)$ and $I(\omega)$ imaginary components as follows,

$$H(\omega) = \frac{1 - R^2}{K \left[(1 - R^2)^2 + (2R\zeta)^2 \right]}, \quad I(\omega) = \frac{-2R\zeta}{K \left[(1 - R^2)^2 + (2R\zeta)^2 \right]} \quad (5.5)$$

where K is stiffness. At resonance $r = 1$ and $\omega_n = \omega$, $I(\omega) = -1/2K\zeta$ and $H(\omega) = 0$. The residue can be find by using the relation between ω_n , ζ and $I(\omega)$.

$$\omega_n = \sqrt{\frac{K}{m}}, \quad R = \frac{1}{m} = \frac{\omega_n^2}{K} = 2I(\omega)\zeta\omega_n^2 \quad (5.6)$$

$$\zeta = \frac{\Delta\omega}{2\omega_n} \quad (5.7)$$

In this study, the transfer function of the system, Mazak FJV-200 UHS Vertical Machining Center (VMC) and the workpiece material is measured by impact hammer and accelerometer as shown in Figure 5.1. In order to obtain the exact hole profile, the transfer function should be measured in the experimental condition. The vibration starts as the tool cuts a hard area in the workpiece material and is largest at the tip point of the tool so the true transfer function values should be found while cutting is in progress. This means that one end, the drill is fixed and the other end of the drill is in the workpiece material so both ends of the drill can be considered as fixed.

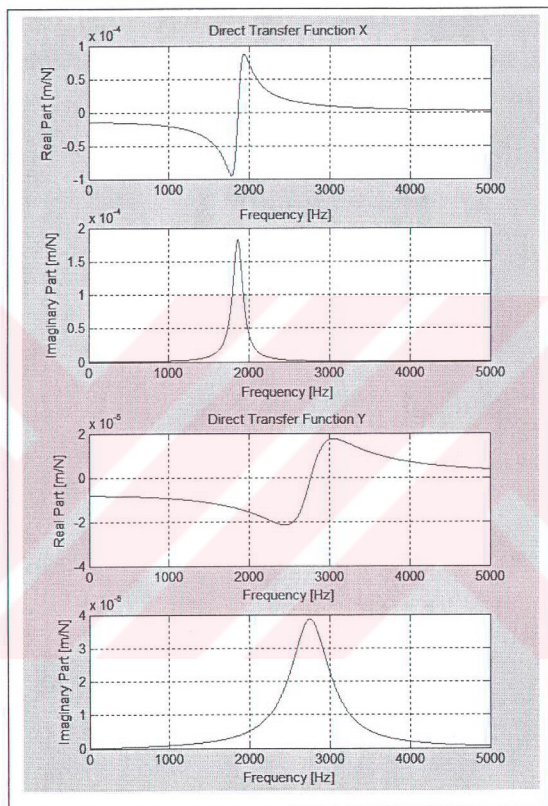


Figure 5.2: Imaginary and real parts of the frequency response functions in X and Y directions

The frequency response functions of the spindle and tool system in X and Y directions for two situations; case 1: for one is fixed and case 2: both end of the drill are fixed. The results can be displayed using CutPro. The real, imaginary parts of the frequency response function plotted in Matlab for both end of the drill is fixed are shown in Figure 5.2. In CutPro, from the plots of real, imaginary parts of the frequency response function, number of the mode of the system can be utilized.

After finding the mode number, for each mode damping ratio, stiffness and natural frequency can be exactly obtained. (See Figure 5.3 for a sample output screen of CutPro).

For cylindrical surface material, the hammer test is performed considering as one end of the drill fixed and the other end of the drill not in the workpiece material (Figure 5.4). In Figure 5.5, a sample output screen of Cutpro can be seen for this situation.

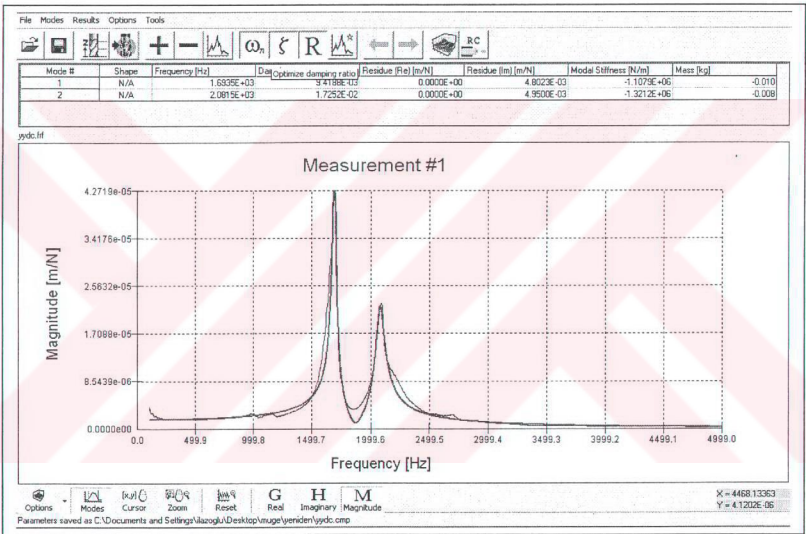


Figure 5.3: Magnitude vs frequency plot in Y direction for both end of the drill is fixed

Experimental results for both end of the drill is fixed show that;

In X direction:

$$(\omega_n)_x = 1663.94 \text{ Hz}, \zeta_x = 2.25\text{E-}02, K_x = 641115.86 \text{ N/m}, R_x = 7.49\text{E-}03 \text{ m/N}, m_x = 6.97\text{E-}03 \text{ kg}.$$

In Y direction first mode:

$$(\omega_n)_y = 1693.49 \text{ Hz}, \zeta_y = 9.42\text{E-}03, K_y = 1107914.48 \text{ N/m}, R_y = 4.8023 \text{ m/N}, m_y = 9.79\text{E-}03 \text{ kg}.$$

second mode:

$(\omega_n)_y = 2081.46$ Hz, $\zeta_y = 1.72\text{E-}02$, $K_y = 1321221.97$ N/m, $R_y = 4.95$ m/N, $m_y = 7.72\text{E-}03$ kg.

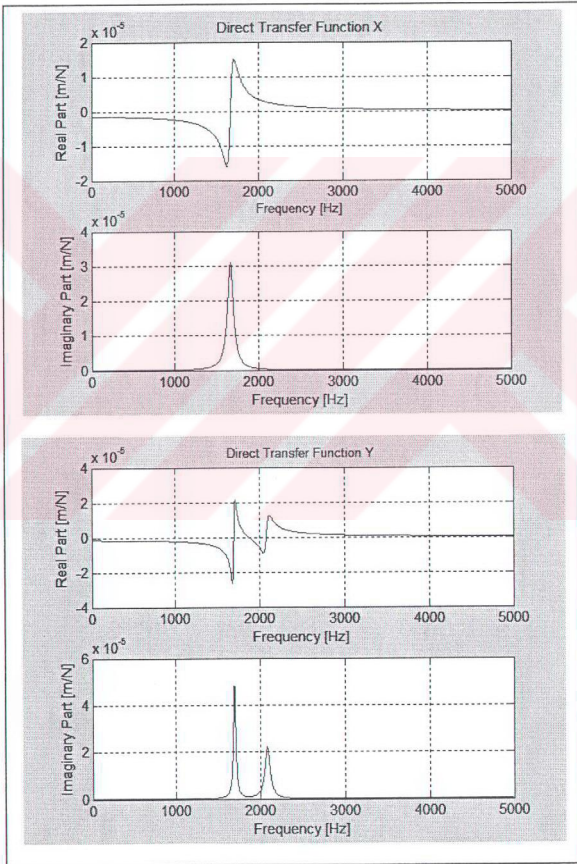


Figure 5.4: Imaginary and real parts of the frequency response functions in X and Y directions

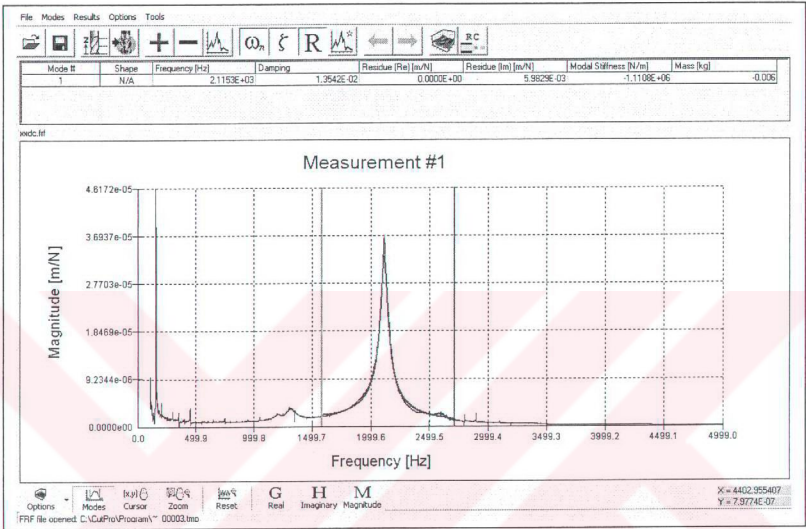


Figure 5.5: Magnitude vs frequency plot in Y direction for one end of drill is fixed

Experimental results for one of the drill is fixed show that;

In X direction:

$(\omega_n)_x = 2116.28$ Hz, $\zeta_x = 1.32E-02$, $K_x = 10670721.44$ N/m, $R_x = 5.98E-03$ m/N, $m_x = 6.04E-03$ kg.

In Y direction:

$(\omega_n)_y = 2121.32$ Hz, $\zeta_y = 1.25E-02$, $K_y = 1119590.6$ N/m, $R_y = 5.35E-03$ m/N, $m_y = 6.30E-03$ kg.

5.3 Determining the Displacements

After obtaining F_x, F_y through use of the model, the displacement in X and Y direction can be calculated from Equation (5.1) using the dynamic model. The transfer function and the cutting forces in s domain are used to evaluate the displacements in X and Y directions. However, in the static

model, the cutting forces in the time domain ($F(t)$) are obtained. For that reason, the transfer function in s domain is converted to z domain in order to calculate the displacement.

The z -transformation technique can be used for the discrete solution of difference equations. The z transform of a function $f(t)$ is the Laplace transform of its discrete version $f^*(t)$.

$$F(z) = Z\{f(t)\} = L\{f^*(t)\} \quad (5.8)$$

Using the definition of the Laplace transform, we have

$$L\{f^*(t)\} = \int_{t=0}^{\infty} f^*(t) \cdot e^{-st} dt \quad (5.9)$$

Because the function $f^*(t)$ is composed of impulses, this integral reduces to the sum

$$L\{f^*(t)\} = \sum_{k=0}^{\infty} f(kT) \cdot e^{-skT} \quad (5.10)$$

The reason for this is that the integral of the product of the size of the impulse $A\delta(t - t_0)$ and a continuous function $g(t)$ will give the product of the size of the impulse (A) and the value of $g(t)$ where the impulse occurs.

