ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

MSc THESIS

Evren KABAKLI

OPTIMIZATION OF PROCESS PARAMETERS OF DRILLING USING THE TAGUCHI METHOD

MECHANICAL ENGINEERING DEPARTMENT

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YÜKSEK LİSANS TEZİ

MAKİNA MÜHENDİSLİĞİ ANABİLİM DALI

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ÖZ

YÜKSEK LİSANS TEZİ

DELME İŞLEMİNDE PROSES PARAMETRELERİNİN TAGUCHI METODU İLE OPTİMİZASYONU

EVREN KABAKLI

Çukurova Üniversitesi

Fen Bilimleri Enstitüsü

Makina Mühendisliği Anabilim Dalı

Danışman : Prof. Dr. Necdet GEREN

Yıl: 2009, Sayfa: 102

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: Prof. Dr. Melih BAYRAMOĞLU
: Yrd. Doç. Dr. Ali KOKANGÜL

Bu çalışmada C 35 Mod By malzemenin Yatay İşleme Merkezi ile delme işleminde değişik çaplarda titanyum karbonitrür (TiCN) kaplamalı takma uçlu matkaplarla kesme parametrelerinin optimizasyonu hedeflenmiştir. Performans göstergeleri olarak yüzey kalitesi, delik dikliği ve silindiriklik seçilmiştir. Kontrol edilen faktörler delik çapları, delik derinlikleri, ilerleme oranı ve teğetsel kesme hızı seçilmiştir. Seçilen faktörler L_9 (3^4) ortogonal dizinine yerleştirilmiş ve deney planı oluşturulmuştur. Deney sonuçlarında performans göstergesi olarak seçilen karakteristikler ölçülmüş ve değişik sinyal gürültü oranları hesaplanmıştır. Varyans analizi metodu kullanılarak da faktörlerin etki seviyeleri tespit edilmiştir. Elde edilen verilerle doğrulama deneyleri yapılmış ve bu deneylerden elde edilen sonuçlar analiz edilmiştir.

Anahtar Kelimeler: Delme işlemi, kaplamalı takma uçlu matkaplar, Taguchi metodu, optimizasyon, varyans analizi

ABSTRACT

MSc THESIS

OPTIMIZATION OF PROCESS PARAMETERS OF DRILLING USING THE TAGUCHI METHOD

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In this study, optimization of process parameters of drilling operation in an horizontal machining center with C35 Mod BY workpiece material with TiCN coated indexable drilling inserts has been targeted. Surface roughness, perpendicularity and cylindiricity were selected as performance characteristics. Controlled factors were selected as hole diameter, hole depth, feed-rate and peripheral cutting speed. A L_9 (3^4) orthogonal array has been employed and experimental runs have been planned. The performance characteristics were measured and various signal to noise ratios were calculated. Analysis of Variance has been carried out and effect levels of the controlled factors has been analyzed. From the analyzed data confirmation experiments have been carried out and the results were analyzed.

KeyWords: Drilling, coated indexable insert drills, Taguchi method, optimization, analysis of variance

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NOMENCLATURE

CNC : Computer Numeric Control
FMS : Flexible Machining Cells
NC : Numeric Control
IT9 : ISO Surface quality range
n : Spindle speed (Rpm)
V_c : Peripheral cutting speed (m/min)
D : Diameter of a circle (mm)
V_f : Feeding speed (mm/min)
f : Feed per revolution (mm/rev)
a_p : Radial depth of cut (mm)
z : number of cutting edge
f_z : feed per edge (mm/edge)
V : removed chip volume (mm^3/min)
L : Drilling length (mm)
h : Drill point depth (mm)
T : Effective drilling time (min)
γ : Rake angle of drill
η : Feed angle
γ_e : Effective rake angle
TiN : Titanium nitride
TiAlN : Titanium aluminum nitride
Ti(C,N) : Titanium carbon-nitride
Al_2O_3 : Alumina
CVD : Chemical Vapor Deposition
PVD : Physical Vapor Deposition
k_c : Specific cutting force (N/mm^2)
F_{pi} : Cutting force per edge (N)
F_p : Feed force or drilling pressure (N)
K_r. : Entering angle

F_c : The total tangential force (N)

F_{ci} : The tangential cutting force per edge (N)

M : Drilling moment (Nm)

r_A : Radius to the centre point of the chip area (mm)

P_C : The drilling power (kW)

BUE : Built-up edge

t : Tool life-time

C : Taylor’s tool life equation constant

n : Taylor’s tool life equation constant

K : Extended Taylor’s tool life equation constant

m : Extended Taylor’s tool life equation constant

p : Extended Taylor’s tool life equation constant

$L_9(3^4)$: Orthogonal array for 9 experiments 4 factors and 3 levels

HSS : High speed steel

$L_{27}(3^{13})$: Orthogonal array for 27 experiments 13 factors and 3 levels

TiAlSiN : Titanium aluminum silicon nitride

Ra : Average surface roughness (µm)

S/N : Signal to noise ratio

ANOVA : Analysis of Variance

ISO : International Standards of Organization

$L_8(2^7)$: Orthogonal array for 8 experiments 7 factors and 2 levels

HIPed : Hot isostatic pressed

Rt : Maksimum peak to valley surface roughness (µm)

PI3 : Plasma Immersion Ion Implantation

DBL : Daimler Benz Lievervorschrift

L(y) : Quality loss function

m : The target value for actual parameter

k : The quality loss coefficient

OA : Orthogonal Arrays

y_{ave} : Mean of the responses

y_i : Response

S : Standard deviation

SN_S : Smaller the better signal to noise ratio

SN_T : Nominal is the best signal to noise ratio

SN_L : Larger the better signal to noise ratio

CMM : Coordinate measuring machine

MSR : Multi-sensor rack

VAST XXT : Scanning probe for CMM

λ_c : Cut-off length (mm)

λ_S : The evaluated profile length (mm)

Rp : The root mean square roughness (μm)

Ry : Maximum peak-to-valley roughness (μm)

L : The sampling length of the subject profile

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1. INTRODUCTION

Drilling is a widely used machining process to remove material and has considerable economical importance because of its existence among finish conditions of the manufactured components. It has been reported that drilling accounts for nearly % 40 of all the metal removal operations in the aerospace and automobile industries (Li, Umemoto, Todaka, Tsuchiya, 2007).

Drilling is a term which covers all methods of making cylindrical holes in a workpiece with chip cutting tools. In drilling material removed from workpiece with a combined rotating main movement and linear feed movement.

Feed and cutting speed are two important process parameters to achieve the desired material removal rate and productivity in drilling. The use of better tool material with higher strength and hot hardness and better drill geometry design can enable larger feed in drilling. The effect of feed in drilling is an area that has not been studied extensively (Li, Parag, Shih, 2007).

It has been mostly recommended the cutting parameters cutting speed and feed for a certain tool type in tool manufacturer's catalogue. Practically it is very difficult to arrange the recommended parameters to the manufacturing applications directly. Because there are so many effects that affect the performance of cutting tools, machines, process and required quality characteristics. As a result selecting the optimum process parameters such as cutting speed, feed rate and tool geometry is became a key point for today's manufacturing industry and also a responsibility for process engineers.

Considering above mentioned facts, importance of finding the optimum tool choice and process parameters for a specific drilling application is obvious in today's manufacturing industry. In automotive industry, conditions of competition is becoming harder and harder every time. To take part in the market in future requires higher level of productivity rates, lower production costs, and lower wasting time during job set-up.

This can be utilized by optimization techniques which can be used in production floors rapidly to achive the maximum productivity, minumum cost, minumum deviations on quality characteristics of the subject production components (design parameters).

The need for selecting and implementing optimal machining conditions and the most suitable cutting tool has been felt over the last few decades. Despite Taylor's early work on establishing optimum cutting speeds in a single pass turning, progress has been slow since all the process parameters need to be optimized. Furthermore, for realistic solutions, the many constraints met in practice, such as low machine tool power, torque, force limits and component surface roughness must over come (Aggarwal, Singh, 2005).

The non-availability of the required technological perfromance equation represents a major obstacle to implementation of optimized cutting conditions in practice. This follows since extensive testing is required to establish emprical performance equations for each tool coating-work material combination for a given machining operation, which can be quite expensive when a wide spectrum of machining operations are considered.

In this study Taguchi Method is used to optimize the process parameters such as cutting speed and feed rate in drilling. An horizontal CNC machining center is used for drilling tests. Medium Carbon Steel defined as C 35 Mod BY is used as material. Surface roughness, perpendicularity and cylindricity are selected as performance characteristics. Then optimum process parameters has been derived from the anlysis of the results. Parameters which have the major effect on performance characteristics and the percentage contribution of the effect have been analysed and finally confirmation tests have been carried out to compare the results with experimental results.

1.1. The Drilling Process

A drill for cutting metal is a rotary end-cutting tool with one or more cutting lips, and usually one or more flutes for the passage of chips and the admission of cutting fluid. Drilling is usually the most efficient and economical method of cutting a hole in a solid metal.

In drilling, rotating main movement combined with a linear feed movement. Previously holes were drilled mainly in conventional, vertical machines and drilling was often the cause of bottlenecks in production. However, this operation is now carried out in most machines and today; the quick formation of short holes in modern FMS, machining centers, NC and CNC lathes is in wide-spread practice.

The fact that drilling is by far the most common machining operation and the great majority of hole diameters are within the range 10-20 mm, shows quite clearly how important the operation is in the field of modern metal cutting.

With the development of tools for short hole drilling, the need for preparatory and subsequent machining has changed drastically. Modern tools have led to solid drilling being carried out in a single operation without previous drilling of centre and pilot holes and to a hole quality where subsequent machining to improve the measurement accuracy and surface texture often is eliminated (Sandvik Coromant, 1994).

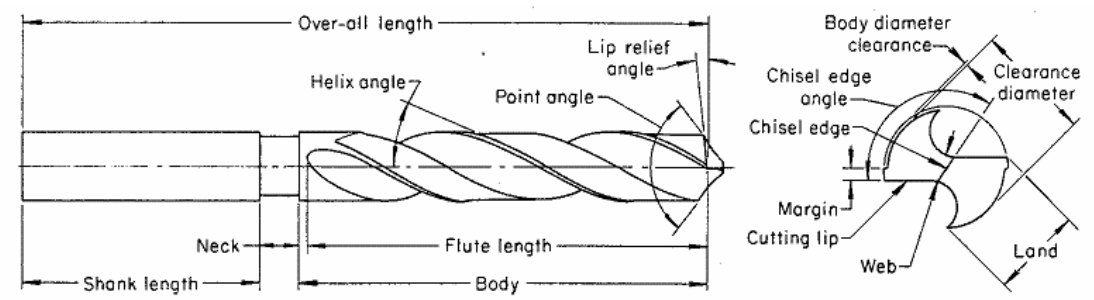


Fig. 1.1 Applied terms to twist drills (ASM, 1995)

1.1.1. Fundamentals of Drilling Process

The process can be compared with turning and milling, in most instances, but the demands on chipbreaking and the evacuation of chips is more accentuated with drilling. The greater the hole depth the more difficult it is to control the process and to remove the chips. Furthermore, in a general comparison, the quality requirement is greater when machining deep holes, while short holes are normally frequently occurring higher material removal rate is desirable for good machining economy.

This means that the differences between short hole drilling are not just restricted to the relationship between the hole depth and its diameter. The parameters which have been mentioned-chip evacuation, quality and material removal rate – form the basis of differing methods of drilling short and long holes. Short hole drilling covers holes with a relatively small hole depth to hole diameter ratio. For hole diameters of up to 30 mm this currently applies to hole depths which are maximum of 5-6 x D, while the hole depth for larger diameters is limited to 2,5 x D. (Akkurt, 1992; Anlağan, 2005).

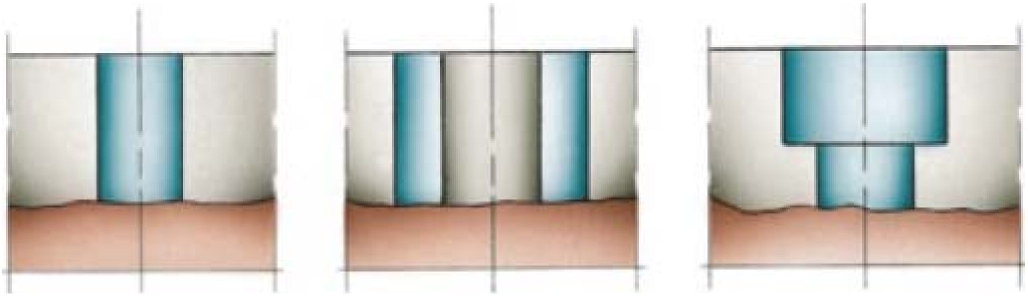
The relationship between hole depth and hole diameter which defines short holes is limited by available technology and could change with tool development. For example, about twenty years ago short hole drilling was classified as a roughing operation, while with today's tool tolerances of IT9 can be obtained which is sufficient in most finishing operation (Sandvik Coromant, 1994).

Drilling is a combination of two movements: a main rotating movement and a linear feed movement. With short hole drilling in conventional machines the most usual form of working is that both the rotating and feeding movements are done by the tool. However, the use of universal NC and CNC controlled lathes for short hole drilling has lead to an increase in the combination of rotating workpiece and non rotating drill.

The most common drilling method is solid drilling shown in Figure 1.2.a, whereby the hole is drilled in solid material to a predetermined diameter and in a single operation.

Trepanning as shown in Figure 1.2.b is a principally used for large hole diameters since this method is not so power-consuming as solid drilling (Sandvik Coromant, 1994). Trepanning is also carried out in one operation but, instead of all the material being removed in the form of chips, a cylindrically shaped core is left at the centre of the hole. The method is for through-hole applications only.

In order to improve the surface quality or the tolerance of the hole in some operations, subsequent counter-boring can be undertaken. This is a third drilling method, as shown in Figure 1.2.c which can certainly be done with short hole drills but does not normally provide sufficient accuracy. The pre-drilled hole can cause deflection of the drill when tools with asymmetrical geometry are used. Many short hole drills are self-centering and in a pre-drilled hole uneven loading of the cutting edges is obtained when the drill searches for the centre. This means the drill follows a crooked path which results in oval holes.



(a) (b) (c)

Fig. 1.2 (a) Drilling, (b) Trepanning, (c) Counter-boring (Sandvik, 2008)

1.1.2. Cutting Conditions

Irrespective of whether a solid drill or a drill with a replaceable (indexable) inserts are used, the basic definitions for the drill's working conditions are the same.

In drilling, the main movement is rotation, which can be done by either tool or workpiece. The spindle speed (n) is the speed at which the main movement takes place and is expressed in the number of revolutions per minute (Rpm).

The cutting speed (v_C – in m/min) is determined for drilling by the periphery speed and can be simply calculated when the number of revolutions per minute is known for spindle speed. During one revolution the periphery of the drill will describe a circle with a circumference of π x D, where D is equal to the tool diameter. If the diameter is expressed in mm, the result must be divided by 1000 in order to obtain the cutting speed in meters per minute.

$$V_C = \frac{\pi \times D \times n}{1000} \text{ (m/min)} \quad (1)$$

$$V_f = f \times n \text{ (mm/min)} \quad (2)$$

The feed speed or penetration rate (v_f – in mm/min) is the feed of the tool in relation to the workpiece or, alternatively, the feed of the workpiece in relation to the tool, expressed in length per unit of time. This is also known as the machine feed or table feed as shown in Figure 1.3.a.