With the definition of the variable z as $z = e^{sT}$, the sum expression for $F(z)$ above becomes

$$F(z) = \sum_{k=0}^{\infty} f(kT) \cdot z^{-k} \quad (5.11)$$

The discrete transfer function $G(z)$ of a linear system is the ratio of the z transform of the response to the z transform of the input function, with zero initial conditions. Given the input function $x(t)$ with its z transform being $X(z)$, the product $Y(z) = G(z) X(z)$ gives the z transform $Y(z)$ of the

response under the condition that the sampled version $x^*(t)$ of the input function is applied to the system. The discrete transfer function $G(z, T)$ that corresponds to the continuous transfer function $G(s)$ is a function of the sampling period T . To obtain $G(z)$ corresponding to a $G(s)$, this $G(s)$ can be inverse Laplace transformed to obtain the impulse response of the system, and then it can be z transformed to obtain $G(z)$. This procedure is called the “impulse-invariant transformation” of $G(s)$ into the z domain, as it is based on the z transformation of the impulse response of the system, giving an exact discrete equivalent for impulse inputs.

Transfer function of the tool & spindle system in Laplace domain is given in Equation 5.1 and it can be expressed by its partial fraction explanation in Equation 5.3. Considering this transfer function and using Equation 5.3 the impulse response can be found as follows,

$$g(t) = R(e^{s_1 t} - e^{s_2 t}) \quad (5.12)$$

where R is residue and can be calculated from Equation 5.3, s_1 and s_2 is the complex conjugate roots of the transfer function and can be calculated from Equation 5.2.

Substituting $t = kT$,

$$g(kt) = R(e^{s_1 kT} - e^{s_2 kT}) \quad (5.13)$$

Using Equation 5.11, the transfer function in z domain is found as,

$$G(z) = R\left(\frac{z}{z - e^{s_1 T}} - \frac{z}{z - e^{s_2 T}}\right) \quad (5.14)$$

After obtaining transfer function for X and Y directions in z domain, cutting forces in X and Y direction are transformed to z domain in the static model for every cutter rotation and using Equation 5.15 displacements in X and Y directions are calculated.

$$X(z) = G_x(z)F_x(z), \quad Y(z) = G_y(z)F_y(z) \quad (5.15)$$

where F_x and F_y are the dynamometer forces that are the vector sum of the cutting forces for two cutting edges of the drill in X and Y directions. As a result, as long as the cutting forces are known, the displacements can be found for every cutter rotation angle.

5.4 Determining the Hole Profile

Using the dynamic model, the displacement in X and Y directions can be found. This means that for every depth and cutter rotation angle, hole profile can be theoretically predicted by using the static and dynamic model. Obtaining the displacements, and adding the diameter of the drill to those displacements, exact profile of the hole after drilling can be plotted. In order to measure the hole profile, the experimental setup shown in Figure 5.6 is used.

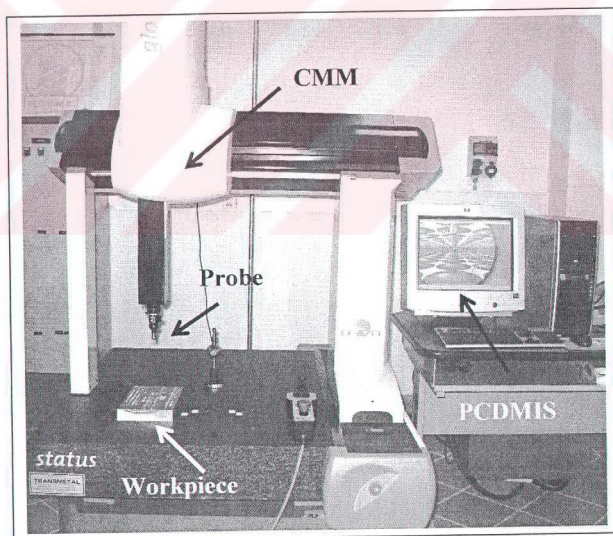


Figure 5.6: The experimental setup for measurement of hole profile

The measurements of the holes profile were performed on CMM Dia Status 7.5.5 with a probe diameter of 1 mm. The probe selection and its calibration, choosing the coordinate system according to workpiece, defining the surface where the hole is by getting three points from the surface and getting at least three points from cylindrical surfaces for two depth to determine the where hole is approximately and finally in DCC mode CMM determines points automatically. The CMM measurements were performed at different levels with selection of longitudinal increment of 0.5 mm at 2 degrees angular increments. After determining the coordinates of the points, the experimental points and the theoretical outputs from the dynamic model are plotted to compare the prediction of displacement in X and Y directions. It is observed that theoretical predictions agree well with CMM measurements and it is seen that the predicted profiles matches very well with experimental measured profiles. The predictions can be seen in Chapter 6.

5.5 Determining the Hole Properties

In addition to the profile, using the CMM data, some properties that describe the hole such as cylindricity, roundness and perpendicularity can be determined and compared with the dynamic model outputs. The dynamic model predicts the displacement in X and Y direction and drilled hole profile, by using these simulated verifications the properties of the drilled hole can be easily determined. As long as defining the conditions of drilling processes in the dynamic model, the resultant drilled hole properties can be found. The important point is the definition of the properties in the dynamic model.

5.5.1 Cylindricity

Cylindricity describes a condition of a surface of revolution in which all points of a surface are equidistant from a common axis. A cylindricity tolerance specifies a tolerance zone bounded by two concentric cylinders within which the surface must lie (Figure 5.7). The cylindricity tolerance is a composite control of form that includes roundness, straightness, and taper of a cylindrical feature. Cylindricity is a radial tolerance, not diametric and can be applied only to cylindrical forms. It is the most complex form of tolerance and also the most difficult to inspect.

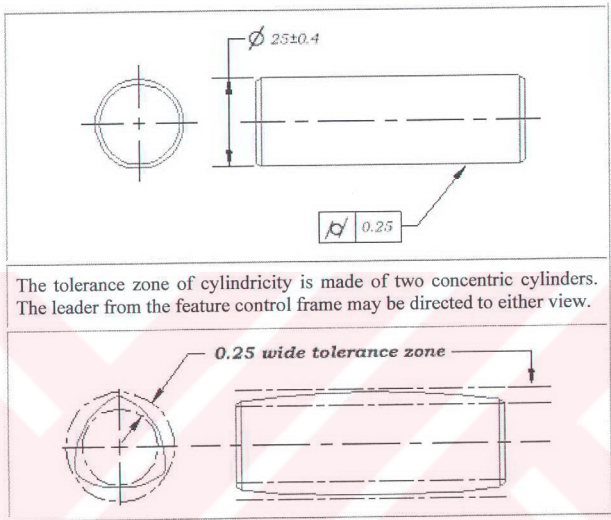


Figure 5.7: An example of tolerance zone of cylindricity

In the dynamic model, after determining the hole profile, for each depth of hole the maximum radii and the minimum radii are found and from these radii the maximum value and the minimum values are chosen. Cylindricity is the subtraction of minimum radius of hole from maximum radius of hole. In Figure 5.8, the geometric explanation of cylindricity is illustrated.

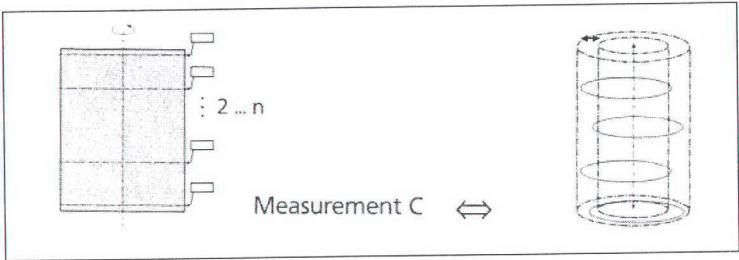


Figure 5.8: The geometric explanation of cylindricity

5.5.2 Roundness

Roundness describes the condition on a surface of revolution where all point of the surface intersected by a plane perpendicular to a common axis. A roundness tolerance specifies a tolerance zone bounded by two concentric circles within which each circular element of the surface must lie, and applies independently at any plane (Figure 5.9). The roundness tolerance is a radial tolerance zone, not diametrical. The roundness tolerance applies at each circular section of the diameter independently.

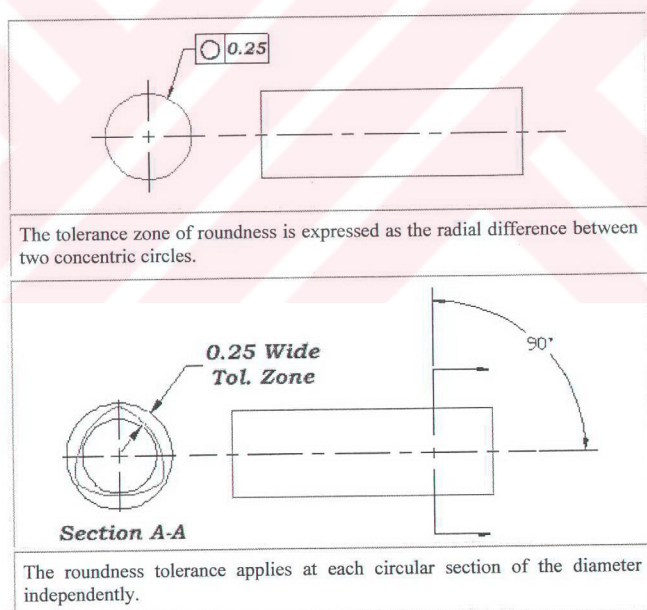


Figure 5.9: An example of tolerance zone of roundness

In the dynamic model, for each depth of hole roundness values are calculated. Roundness can be expressed as the difference of maximum radius and the minimum radius of hole for specific depth of hole profile. In Figure 5.10, the geometric explanation of roundness is illustrated.

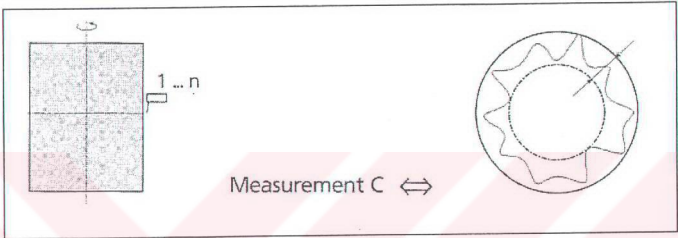


Figure 5.10: The geometric explanation of roundness

5.5.3 Perpendicularity

Perpendicularity is the condition of a surface, axis, or line which is 90 degrees from a datum plane or a datum axis. Perpendicularity can be defined as angle or the displacement. A cylindrical tolerance zone that is perpendicular to a datum plane, the axis of the considered feature must lie in this zone (Figure 5.11).