Feed per revolution (f – in mm/rev) expresses the movement of the tool or workpiece during one revolution and is used to calculate feed, and shown in Figure 1.3.a.

The cutting width or radial cutting depth (a_p – in mm) is that part of the workpiece surface which the tool covers and is measured, as for turning, on half of diameter and shown in Figure 1.3.b and Figure 1.3.c for solid drilling and trepanning.

$$a_p = \frac{D - d}{2} \text{ (mm)} \tag{3}$$

Since the drilling tool is equipped with several cutting edges (z = number of edges), the feed per edge (f_Z – in mm/edge) is used to define the chip area (A – in mm^2), which is the area of the material removed in one cut, i.e. the radial cutting depth times feed per edge and shown in Figure 1.3.c.

$$f_Z = \frac{f}{Z} \text{ (mm / edge)} \tag{4}$$

$$A = a_p \times f_Z \text{ (mm}^2\text{)} \tag{5}$$

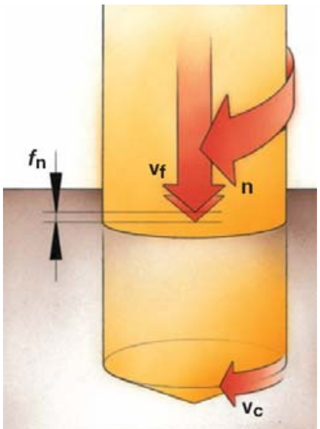
By using some of these definitions the material removal rate (V – in mm^3/min), or the volume of material removed per unit of time, can be established. The volume is the cutting speed multiplied by the chip area. If the cutting speed is expressed in m/min the result must be multiplied by 1000 to obtain mm^3/min.

$$V = A \times V_C \times 1000 \text{ (mm}^3\text{/min)} \tag{6}$$

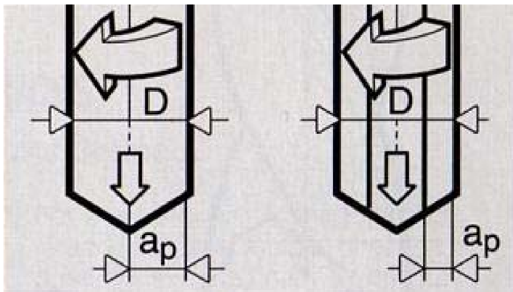
By stipulating the length fed (L + h – in mm) and dividing it by the feed speed, the effective drilling time (T – in min) is obtained. The drilled, or fed, length is equal to the hole depth plus the height of the drill's point.

$$h = \frac{D}{2} \times \cot \frac{\varphi}{2} \text{ (mm)} \tag{7}$$

$$T = \frac{L + h}{v_f} \text{ (min)} \qquad (8)$$



(a)



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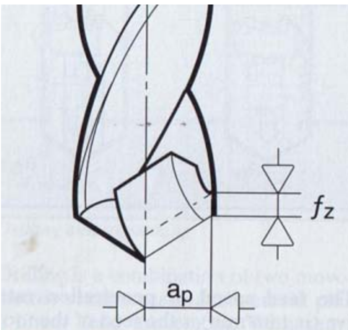
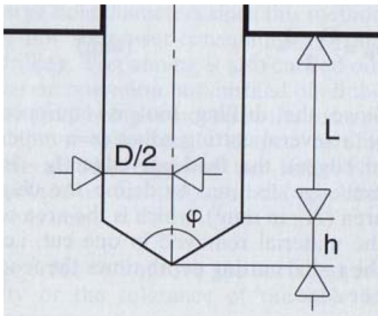


(c)



(d)

Fig. 1.3 (a) Cutting speed and feed, (b) Cutting depth, (c) Cutting depth and feed per edge, (d) Length fed (Sandvik Coromant, 2008; Sandvik Coromant, 1994)

1.1.3. Chip Formation

Most short drills have two chip channels and, generally, two cutting edges. The chips are evacuated via chip channels and, with modern machines and drilling tools, this can be done very effectively by cutting fluid internally through the tool's coolant holes. Chip formation is influenced by the workpiece material, tool geometry, cutting speed and choice of cutting fluid. Generally, increased feed and/or reduced cutting speed produces shorter chips. The chip length can be said to be acceptable if the chips can be led away from the drill's cutting edges without any problem.

By studying the chipbreaking range, good guidance is obtained as to how the cutting data should be adjusted. The chipbreaking area is obtained by test running of the tool with various combinations of cutting speed and feed in the material concerned and constitutes the part where satisfactory chipbreaking is obtained. In Figure 1.3.a the cutting speed will be too high at the periphery for satisfactory chip-breaking to be obtained. In this example the problem can be solved by increasing the feed. If the power of the machine or stability is a critical factor it may be more appropriate to reduce the cutting speed.

Since the cutting speed is lower progressively from the periphery towards the centre of the drill, the risk of build-up edge must be taken into account when reducing the cutting speed. A certain amount of build-up edge in the vicinity of the centre of the drill must be accepted in most cases, but reducing the cutting speed means that build-up edge starts closer to the periphery.

Since the chip material which is separated in the chipbreaking process undergoes plastic deformation, the deformed chip thickness, h_1 shown in Figure 1.4, differs from the theoretical chip thickness when drilling increases with increased feed per edge and increased point angle.

$$h = f_Z \times \sin \frac{\varphi}{2} \text{ (mm)} \qquad (9)$$

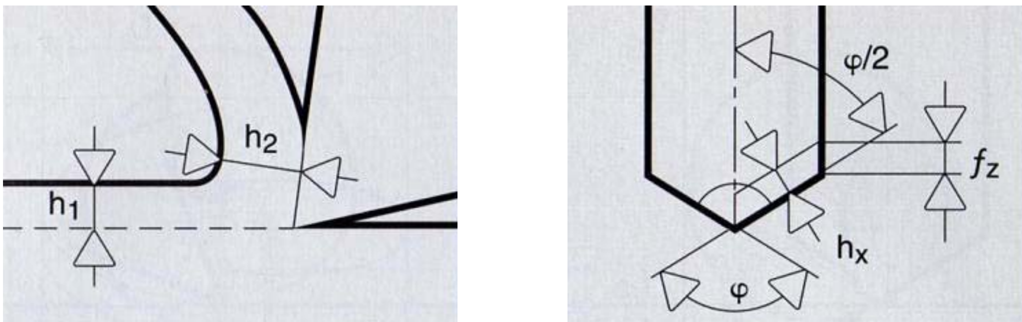


Fig. 1.4 Chip formation factors (Sandvik Coromant, 1994)

The working conditions of the insert when drilling are similar to turning as shown with 1 in Figure 1.5. The rake angle γ shown in Figure 1.5, which is the angle between chip surface and a line at right angles to the direction of cutting shown with "B" in Figure 1.5 will, however, be changed on engagement. When machining is in process the insert edge moves along a spiral path which inclines the feed angle η and the effective rake angle on engagement γ_e will increase.

$$\gamma_e = \gamma + \eta \tag{10}$$

$$\tan \eta = \frac{f}{\pi \times D} \tag{11}$$

$$\alpha_e = \alpha - \eta \tag{12}$$

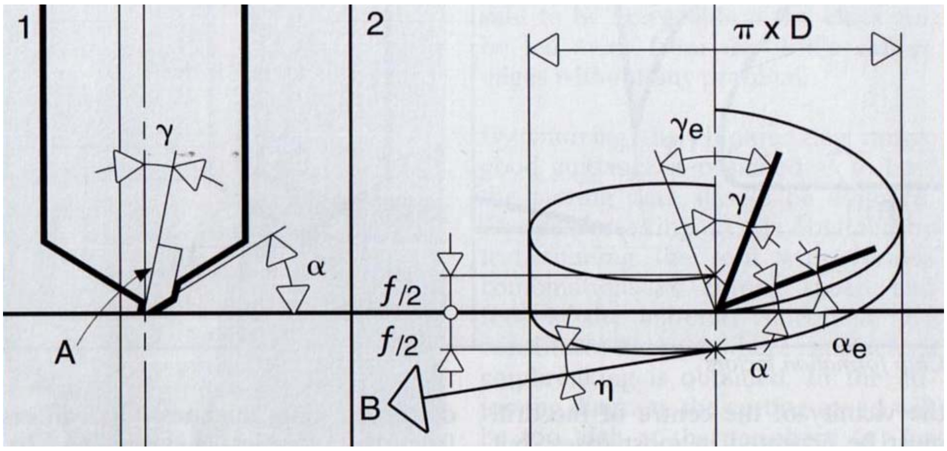


Fig. 1.5 Cutting edge action in drilling (Sandvik Coromant, 1994)

With increased feed, the feed angle η increases and the clearance α is reduced. This reduction is greatest nearest the centre which means that the clearance angle should increase from the periphery towards the centre in order to avoid abrasion between the tool and the walls of the hole.

The rake angle γ_e shown in Figure 1.5, varies along the cutting edge and drops in size from the periphery towards the centre of the drill. Since the cutting speed also drops from the periphery towards the centre, where it is zero, the cutting edge will work very ineffectively at the point of the drill. As the point of drill pressed and scrapes the material rather than cutting it, a plastic deformation occurs where the rake angle is negative and the cutting speed approaches zero. This pressure gives rise to a relatively high axial force component. If the machine is weak in relation to the size of hole to be drilled, the machine spindle may spring due to the feed force being too large and, as a result, oval holes may be obtained. The problem with the unfavourable working relationship of the chisel edge has spurred tool development. The chisel edge has been greatly diminished or is totally eliminated and instead the cutting edge passes in a radius towards the centre of the drill shown with "A" in Figure 1.6. On conventional twist drills web thinning can be applied, which means that the spiral slot at the point of the drill is ground down. In this way the length of the transverse cutting edge is reduced and the main cutting edge will form a broken line shown in Figure 1.6 with "B".

In order to obtain straight main cutting edges after web thinning, corrective grinding is often subsequently carried out. Corrective grinding involves the whole or part of the chip sides of the main cutting edge so that a constant rake angle is obtained during the operation. For example during drilling brittle materials it may be advisable to use a drilling tool with a smaller rake angle along the whole cutting edge.

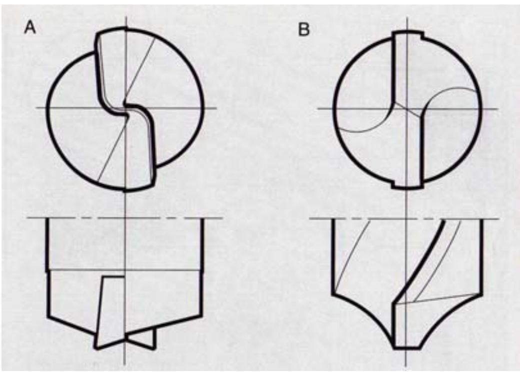


Fig. 1.6 Reduction of chisel edge cutting direction (Sandvik Coromant, 1994)

1.1.4. Cutting Tool Materials for Drilling

Tool materials are the subject of intense development. Today, there is a tool material to optimize every metal cutting operation – one that will cut a certain workpiece, under certain conditions in the best way. Not only have completely new materials appeared but high speed steel, which was the major breakthrough at the beginning of the century, has been developed to machine several times faster.

A cutting tool is sharp and harder than the workpiece, so cutting tools cut metal (Akkurt, 1992; Sandvik Coromant, 1994; Anlağan, 2005). But the high productivity situation is more complex. The tool for an operation, therefore, is a combination of geometry and tool material, selected and applied of following several factors:

- Operation
- Workpiece shape and material
- Machine tool
- Cutting data
- Required finish
- General stability
- Machining costs

The operation factors are determined by roughing or finishing demands, working allowances and continuous or interrupted cuts. The workpiece is characterized mainly by material type, structure, hardness, strength, material affinity and various inclusions. Condition, power, rigidity, mechanism, speed and feed capability and workpiece fixturing should be considered as machine tool. Cutting data affects the temperature and stresses against the cutting edges of the tool during cutting. Finishing properties required by the design such as roughness and accuracy are constraints for tool material and tool type.

The most common and important properties for cutting tool materials against higher speeds and higher feed ranges are hardness, wear resistance, toughness and hot hardness (Anlağan, 2005). Other properties become relevant for lower speed ranges also.

Hardness: The resistance to penetration by diamond-hard indenter, measured at room temperature.

Wear Resistance: The ability to stand up to various types of wear, so that the cutting edge retains its ability to perform in the planned conditions.

Toughness: To strength against breakage, ability to absorb energy, usually expressed as bending strength and rupture strength.

Hot Hardness: The ability to retain high hardness and chemical stability at elevated temperatures.

Most drills are made of common grades of high-speed tool steel. At comparatively low cost, these grades provide strength, toughness, and high-temperature hardness suitable for most drilling applications. For excessively hard or abrasive materials, drills can be made of higher alloy high-speed tool steels, these steels, however, are used to make only a small percentage of the drills produced.

Carbide-tip drills are used for special applications, notably, for drilling abrasive metals of low tensile strength (such as cast iron and castings of high-silicon aluminum alloys) or heat resistant alloys. Solid-carbide drills are used for extreme rigidity and drilling accuracy.

Various surface treatments are applied to high-speed tool steels to increase the hardness of the outer layer. So the friction between drill, workpiece and chips in the flutes reduces. These treatments are normally applied post finish ground. The treatments produce a hard thin layer on the outer layer and include nitriding, carbonitriding and carburizing. Also other coating methods can used to maintain hard thin outer layer or layers included TiN, TiAlN, multilayered Ti(C,N)- TiN and Al_2O_3 with CVD(Chemical Vapor Deposition) and PVD(Physical Vapor Deposition).

1.1.5. Cutting Forces

The specific cutting force (k_c – N/mm^2) is important when calculating the feed force, torque and power required. The specific cutting force is a measurement of machinability for a particular material with a determined rake angle and chip thickness. The specific cutting force is defined as the tangential force required cutting a chip with a cross section of one square mm or the effective cutting force divided by the theoretical chip area. For carbon steel (C 0,8%) this value is 2700 N/mm^2 and for normal aluminium alloys 750 N/mm^2. The specific cutting forces fall in size with increased positive rake angle and increased average chip thickness. For each degree of increase in the rake angle, the k_c value decreases by 1-1,5% (Sandvik Coromant, 1994).

The cutting force, which is considered to operate in the centre of the theoretical chip area, consists of three components which act in tangential, radial and axial directions. They are influenced by the workpiece material, cutting depth, feed and tool geometry. The sum of the axial force components, that is the product of the number of cutting edges and the axial cutting force per edge F_{pi} shown in Figure 1.7, gives rise to the feed force or drilling pressure F_p, which is shown in Figure 1.7. The feed force increases with increased entering angle K_r. The entering angle is the angle between the main cutting edge and the feed direction.