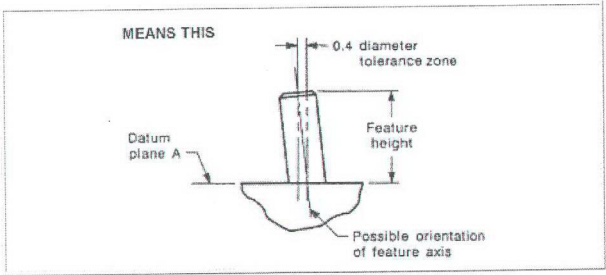


Figure 5.11: An example of tolerance zone of perpendicularity

In the dynamic model, the radius of hole for the depth being equal to the cutting edge height and the radius of hole for the depth being equal to height of the hole are calculated. Perpendicularity can be expressed as the difference of these radii. In Figure 5.12, perpendicularity is the distance between the line that passing through the center of circles for each depth of hole and the datum plane.

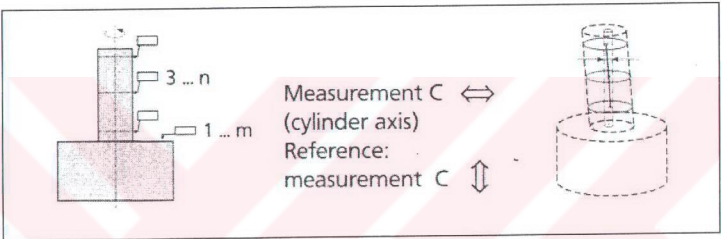


Figure 5.12: The geometric explanation of perpendicularity

Chapter 6

VALIDATION TESTS

6.1 Introduction

Various tests have been performed for validation of the proposed force model. The same experimental setup in calibration has been used in validation tests. The experiments for validation were performed on Mazak FJV-200 UHS Vertical Machining Center and the measurements of the hole profiles were performed on CMM Dia 7.5.5 with a probe diameter of 1 mm. Kistler 3-component dynamometer (Model 9257B) was used to measure cutting forces.

The feedrate interval of 110-198 mm/min has been tested at specific spindle speed. Cutting has been realized not only along the height of the cutting edges but also longer than the height of the cutting edge to determine the hole profile in all cases. The applied conditions and results of the performed cutting tests are presented in this chapter. The predicted hole profile is given in all cases together with the predicted and measured cutting forces.

6.2 Cutting Forces for Flat Surfaces

6.2.1 Drilling Process in Aluminum Alloy

The validation experiments were performed in Al7039. Cutting has been realized with different feedrates. Validation tests were performed at the spindle speed of 1100 rpm and for the feedrate interval of 110 - 198 mm/min. In the simulations, the force calculations were performed every 10 degrees of cutter rotation but this cutter rotation is optional in simulation program and can be variable depending on the desired precision and computation time. In the charge amplifier the gain is 100 for X and Y channel and 200 for Z channel. The sensitivity values for the three channels (x, y and z) in the amplifier were -7.87, -7.90, and -3.69 pC/N, respectively

Drilling is performed along the height of the cutting edge, in other words until the cutting edges engage with the workpiece. Cutting conditions are summarized in Table 6.1.

Table 6.1 Cutting conditions for drilling in Aluminum

Feedrates	110 – 132 – 154 – 176 - 198 mm/min
Depth of cut	2.2 mm
Spindle Speed	1100 rpm
Drill Number	1 (single cutting edge)
Amplifier gain (Channel)	100 (X) – 100 (Y) – 300 (Z)
Sampling frequency	1000
Sampling time	1 s

The prediction of cutting forces in all X-Y-Z directions and radial force showed very good agreement with actual force values. Predicted and measured forces are plotted versus depth of cut in Figure 6.1 to Figure 6.4 for various feedrates.

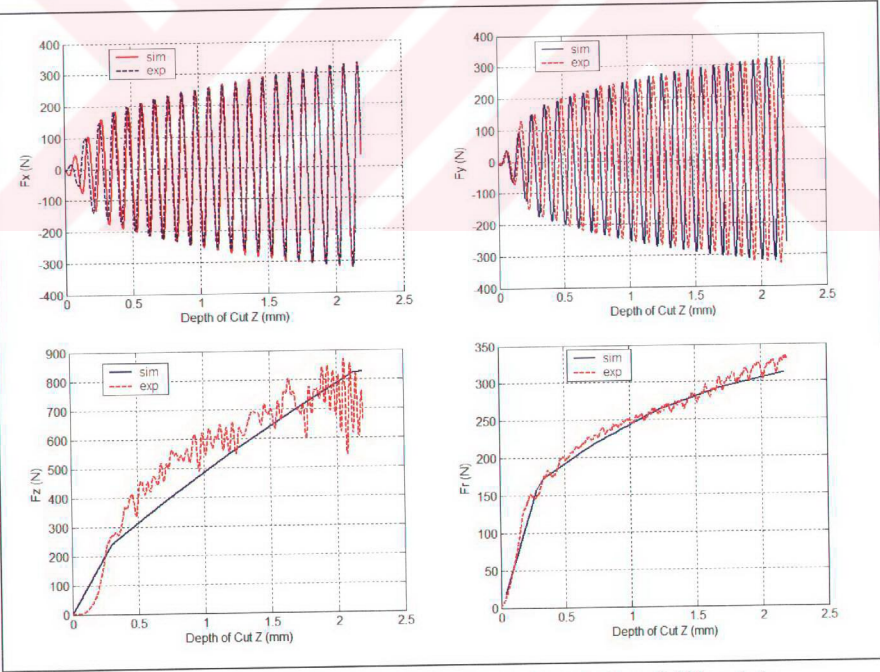


Figure 6.1: Predicted and measured forces vs. depth of cut; feedrate of 110 mm/min

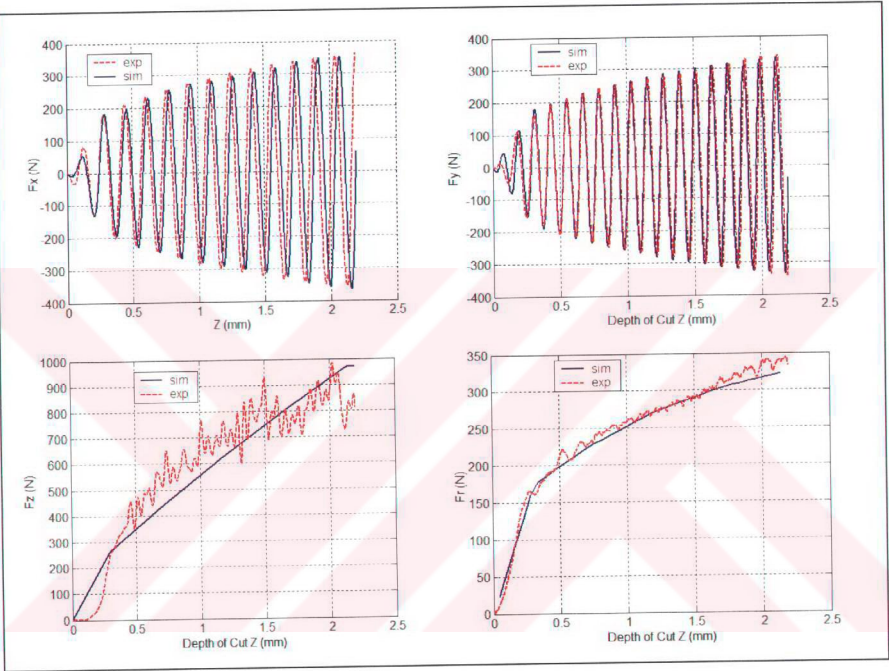


Figure 6.2: Predicted and measured forces vs. depth of cut; feedrate of 132 mm/min

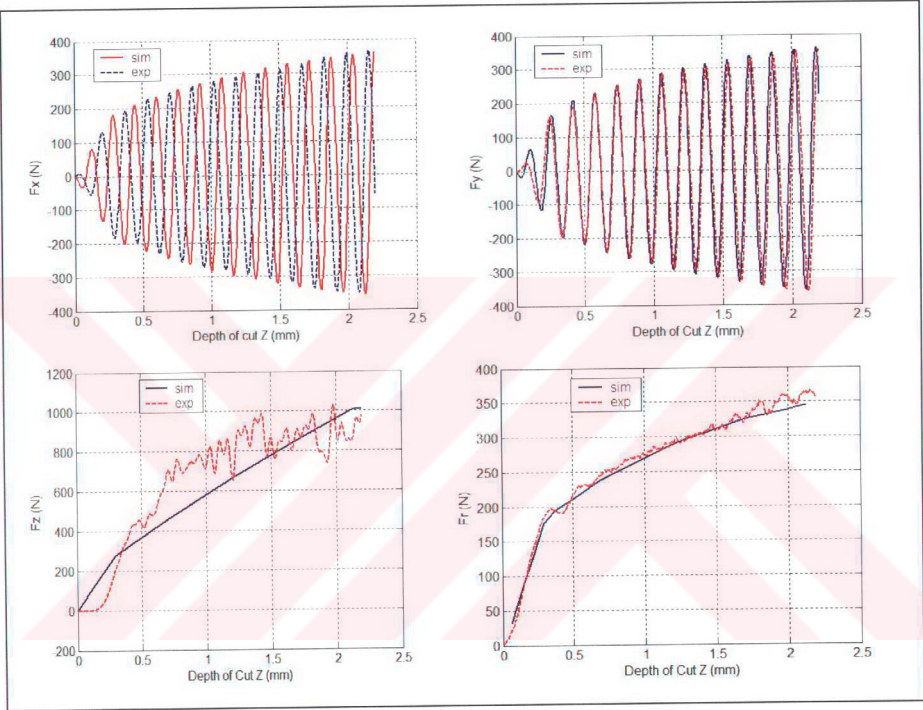


Figure 6.3: Predicted and measured forces vs. depth of cut; feedrate of 176 mm/min

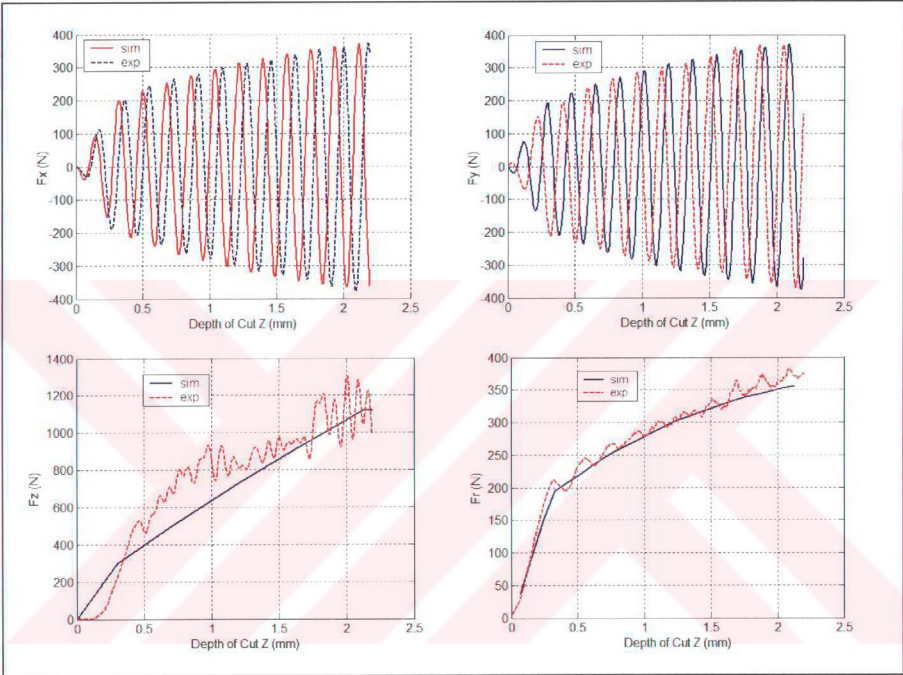


Figure 6.4: Predicted and measured forces vs. depth of cut; feedrate of 198 mm/min

6.2.2 Drilling Process in Powder Metal

Hole drilling tests were carried out on a series of cylindrical compacts produced from four different element powders with powder metallurgy. Each component die pressed to approximately 52 mm in diameter and 25 mm in height. In Figure 6.5 the spectrum of the elements in powder metal can be seen and details of the elements in powder metal are given in Table 6.2. An attempt was made to asses the degree of consistency and repeatability of the drilled holes under the same conditions. Cutting has been realized with different feedrates. Validation tests were performed at the spindle speed of 1100 rpm and for

the feedrate interval of 110 - 198 mm/min. In the simulations, the force calculations were performed every 10 degrees of cutter rotation. In the charge amplifier the gain is 100 for X and Y channel and 300 for Z channel.