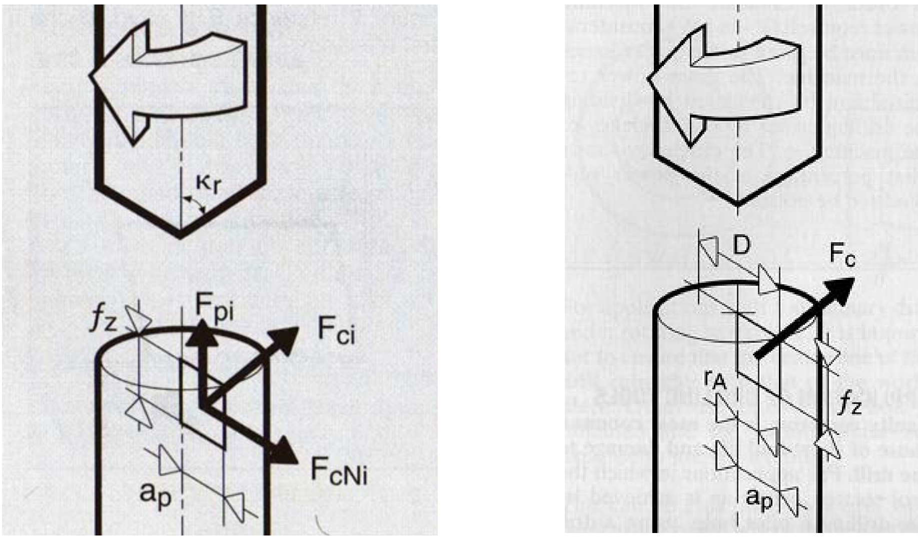


Fig. 1.7 Cutting force components

$$F_P = 0,5 \times k_C \times a_P \times f_r \times \sin K_r \text{ (N)} \quad (13)$$

$$F_C = k_C \times a_P \times f_r \text{ (N)} \quad (14)$$

The total tangential force F_c, or main cutting force, gives rise to the torque. F_c is the product of the number of cutting edges and the tangential cutting force per edge F_{ci}. The torque is the sum of the moment on each cutting edge. This means total drilling moment M – in Nm, is the product of the tangential cutting force and the radius to the centre point of the chip area, r_A. The hole diameter D, can be given in mm since it is squared and will be cancelled out by k_C. In order to obtain the torque expressed in Nm the product must be divided by 1000 if the feed is given in mm/rev.

$$M = F_C \times r_A \text{ (Nm)} \quad (15)$$

$$r_A = \frac{d}{2} + \frac{a_P}{2} = \frac{D + d}{4} = \frac{D}{4} \text{ (N)} \quad (16)$$

where d = 0 for solid drilling then

$$M = \frac{k_C \times f}{1000} \times \left(\frac{D^2}{8} \right) \text{ (Nm)} \quad (17)$$

Increased feed results with increased chip thickness, therefore requires smaller specific cutting force. But at the same time chip area increases and with increased feed results with larger tangential force and moment. If the point angle increased, which will increase the chip thickness at the same time the tangential force and torque will reduce as a result of a smaller k_C value (Sandvik Coromant, 1994).

The drilling power P_C, in kW is the product of the drill's turning moment and its angular speed, w. The angular speed is 2π times the spindle speed. The power is expressed in kW. It is equal to thousand Nm per second. If the moment is given in Nm, the result must be divided by 1000, and also the spindle speed is given in rpm, result must additionally be divided by 60 to convert it to seconds.

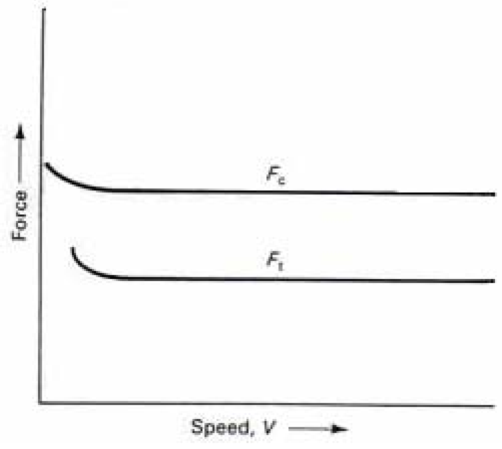
$$P_C = M \times w \quad (18)$$

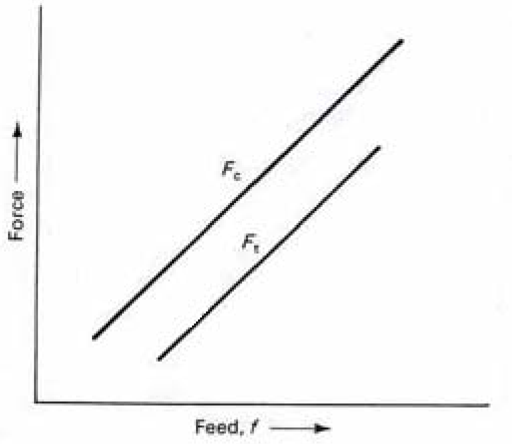
$$w = 2\pi \times n \quad (19)$$

$$n = \frac{V_C \times 1000}{\pi \times D} \text{ (rpm)} \quad (20)$$

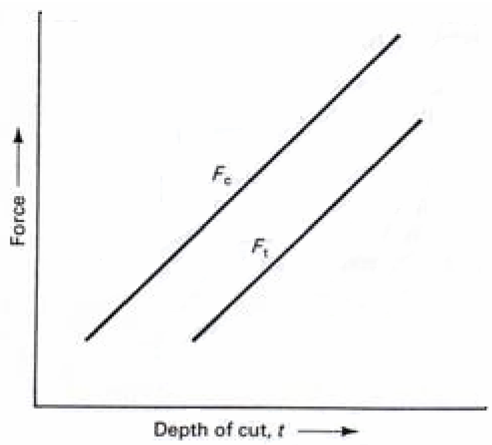
$$P_C = k_C \times \frac{f}{1000} \times \left(\frac{D^2}{8} \right) \times \frac{2\pi \times V_C \times 1000}{\pi \times D \times 60 \times 1000} \quad (21)$$

$$P_C = k_C \times f \times \frac{D^2 \times V_C}{D \times 240000} \text{ (kW)} \quad (22)$$





(a) (b)



(c)

Fig. 1.8 General relationship of orthogonal cutting forces to primary cutting parameters speed (a), feed (b) and depth of cut (c) ((ASM, 1995)

The cutting force, F_C, is the dominant force in this system, and it is important to understand how it varies with changes in the cutting parameters. As seen in figure 1.8, the cutting forces typically double when the feed or depth of cut doubled, but cutting forces remain constant when cutting speed increased. In addition, the forces will increase when the rake angle is reduced (ASM, 1995).

1.1.6. Tool Wear

Cutting tools wear because of the higher levels of normal loads generated by cutting chips and workpiece on the wear surface. The temperature of the tool material increases because of the cutting action and the friction at the contact surfaces. This accelerates the physical and chemical processes resulted with tool wear. These forces and motions are necessary to remove chips: therefore, cutting tool wear is a production management problem. Wearing continues during cutting until the cutting tool reaches the end of its tool life. It is the productive time period that the cutting edges perform their jobs within the limiting parameters (tolerances).

As a result of the load factors impress the cutting edge during machining a few basic wear mechanisms dominate metal cutting called as abrasion wear, diffusion wear, oxidation wear, fatigue wear and adhesion wear. The wear surfaces and relationship between chip, workpiece and tool are shown in Figure 1.9a and Figure 1.9.b.

Abrasion wear: Abrasion wear is very common and caused mainly by the hard particles of the workpiece material. This is similar to grinding process where the hard particles exist between the surface of the workpiece and tool. It is as a result of a mechanical load on the insert that leads to the wearing of a flat face on the cutting edge flank. The resistance of the cutting tool against abrasive wear depends on mainly to the hardness of the tool material.

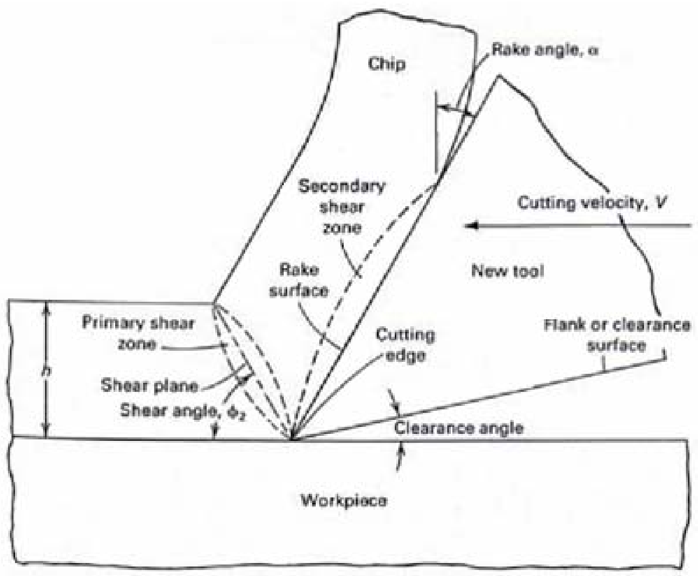
Diffusion wear: Diffusion wear more affected by the chemical load during the cutting process. The chemical properties of the tool material and the affinity of the tool material to the workpiece material will decide the development of the diffusion wear mechanism. The metallurgical relationship between the materials will determine the amount of the wear mechanism. Some cutting tool materials are inert against most workpiece materials, but some of them have great affinity to some of the workpiece materials. Tungsten carbide and steel have affinity towards each other leading to the diffusion wear mechanism developing. This results in the formation of a crater on the chip face on the insert.

Oxidation wear: High temperatures and the presence of the air cause oxidation for most of the metals, although the oxides are quite different. Tungsten and cobalt form porous oxide films which are more easily removed by the chip. Some oxides like aluminum oxide are more stronger and harder. Some cutting tool materials are more tend to wear due to oxidation than others. Especially the interface part of the edge, where the chip width finishes (at the depth of cut), air gains access to the cutting process. Oxidation there leads to typical notches being formed in the edge.

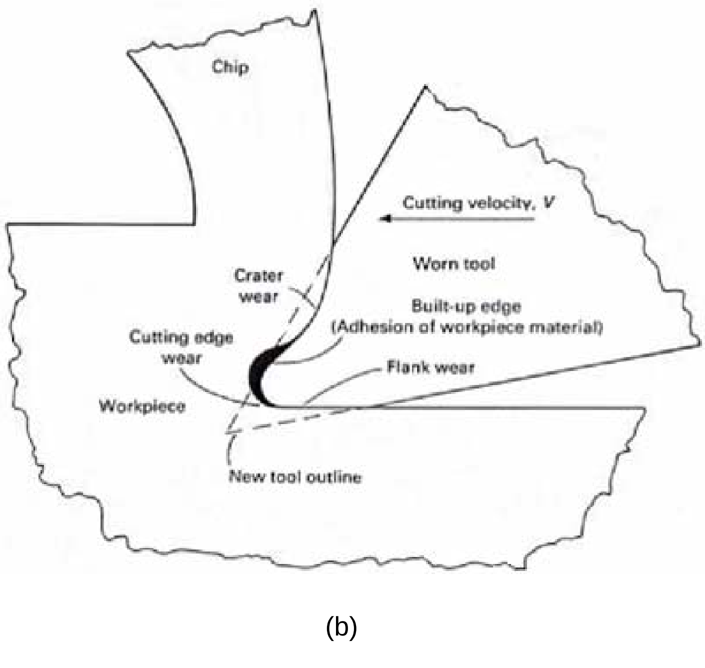
Fatigue wear: Fatigue wear is often a thermo-mechanical combination. Temperature fluctuations and the loading and un-loading of cutting forces can lead to cutting edges cracking and breaking. Intermittent cutting action leads to continual generation of heat and cooling as well as shocks of cutting edge engagement. Some cutting tool materials are more sensitive than others to the fatigue mechanism. Pure mechanical fatigue can occur also from the cutting forces being too high for the mechanical strength of the cutting edge. This can be from hard or strong workpiece materials, very high feed rates or when the tool material has not the hardness required.

Adhesion wear: Adhesion wear occurs mainly at low machining temperatures on the chip face of the tool. It can take place both with long or short-chipping workpiece materials – steel, aluminum and cast iron. This mechanism often leads to the formation of built-up edge, between chip and edge. The build up edge BUE, can be sheared off and begin to build-up again or cause the edge to break away in small pieces or fracture. Some cutting materials and some workpiece materials are more tend to this pressure-welding than the others. A certain temperature range, affinity between tool and workpiece materials and the load from cutting forces combine to create the adhesion wear mechanism. During machining deformation-hardening materials such as austenitic stainless steels, this mechanism leads rapidly local wear at the maximum limit of depth of cut.

These basic mechanisms often combine to attack the original material and shape of the cutting edge along small portion in cut. Depending mainly upon the properties of the tool material, these mechanisms will affect the cutting edge and certain wear types developed (ASM, 1995; Akkurt, 1992).



(a)



(b)

Fig. 1.9 (a) Chip, workpiece and tool relationship, (b) Typical wear surfaces (ASM, 1995)

Flank wear takes place on the flanks of the cutting edge and mainly from abrasive wear mechanism. The clearance sides; leading, trailing and the nose radius or parallel land are subjected to the workpiece during and after chip formation. This is usually the most normal type of wear. After excessive flank wear, the surface roughness, accuracy becomes poorer and increased friction causes the change of the edge shape.

Crater wear mainly caused by abrasive and diffusion wear mechanism together on the rake surface (chip face). The crater is formed through tool material being removed from the rake surface either by the grinding action or at the hottest part of the rake surface through the diffusive action between the chip and tool material. Hardness, hot hardness and minimum affinity between materials minimize the tendency for crater wear. Excessive crater wear changes the geometry of the edge, worsens the chip formation, changes cutting force directions and weaken the edge.

Plastic deformation takes place as a result of a combined high temperatures and high pressure on the cutting edge. High speeds and feeds and hard workpiece materials mean heat and pressure. For tool materials hot hardness is critical against this wear mechanism. The size of the cutting edge rounding and cutting geometry also play a role in resisting this wear type.

Notch wear is a typical adhesion wear on the trailing edge. It can be increased by oxidation wear mechanism. The notch will be formed where the cutting edge and material part. The wear will be much localized at the end of cut, so air can get to the cutting zone. On the leading edge, notch wear is mechanical and often formed with harder materials. Excessive notch wear affects the surface roughness and weakens the cutting edge.

Thermal cracking is mainly fatigue wear due to thermal cycling. The cracks form, perpendicular to the cutting edge and pieces of tool material between the cracks can be pulled out of the edge. The cutting fluid will amplify the temperature variations between in-cut and out-of-cut.

Mechanical fatigue cracking occurs when the cutting force shocks are excessive. Due to continual variations in load (not large for fracture) cracks formed parallel to the cutting edge.

Chipping of the cutting edge is the line breakage of the cutting edge rather than wear. This fatigue, usually from cycles of loading and unloading, leads the particles of tool materials leaving the tool material surface. Intermittent (Interrupted) cutting is a usual reason of this wear type.

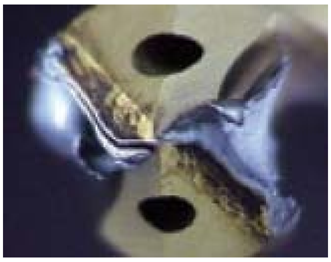
Fracture is the end of the tool life caused by breakage of the cutting edge. It is so harmful and should be avoided as far as possible. The change of geometry, weakening of the edge, rise of temperatures and forces will lead failure on the edge.

Built-up edge, BUE is negative for the cutting edge as the geometry changes and particles from the tool material can break away with the welded material that forms the build up edge BUE. The affinity of tool material to workpiece material forms an important role as well. The lower temperatures and high pressure-welding of workpiece material from the chip on the rake surface of the tool. Fortunately the temperature and cutting speed areas of build up edge BUE formation are relatively well-defined and can be avoided. If this type of wear is allowed to continue, there is a risk of rapid edge breakdown and even fracture.