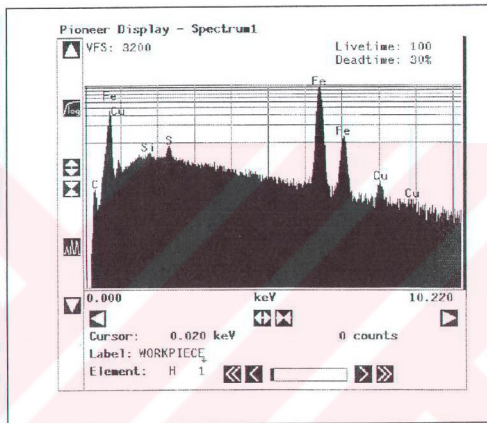


Figure 6.5: Powder Metal Component

Table 6.2 Details of elements in powder metal

Element	Element Wt %
Fe	96.70
Cu	2.30
S	0.80
Si	0.20

Drilling is performed in deeper height than the cutting edge to analyze the effect of cutting edges and the helix part on the cutting forces. Cutting conditions are summarized in Table 6.3. There is an important point that before grinding one cutting edge of the drill along its length, the cutting forces

are obtained to measure the vector sum of the two cutting edges. After determining the cutting forces for single cutting edge performing calibration procedure and using mathematical model, the vector sum of the two cutting edges can be obtained by using the tip angle, chisel edge angle and chisel width for each cutting edges in the model. The validation experiments are performed for different three drills (For details refer to Chapter 3 Table 3.1 and Table 3.2). The validation plots can be seen from Figure 6.6 to Figure 6.13.

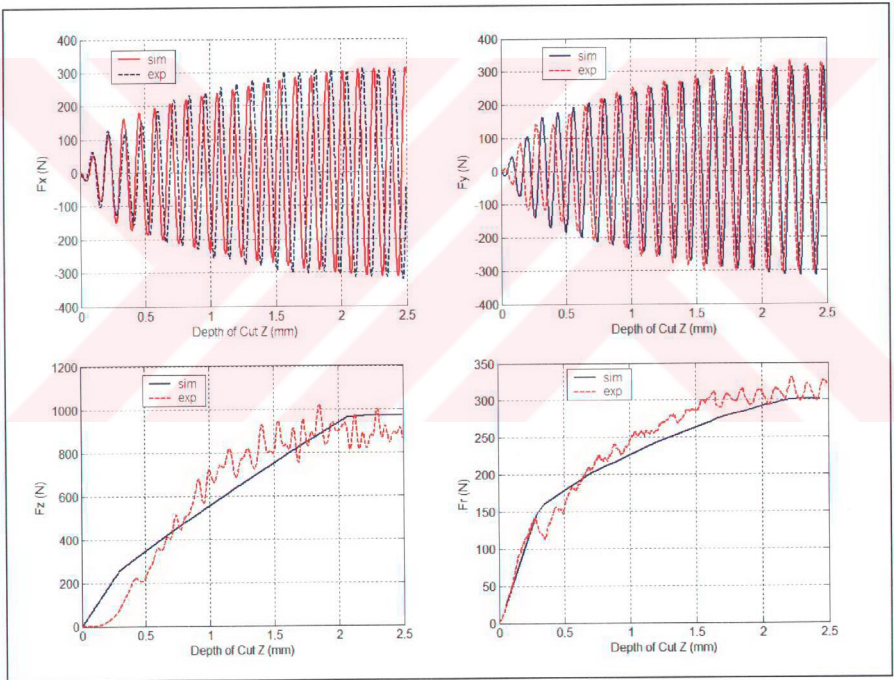


Figure 6.6: For drill number 2 with single edge predicted and measured forces vs. depth of cut; feedrate of 132 mm/min

Table 6.3 Cutting conditions for drilling in powder metal

Feedrates	110 - 132 - 154 - 176 - 198 mm/min
Depth of cut	2.2 mm
Spindle Speed	1100 rpm
Drill Number	2 – 3 – 4 (single cutting edge)
Amplifier gain(Channel)	100(X) – 100(Y) - 300(Z)
Sampling frequency	1000
Sampling time	1 s

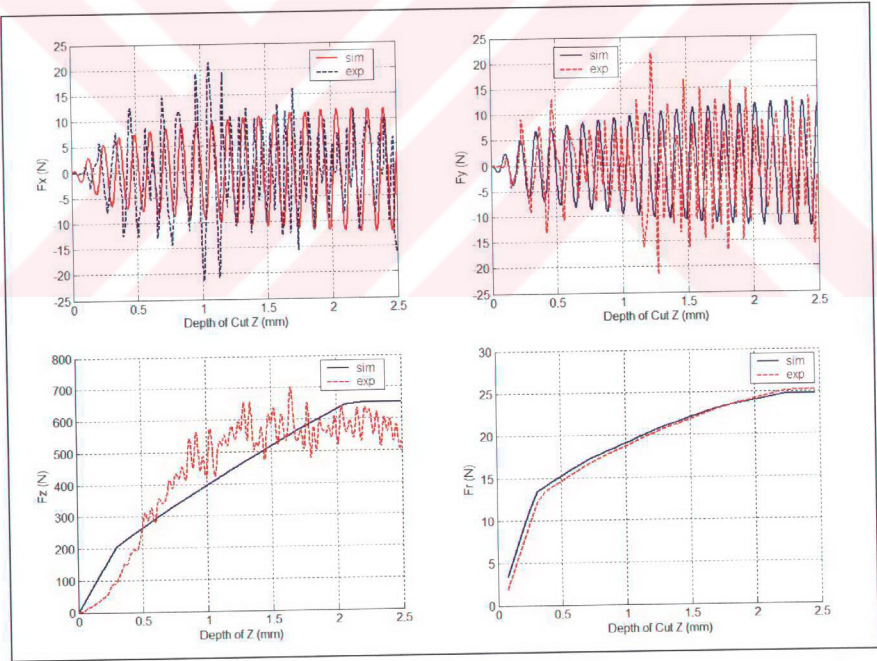


Figure 6.7: For drill number 2 with two cutting edge (dynamometer force) predicted and measured forces vs. depth of cut; feedrate of 132 mm/min

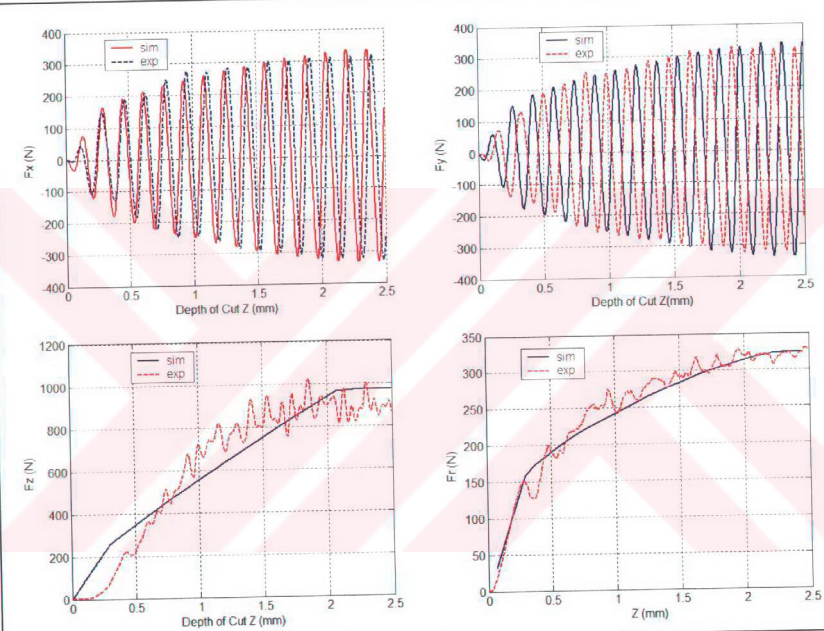


Figure 6.8: For drill number 2 with single cutting edge predicted and measured forces vs. depth of cut; feedrate of 176 mm/min

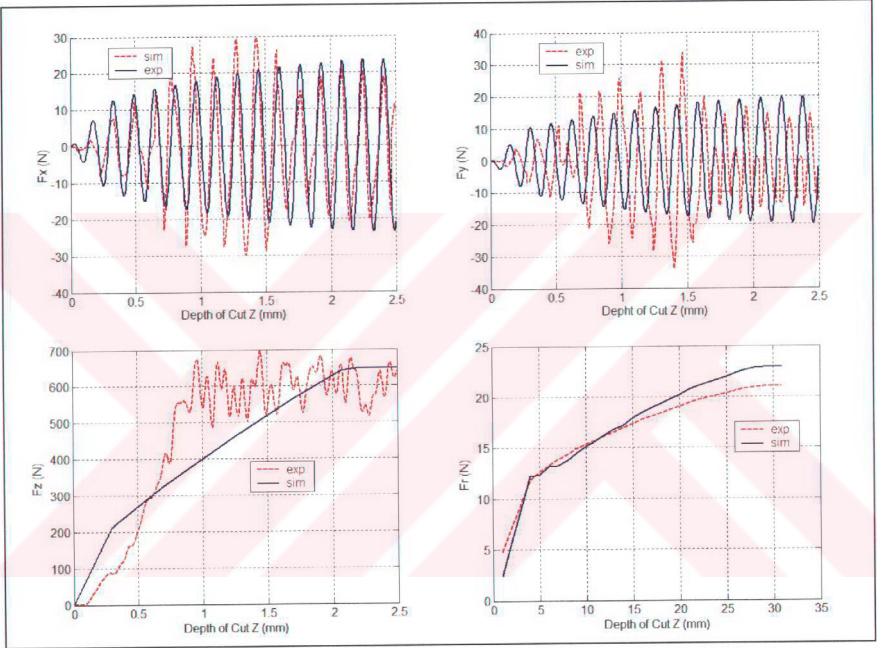


Figure 6.9: For drill number 2 with two cutting edge (dynamometer force) predicted and measured forces vs. depth of cut; feedrate of 176 mm/min