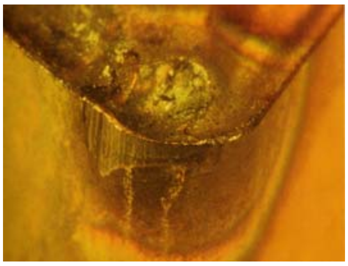
Typical wear types are shown in Figure 1.10, as flank wear, crater wear, thermal cracking and notch wear, mechanical fatigue cracking, chipping of cutting edge, fracture and build up edge.

1.1.7. Tool Life

Tool life defined as chip forming time that the cutting tool reaches the allowed tool wear limit. The wear limit of the tool has estimated at the beginning. After that time cutting tool has considered that it can not performed its task satisfactorily it was chosen for, consequently the tool needs re-grinded or replaced due to supposed as worn out. At this way tool life can be explained as the period of working time of the tool between two re-grinding operation. In certain operations such as drilling, planing or broaching, tool life can be expressed as machining length,



(a)



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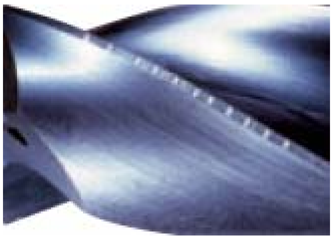
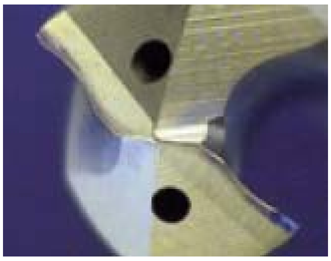


(c)

(d)



(e)

(f)

(g)

Fig. 1.10 Typical Tool Wear Types (a) Flank wear, (b) Crater wear, (c) Thermal cracking and notch wear, (d) Mechanical fatigue cracking, (e) Chipping of cutting edge, (f) Fracture, (g) Built-up edge (Sandvik, 2008; Sandvik Coromant, 1994)

or chip volume in milling.

When the end of the tool life is reached, the cutting edge is changed before any nonconforming components are manufactured or tool breakdown with damage occurs. It is a key point in modern process engineering that the cutting edge is worn out, not broken down (Akkurt, 1992; Sandvik Coromant, 1994).

Tool life is basically depends on tool wear, so such factors workpiece material, tool material, tool geometry, chip geometry, cutting speed and cutting fluid which affect tool wear, also affect tool life, too.

One of the earliest applications of science to production management was done by F.W. Taylor. It has been recognized that tool wear was dependent on cutting speed (Akkurt, 1992; ASM, 1995).

$$V\, t^{n} = C \qquad (23)$$

This became known as Taylor tool life equation, in which the tool lifetime, t, was related to cutting speed, V, by means of the constants n and C. These constants were obtained by testing cutting tools at different cutting speeds using a “tool life criterion” to establish the point at which the useful life of the cutting tool had ended. This criterion was a wear limit that could not be exceeded if a wear failure event was to be avoided (ASM, 1995).

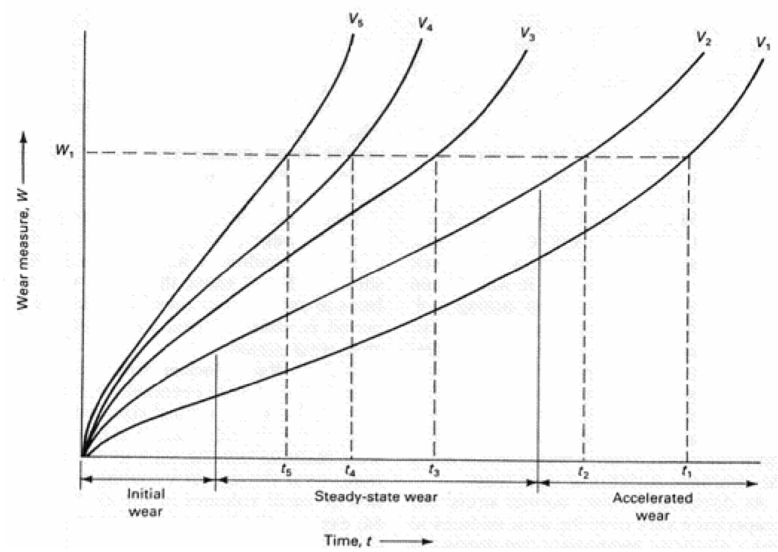


Fig. 1.11 Tool wear curves for different cutting speeds (ASM, 1995)

Typical tool wear curves for different cutting speeds are given in figure 1.11. The wear limit or failure criterion, W_1, shows that the elapsed time before tool replacement increases with a decrease in cutting speed. Taylor's relationship models this behavior and has been used by industry as originally or in modified forms to the present time.

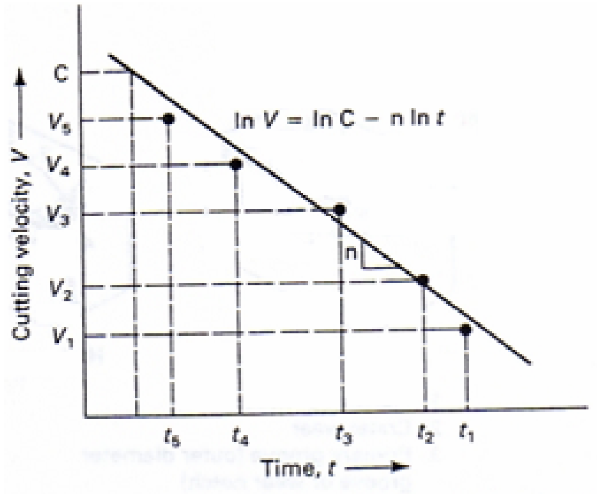


Fig. 1.12 Taylor tool life model using data from Fig. 1.11 and a ln-ln plot (ASM, 1995)

The constant C, equals the cutting speed for 1 minute of elapsed time before reaching the wear limit of the tool. The position and slope of the line in figure 1.12 is affected by the workpiece material, tool material and feed rate. If the feed rate altered the position of the curves will change. Higher feed rate leads shorter tool life, but provides faster machining and material removal rates for a certain cutting speed. Several combinations of cutting speed and feed rate can be achieved to give the same tool life.

The extended Taylor tool life equation can be written considering chip amount and feed. This is known as Extended Taylor tool life equation. Where f, feed rate, a_p, is the depth of cut. K, m and p are coefficients which are obtained with certain tests by some researchers (Akkurt, 1992).

$$t = \frac{C_s}{V^k \times f^m \times a_p^p} \qquad (24)$$

1.1.8. Effects Of Cutting Parameters On Drill(Tool) Life

Apart from drill design and material, and rigidity of the set up, the variables that most affect the life of drills are cutting speed, feed rate, and depth of cut. Cutting speed, feed rate and depth of cut can be defined as cutting conditions for drilling (Akkurt, 1992; ASM, 1995).

Cutting speed: Drill life decreased rapidly as cutting speed was increased. For a given cutting speed, drill life was shortened when feed rate increases. To fix the tool life, when increasing cutting speed, reducing feed rate, depth of cut, or reducing both feed rate and depth of cut has to be considered. This is a key point when surface roughness has considered (Akkurt, 1992; ASM, 1995).

For a certain cutting speed, to fix the tool life feed rate must be reduced and depth of cut must be increased. This provides a increasing in productivity.

Feed rate: The use of a light feed reduces cutting temperature and cutting force. But if feed rate is reduced, the area of chip passing over the cutting edge is increased. As a result, tool wear is likely to increase. Therefore, whether reducing the feed rate is advantageous or not depends on whether the lower cutting temperature and lighter cutting force offset the increased area of chip passing over the cutting edge. At high cutting speed, for which cutting temperature is a critical factor in drill life reducing the feed is an advantageous. At low cutting speed, for which cutting temperature is less critical, the longer chip and the increased rubbing over the cutting edge are likely to offset the advantages of lower feed, and drill life is likely to decrease.