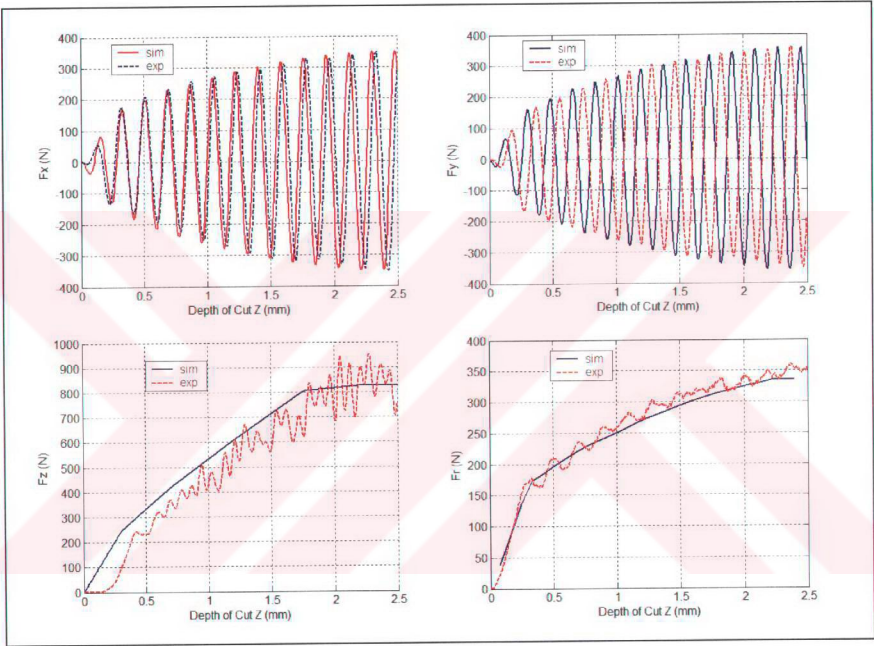


Figure 6.10: For drill number 3 with single cutting edge predicted and measured forces vs. depth of cut; feedrate of 198 mm/min

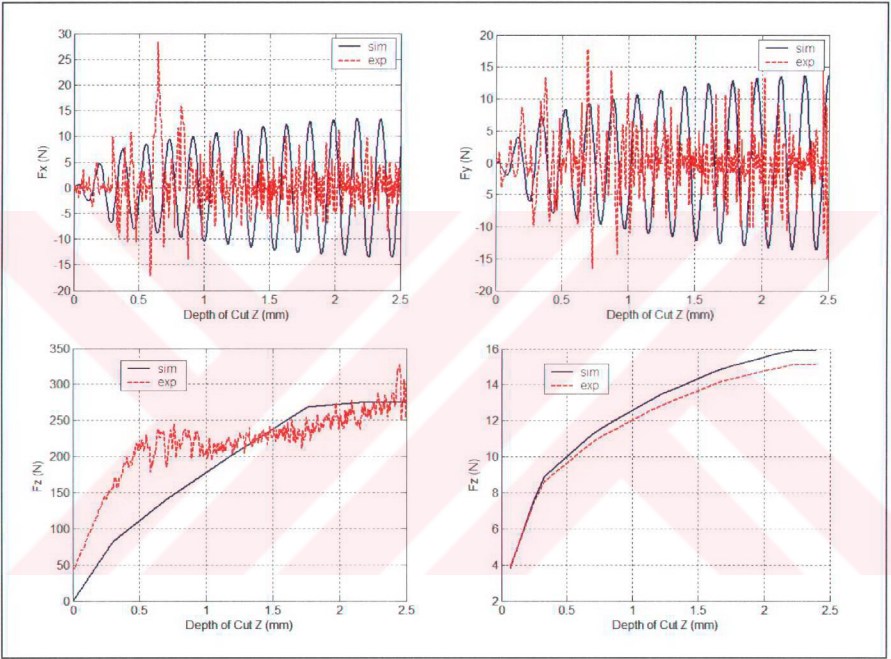


Figure 6.11: For drill number 3 with two cutting edge (dynamometre force) predicted and measured forces vs. depth of cut; feedrate of 198 mm/min

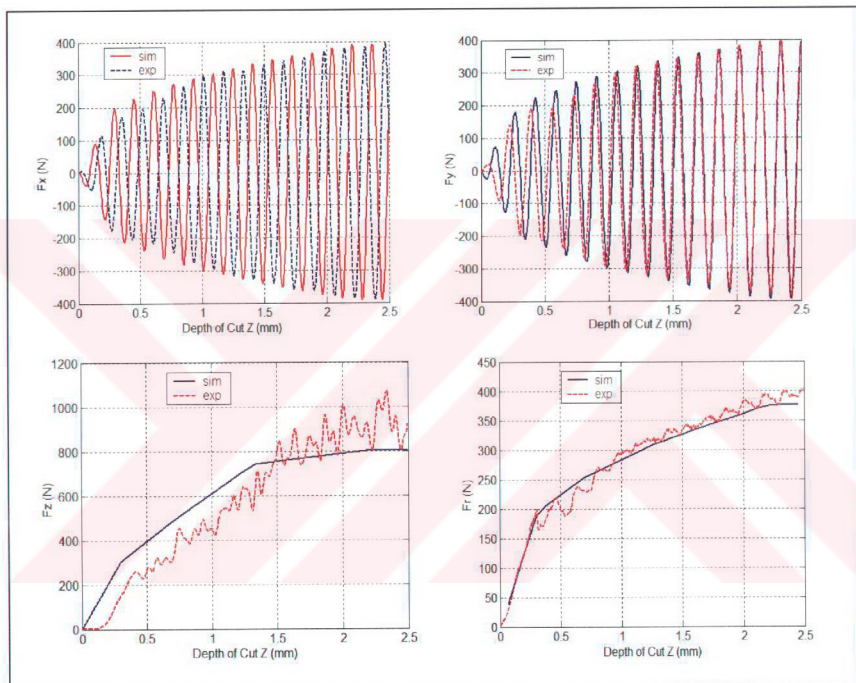


Figure 6.12: For drill number 4 with single cutting edge predicted and measured forces vs. depth of cut; feedrate of 176 mm/min

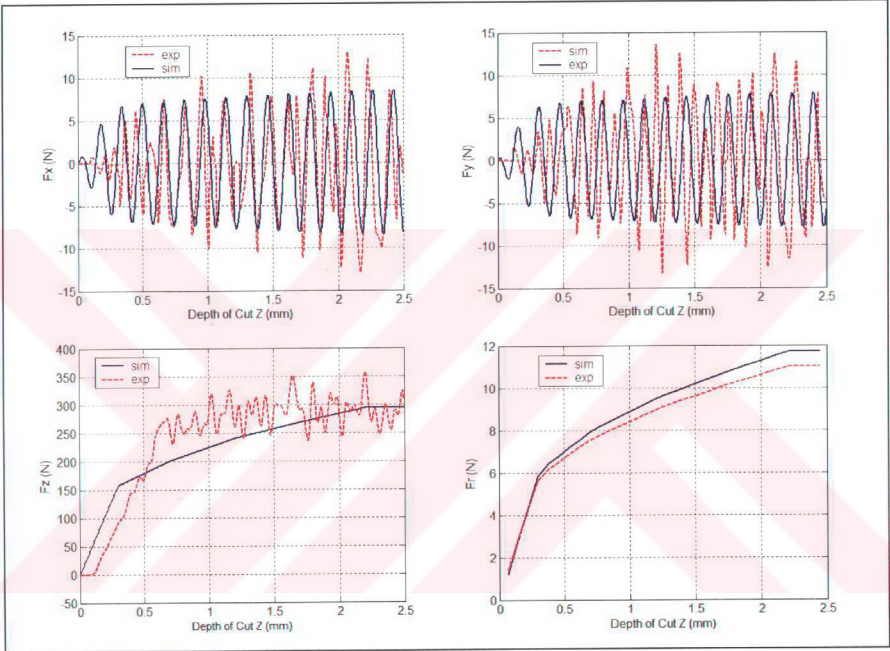


Figure 6.13: For drill number 4 with two cutting edge (dynamometre force) predicted and measured forces vs. depth of cut, feedrate of 176 mm/min

The effect of tip angle on the cutting forces for feedrates of 132-176 mm/min, obtained F_x , F_y , F_z , forces for different tip angles plotted in the same plots (Figure 6.14 to 6.19) and the experimental cutting conditions can be seen in Table 4.3.

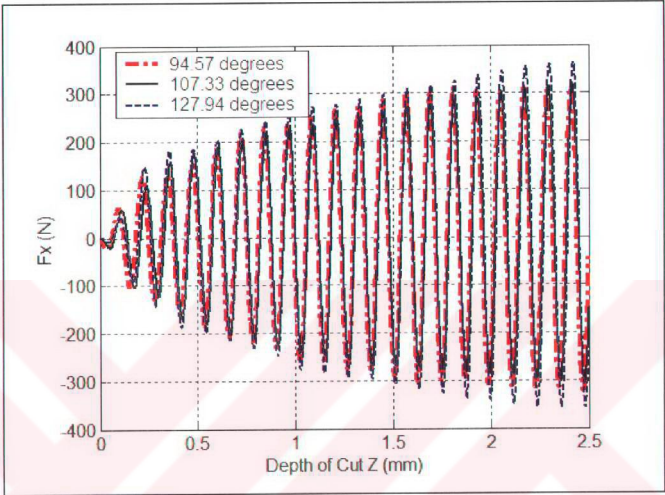


Figure 6.14: The experimental cutting forces for three drills that have different tip angle, feedrate of 132 mm/min

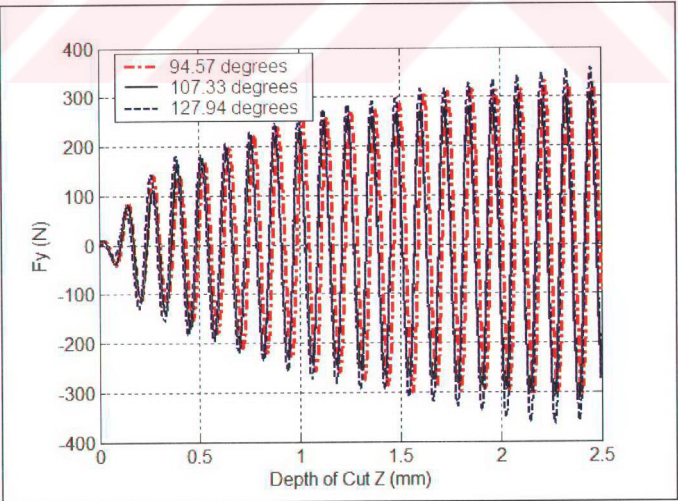


Figure 6.15: The experimental cutting forces for three drills that have different tip angle, feedrate of 132 mm/min

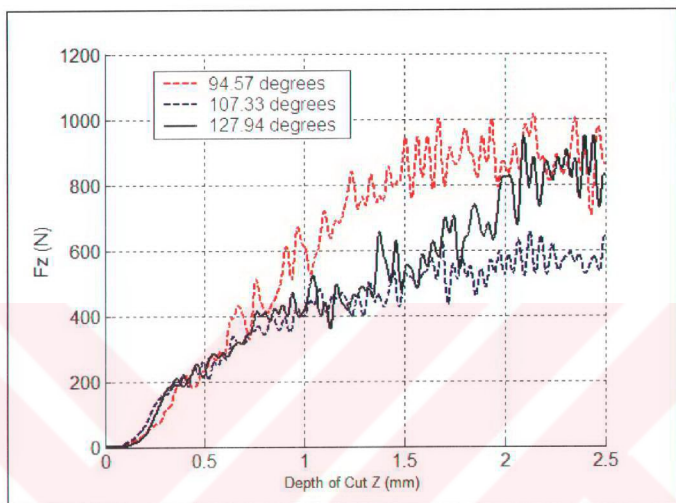


Figure 6.16: The experimental cutting forces for three drills that have different tip angle, feedrate of 132 mm/min

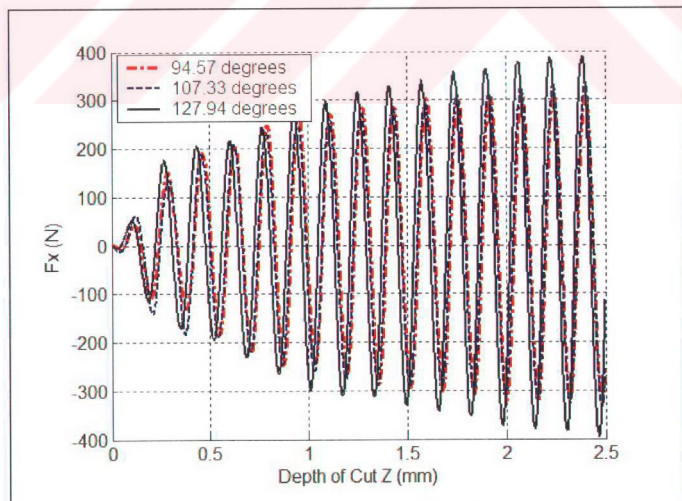


Figure 6.17: The experimental cutting forces for three drills that have different tip angle, feedrate of 176 mm/min

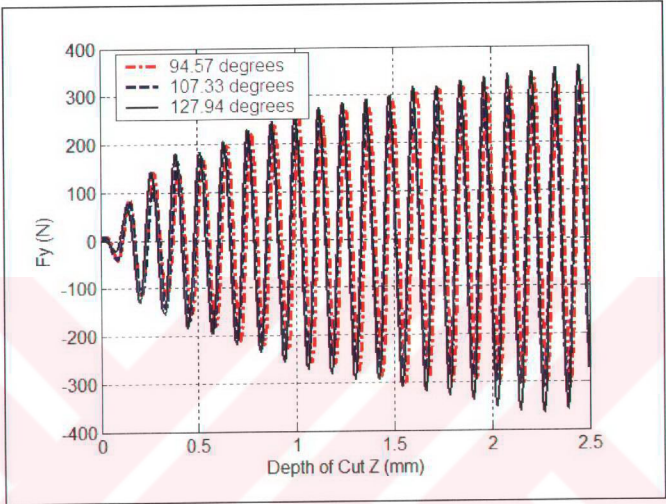


Figure 6.18: The experimental cutting forces for three drills that have different tip angle, feedrate of 176 mm/min

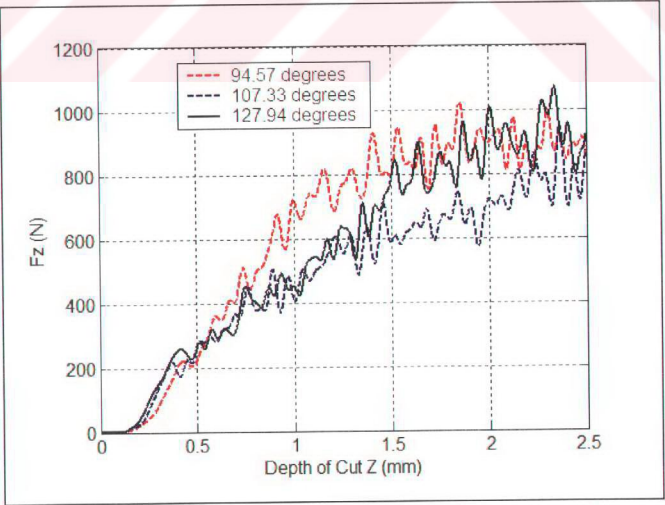


Figure 6.19: The experimental cutting forces for three drills that have different tip angle, feedrate of 176 mm/min

From the cutting forces figures, following results are obtained. As the tip angle increases F_x , F_y increase but as the tip angle increases F_z decreases. The explanation of these results may be based on the cutting coefficients and as the tip angle increases the cutting coefficients increase and these may cause the F_x , F_y increase but in z direction only the tip angle is an important parameter, as the tip angle decreases, the differential forces in z direction increases and this may cause F_z increases. As a result, both the evidence of the effect of tip angle can be seen in Chapter 4 on the cutting coefficients and in this chapter on the cutting forces.

6.3. Cutting Forces for Cylindrical Surfaces



Figure 6.20: Experimental setup of measuring cutting forces for cylindrical surfaces

The same testing environment is used for drilling cylindrical surfaces of the compressor pistons (Figure 6.20 and Figure 6.21). The main difference is the testing material and the surface of the drilled material. The drilled material is a series of cylindrical compacts produced from four different element powders (Fe-S-Si-Cu) with powder metallurgy. Each component die pressed to

approximately 52 mm in diameter and 25 mm in height. The drilled part is a piston of a compressor of a refrigerator. The cutter has a diameter of 7.696 and it's (drill number 5) properties can be seen in Table 3.1 and Table 3.2.

In order to fix the piston, fixtures are used and the setup can be seen in Figure 6.22. A hydraulic control unit is used to move the fixtures in vertical direction (up and down). After setting the test environment, the conditions are determined. Each cylindrical surfaces have been tested for three different feed rates; 132, 176 and 198 mm/min. The spindle speed (ω) was kept constant at 1100 rpm. Data has been collected for 1 second and with sampling frequency rate (f_s) of 1000 Hz at all tests. After recording the cutting forces, the cutting force model output for these conditions are compared with the experimental results.



Figure 6.21: Fixture

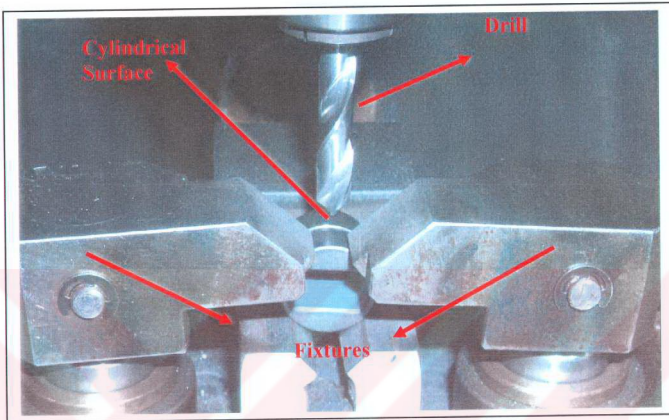


Figure 6.22: Detail view of fixing the piston

Validation tests were performed at the spindle speed of 1100 rpm and for the feedrate interval of 132 - 198 mm/min. In the simulations, the force calculations were performed every 10 degrees of cutter rotation but this cutter rotation is optional in the mathematical model in Matlab. In the charge amplifier the gain is 100 for X and Y channel and 300 for Z channel. Cutting conditions are summarized in Table 6.4.

Table 6.4 Cutting conditions for drilling in Aluminum

Feedrates	110 – 132 – 154 – 176 – 198 mm/min
Depth of cut	2.5 mm
Spindle Speed	1100 rpm
Drill Number	3 (single cutting edge)
Amplifier gain(Channel)	100 (X) – 100 (Y) – 300 (Z)
Sampling frequency	1000
Sampling time	1 s

The prediction of cutting forces in all X-Y-Z directions and radial force showed very good agreement with actual force values. Predicted and measured forces are plotted versus depth of cut in Figure 6.23 and Figure 6.24 for various feedrates.

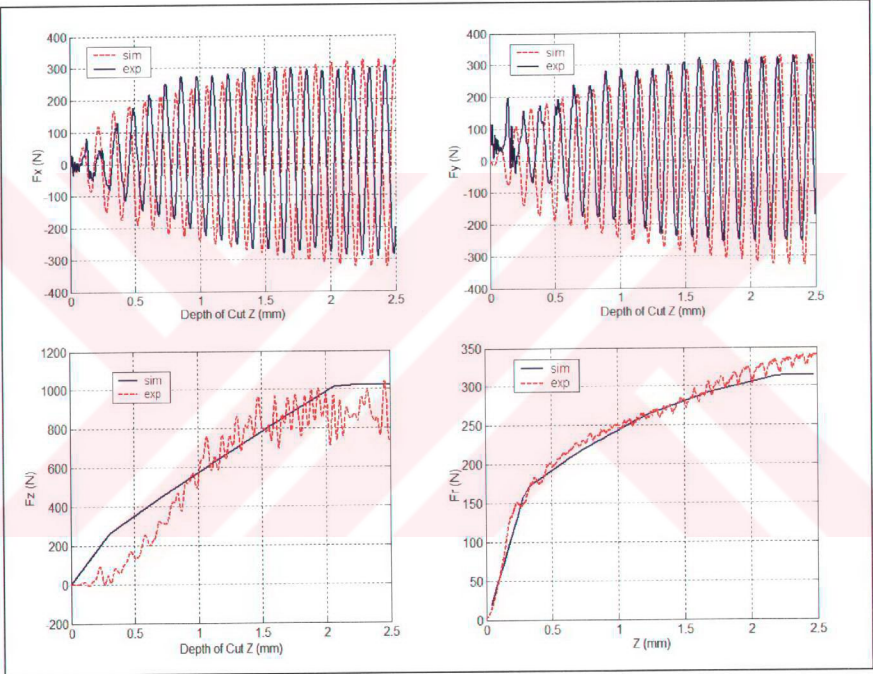


Figure 6.23: Predicted and measured forces vs. depth of cut; feedrate of 132 mm/min

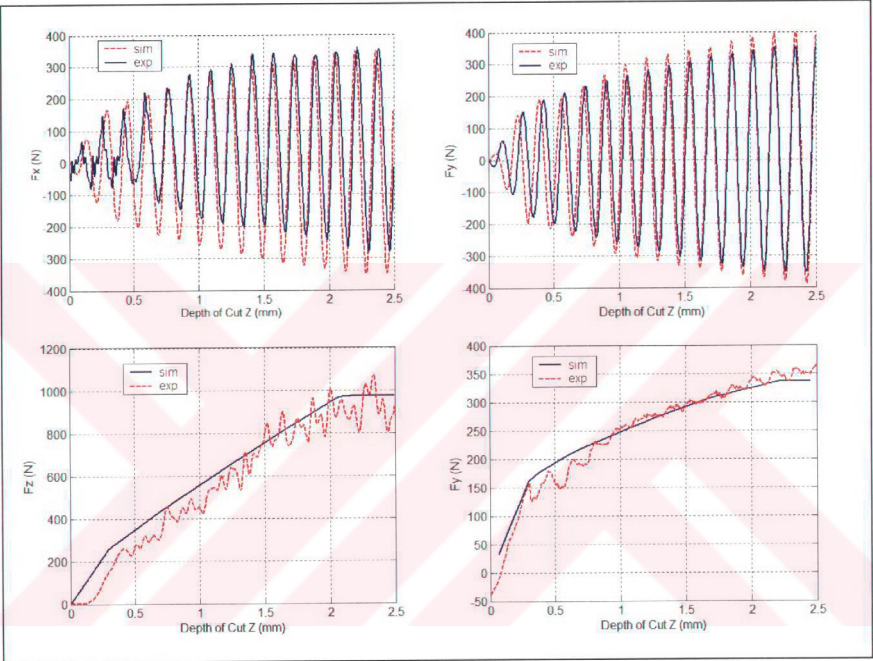


Figure 6.24: Predicted and measured forces vs. depth of cut; feedrate of 176 mm/min

6.4. Hole Quality Predictions for Flat Surfaces

6.4.1 Displacement in X and Y Directions in Powder Metal

As mentioned before, after determining the cutting forces for the drill that has two cutting edges using the cutting force model, the displacement of the drilled hole under these forces can be found using the dynamic model. In this part of the chapter, the displacements for prespecified depth of cuts are plotted. The cutting and simulation conditions can be seen in Table 6.5. The validation plots can be seen from Figure 6.25 to Figure 6.28.

Table 6.5: Cutting and simulation conditions for drilling in powder metal

Feedrates	132 - 176 mm/min
Depth of cuts	0.5 - 1.0 - 1.5 - 2.0 mm
Spindle Speed	1100 rpm
Drill Number	5 (two cutting edge)
Material	Powder Metal

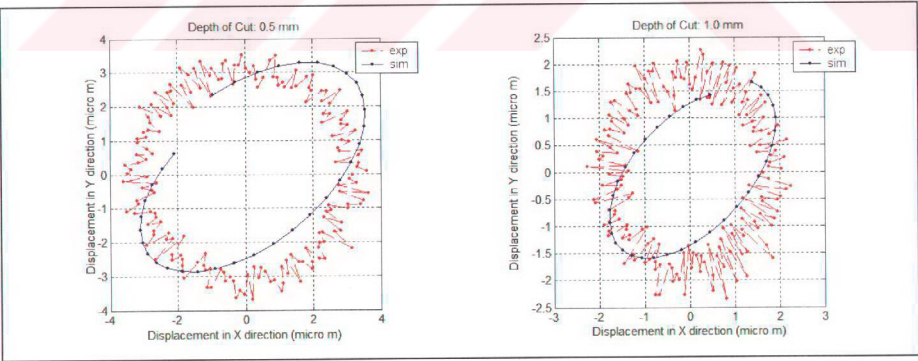


Figure 6.25: Predicted and measured displacement in x and y directions, feedrate of 132 mm/min, 0.5 and 1.0 mm depth of cut

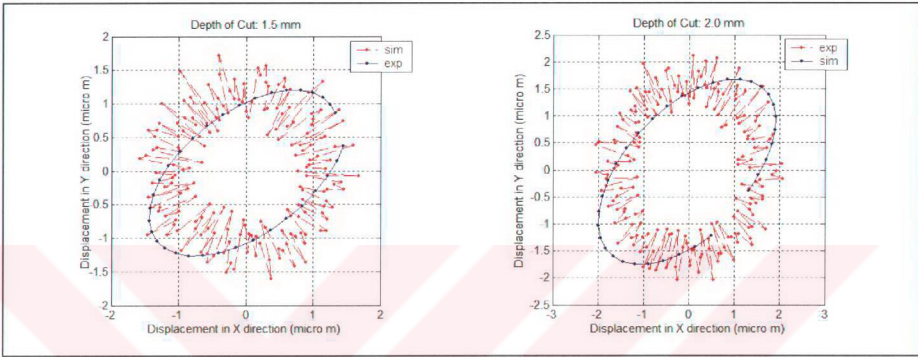


Figure 6.26: Predicted and measured displacement in x and y directions, feedrate of 132 mm/min, 1.5 and 2.0 mm depth of cut

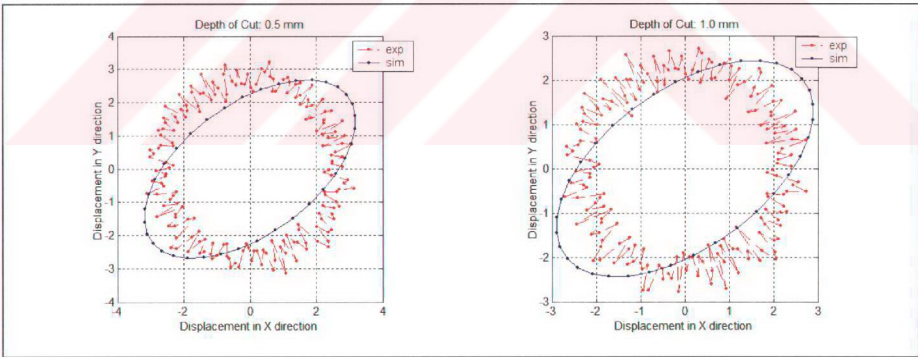


Figure 6.27: Predicted and measured displacement in x and y directions, feedrate of 176 mm/min, 0.5 and 1.0 mm depth of cut

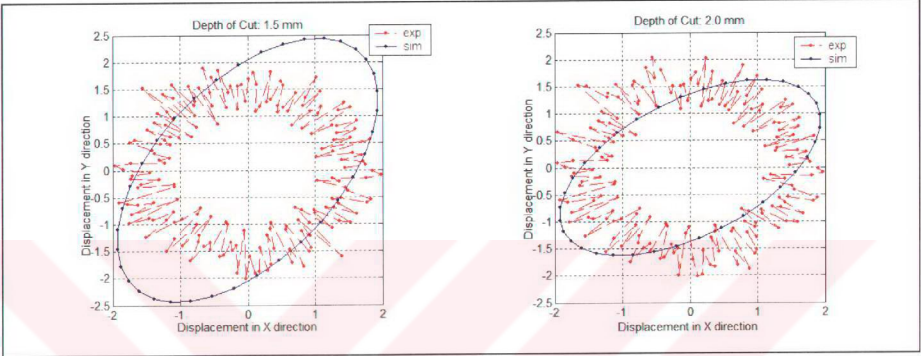


Figure 6.28: Predicted and measured displacement in x and y directions, 176 mm/min, 1.5 and 2.0 mm depth of cut

6.4.2 Displacement in X and Y Directions in Aluminum Alloy

The cutting and simulations were performed in those conditions shown in Table 6.6. The comparison of the predicted and measured displacements can be seen from Figure 6.29 to Figure 6.32.

Table 6.6: Cutting and simulation conditions for drilling in aluminum alloy

Feedrates	132 - 176 mm/min
Depth of cuts	0.5 - 1.0 -1.5 - 2.0 mm
Spindle Speed	1100 rpm
Drill Number	6 (two cutting edge)
Material	Aluminum Alloy

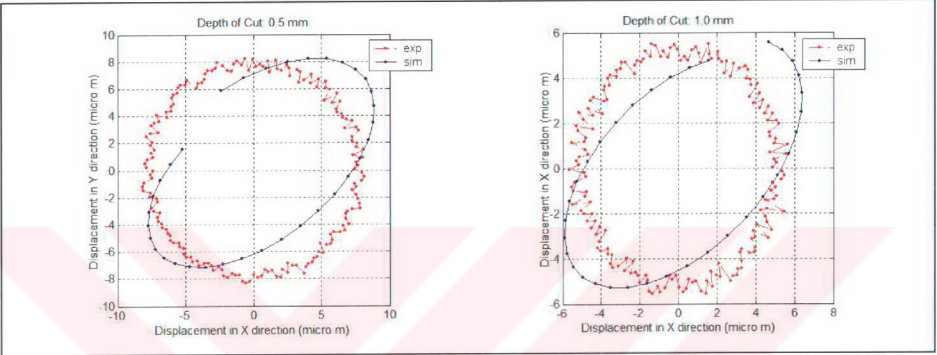


Figure 6.29: Predicted and measured displacement in x and y directions, 132 mm/min, 0.5 and 1.0 mm depth of cut

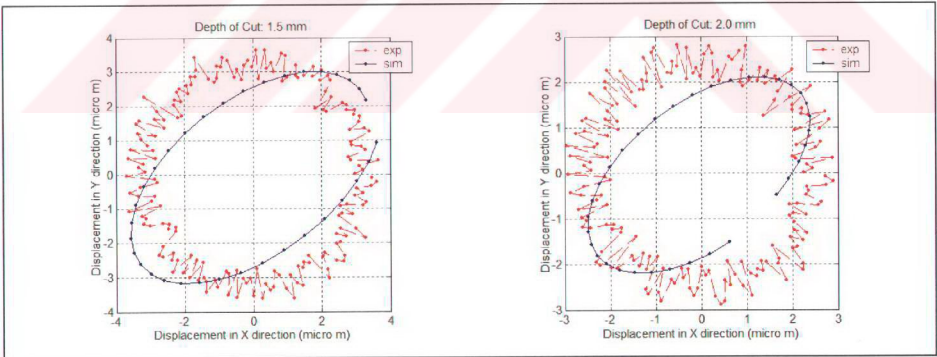


Figure 6.30: Predicted and measured displacement in x and y directions, 132 mm/min, 1.5 and 2.0 mm depth of cut

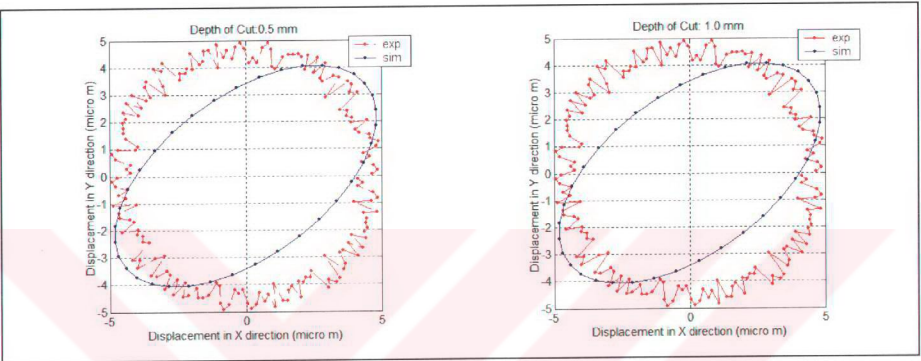


Figure 6.31: Predicted and measured displacement in x and y directions, 176 mm/min, 0.5 and 1.0 mm depth of cut

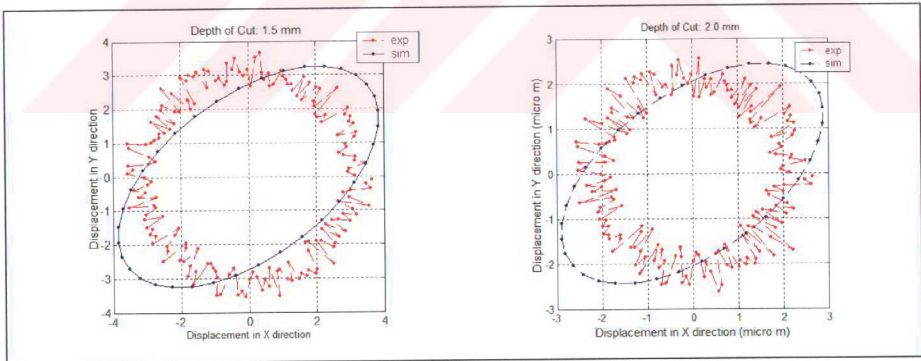


Figure 6.32: Predicted and measured displacement in x and y directions, 176 mm/min, 1.5 and 2.0 mm depth of cut

6.4.3 Hole Profile Prediction in Powder Metal

Obtaining the displacement in x and y directions, the drilled hole profile can be determined by enlarging the displacement values by the drill radius. The cutting conditions are in Table 6.5. The predicted and measured hole profiles are compared in Figure 6.33 and 6.34. In the figures, the profile is formed from different 5 depths of cut. The blue points are CMM (experiment) results, the red points are the simulation results.

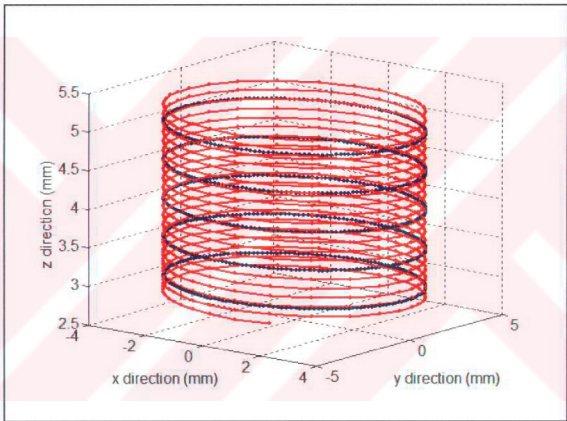


Figure 6.33: Predicted and measured hole profiles, 132 mm/min

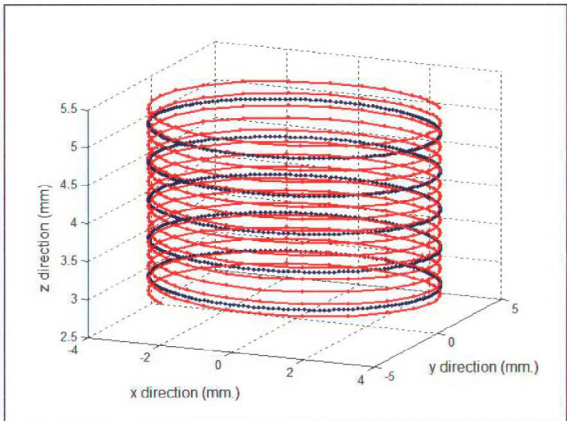


Figure 6.34: Predicted and measured hole profiles, 176 mm/min

6.4.4 Hole Profile Prediction in Aluminum Alloy

The cutting conditions are shown in Table 6.6. The predicted and measured hole profiles can be seen in Figure 6.35 and 6.36. The blue points are CMM (experiment) results, the red points are the simulation results.

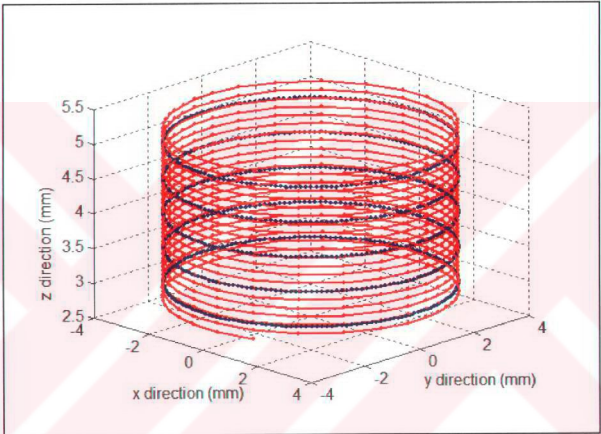


Figure 6.35: Predicted and measured hole profiles, 132 mm/min

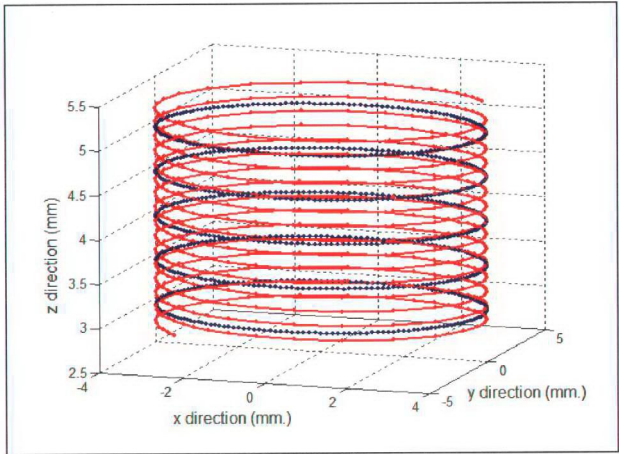


Figure 6.36: Predicted and measured hole profiles, 176 mm/min

6.4.5 Comparison of Hole Properties

Addition to the hole profiles, using the CMM data, cylindricity, roundness and perpendicularity can be determined. These properties of the drilled hole were measured with CMM and compared with the dynamic model outputs. The comparison will be performed below in Table 6.7 that contains the prediction, measured values and the cutting conditions.

Table 6.7: Predicted and measured hole properties for powder metal

Spindle Speed (rpm)	Feedrate (mm/min)		Depth of Cut (mm)	Roundness (micro m)	Perpendicularity (micro m)	Cylindricity (micro m)
1100	132	PREDICTED	0.5	1.3354	5.7235	1.3354
			1.0	1.2960		
			1.5	1.1536		
			2.0	1.1699		
1100	132	MEASURED	0.5	1.1971	7.6159	1.458
			1.0	1.7901		
			1.5	1.0564		
			2.0	1.7799		
1100	176	PREDICTED	0.5	1.6364	2.0487	1.9273
			1.0	1.6245		
			1.5	1.5281		
			2.0	1.9176		
1100	176	MEASURED	0.5	1.2225	4.8955	1.3330
			1.0	1.2491		
			1.5	1.2241		
			2.0	1.2496		

Table 6.8: Predicted and measured hole properties for aluminum

Spindle Speed (rpm)	Feedrate (mm/min)		Depth of Cut (mm)	Roundness (micro m)	Perpendicularity (micro m)	Cylindricity (micro m)
1100	132	PREDICTED	0.5	1.3354	5.7235	1.3354
			1.0	1.2960		
			1.5	1.1536		
			2.0	1.1699		
1100	132	MEASURED	0.5	1.2112	8.8925	1.2978
			1.0	1.2037		
			1.5	1.2335		
			2.0	1.2352		
1100	176	PREDICTED	0.5	1.5922	1.7386	3.0526
			1.0	1.2261		
			1.5	1.3428		
			2.0	2.0536		
1100	176	MEASURED	0.5	1.1514	2.6815	1.2804
			1.0	1.1663		
			1.5	1.1519		
			2.0	1.2782		

Chapter 7

CONCLUSION

The objective of the thesis has been to develop a practical method to predict the behavior of drilling operations. Special emphasis has been placed on the prediction of cutting forces which are widely used in machining dies, molds, automobile and aerospace parts. The results of this study provide the prediction of the direction and amplitude of cutting forces applied on the cutter and workpiece structures together with the prediction of resulting displacements in X, Y direction and the drilled hole profile. The prediction of cutting forces helps the process engineers to select 'appropriate values' for the process parameters to achieve a more productive machining level. Besides, knowledge on the cutting forces helps to predict the drilled hole quality.

In this study, the tool geometry of the drill has been defined in Cartesian coordinates initially. The previous models usually employed transformation methods to make use of orthogonal cutting constants, in this study, the cutting constants have been directly calculated using a practical calibration method. Cutting forces have been analyzed for different regions of the drill and it is seen that these forces have a linear behavior for changing feed rate at each region. As a result cutting and edge constants have been derived through use of the linear relationship between feed rate and cutting forces. The cutting constants had substantially high values near the tip of the cutter.

Most of the previous drilling models do not take into consideration the forces in vertical direction. In order to accomplish this, a constant pressure that contributes to the vertical cutting force is analyzed in this work. An equation has been obtained for this pressure value for changing feed rate. Later, the obtained pressure value has been multiplied with the contact area of the drill cutter for all instants of the simulation in order to obtain the contribution to force in vertical direction at any instant.

After all inputs for the force model to function have been provided, validation tests have been made in order to test the system. All tests have been realized in the 110 mm/min - 198 mm/min feed rate interval since the performed calibration covered this interval. Predicted and measured forces

showed good agreement in all the performed tests. Besides predicting the cutting forces in X and Y directions, the dynamic model was also able to determine the hole profile which can be visualized in 3D. The measured dynamometer forces can be predicted by the force model and these forces are the input of the dynamic model. The dynamic model includes the total cutting forces and the transfer functions of the system in X and Y direction. The displacements in X and Y direction and hole profile predicted by the dynamic model matched quite well that of the measured machined workpiece in all the tests.

The model developed in this study is supposed to contribute to increasing the productivity of a manufacturing system and the prediction of the hole profile under cutting conditions directly. Once the drill parameters and cutting conditions are determined, the model will give the cutting forces and the displacements that occur in X and Y direction under low frequency vibration. These will help the manufacturer to predict the drilled hole profile during the drilling operation.

As a future work, calibration procedure can be applied to different materials and cutting forces can be found for these materials. In the mechanistic approach, the cutting edges and the chisel edge modeled together and only the cutting edge errors are considered. The effects of the chisel edge on the cutting force can be found separately and the chisel edge errors can be added to the model.

In dynamic part only low frequency vibrations are considered, chatter can be added to this dynamic model. Also a dynamic model that computes the drill deflection and updates the chip thickness and chip load will enable in accurately predicting the cutting forces and the hole profile.

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