Depth of cut: Increasing depth of cut decreases the tool life, but comparing with cutting speed and feed rate, experiments shown that depth of cut influences the tool life less than cutting speed and feed rate (Akkurt, 1992).

Hardness and composition of work metal: The composition of carbon and low-alloy steels is usually of only secondary importance in its direct effects on drill life. Effects of practical significance include those of free-cutting additives, differences of 0,10% or more in carbon content and substantial differences in the content of alloying elements. Some of these differences in composition also produce changes in hardness. Composition of primary importance when it is necessary to improve drill life by heat treatment or cold reduction of the work material, or by selecting of a more suitable work material (ASM, 1995).

2. PREVIOUS STUDIES

2.1. Optimization Methods

Traditionally, the selection of cutting conditions for metal cutting is left to the machine operator. In such cases, the experience of the operator plays a major role, but even for a skilled operator it is very difficult to attain the optimum values each time. Following the pioneering work of Taylor (1907) and his famous tool life equation, different analytical and experimental approaches for the optimization of machining parameters have been investigated. Some traditional optimization techniques and subjects are as follows:

A.V.S.R.K. Prasad et al (1997), reported the development of an optimization module for determining process parameters for turning operations as part of a PC-based generative CAPP system. The work piece materials considered in their study include steels, cast iron, aluminium, copper and brass. HSS and carbide tool materials are considered in this study. The minimization of production time is taken as the basis for formulating the objective function. The constraints considered in this study include power, surface finish, tolerance, work piece rigidity, range of cutting speed, maximum and minimum depths of cut and total depth of cut. Improved mathematical models are formulated by modifying the tolerance and work piece rigidity constraints for multi-pass turning operations. The formulated models are solved by the combination of geometric and linear programming techniques (Prasad et al, 1997).

J.S. Agapiou (1992), formulated single-pass and multi-pass machining operations. Production cost and total time were taken as objectives and a weighting factor was assigned to prioritize the two objectives in the objective function. He optimized the number of passes, depth of cut, cutting speed and feed rate in his model, through a multi-stage solution process called dynamic programming. Several physical constraints were considered and applied in his model. In his solution methodology, every cutting pass is independent of the previous pass, hence the optimality for each pass is not reached simultaneously (Agapiou, 1992).

B. Gopalakrishnan & F.A. Khayyal (1991), described the design and development of an analytical tool for the selection of machine parameters in turning. Geometric programming was used as the basic methodology to determine values for feed rate and cutting speed that minimize the total cost of machining SAE 1045 steel with cemented carbide tools of ISO P-10 grade. Surface finish and machine power were taken as the constraints while optimizing cutting speed and feed rate for a given depth of cut (Gopalakrishnan, Khayyal, 1991).

Some of latest optimization techniques are as follows:

Fuzzy logic: Fuzzy logic has great capability to capture human commonsense reasoning, decision-making and other aspects of human cognition. Fuzzification expresses the input variables in the form of fuzzy membership values based on various membership functions. Governing rules in linguistic form, such as if cutting force is high and machining time is high, then tool wear is high, are formulated on the basis of experimental observations. Based on each rule, interference can be drawn on output grade and membership value. Inferences obtained from various rules are combined to arrive at a final decision. The membership values thus obtained are defuzzified using various techniques to obtain true value, say of flank wear.

Genetic algorithm: These are the algorithms based on mechanics of natural selection and natural genetics, which are more robust and more likely to locate global optimum. The variables are encoded as n-bit binary numbers assigned in a row as chromosome strings. To implement constraints in GA, penalties are given to individuals out of constraint. If an individual is out of constraint, its fitness will be assigned as zero. Because individuals are selected to mate according to fitness value, zero fitness individuals will not become parents. Thus most individuals in the next generation are ensured in feasible regions bounded by constraints. The GA is initialized by randomly selecting individuals in the full range of variables. Individuals are selected to be parents of the next generation according to their fitness value. The larger the fitness value, the greater their possibility of being selected as parents.

Scatter search : This technique originates from strategies for combining decision rules and surrogate constraints. Scatter search is completely generalized and problem-independent since it has no restrictive assumptions about objective function, parameter set and constraint set. It can be easily modified to optimize machining operation under various economic criteria and numerous practical constraints. Machining models are required to determine the optimum machining parameters including cutting speed, feed rate and depth of cut, in order to minimize unit production cost. Unit production cost can be divided into cutting cost by actual cut in time, machine idle cost due to loading and unloading operation and idling tool motion cost, tool replacement cost and tool cost.

For the optimization of unit production cost, practical constraints which present the state of machining processes need to be considered. The constraints imposed during machining operations are parameter constraint (Ranges of cutting speed, feed rate and depth of cut), tool life constraint (Allowable values of flank wear width and crater wear depth) and operating constraint (Maximum allowable cutting force, power available on machine tool and surface finish requirement).

Response surface methodology : Experimentation and making inferences are the twin features of general scientific methodology. Statistics as a scientific discipline is mainly designed to achieve these objectives. Planning of experiments is particularly very useful in deriving clear and accurate conclusions from the experimental observations, on the basis of which inferences can be made in the best possible manner. The methodology for making inferences has three main aspects. First, it establishes methods for drawing inferences from observations when these are not exact but subject to variation, because inferences are not exact but probabilistic in nature. Second, it specifies methods for collection of data appropriately, so that assumptions for the application of appropriate statistical methods to them are satisfied. Lastly, techniques for proper interpretation of results are devised.

Taguchi technique: It is both the philosophy and methodology for process or product quality improvement that depends heavily on statistical concepts and tools, especially statistically designed experiments. Taguchi’s major contribution has involved combining engineering and statistical methods to achieve rapid improvements in cost and quality by optimizing product design and manufacturing processes. This technique will be explained in next section.

2.2. Optimization with Taguchi Method

V.N. Gaitunde, S.R. Karnik, B.T. Achyutha and B. Siddeswarappa (2008), have optimized the burr size (burr height and burr thickness) by Taguchi optimization method using multi performance objective based on membership function when drilling AISI 316L stainless steel. The objective function was a membership function of burr height and burr thickness. Optimal values of cutting speed, feed, point angle and lip clearance angle were determined for selected drill diameter values to minimize burr size during drilling of AISI 316L stainless steel workpiece. They have proposed a simple modification to the Taguchi method for the multi-objective drilling process optimization, which has employed the multi-performance objective for each trial of the $L_9(3^4)$ orthogonal array based on membership functions associated with burr height and burr thickness. Controlled factors were cutting speed, feed, point angle and lip clearance angle and have 3 levels. The experiments have carried out for four HSS twist drill diameters of 4 mm, 10 mm, 20 mm and 28 mm. Furthermore they observed that cutting speed and lip clearance angle are independent of the drill diameter. On the other hand larger point angle was required to minimize burr size at higher drill diameters. Low values of feed ensure minumum thrust force in order to reduce the burr formation (Gaitunde, Karnik, Achyutha, Siddeswarappa, 2008).

A. Manna and S. Salodkar (2008), have described a procedure to obtain the machining conditions for turning operation considering unit cost of production as an objective function. Krononberg's data have been considered for standard turning operation and a mathematical model was developed for cost estimation which is dependent to directly cutting speed, feed and depth of cut. $L_{27}(3^{13})$ orthagonal array has been used and Ra, surface roughness has been selected as performance characteristic. Controlled factors were cutting speed, feed and depth of cut and have 3 levels. The workpiece material was E0300 alloy steel. A PVD coated (TiAlSiN)

DNMG15608EF grade 8030 single point cutting tool has been used during cutting experiments. During turning of E0300 alloy steel, it was shown that cutting speed is the most effecting parameter on Ra surface roughness compared to feed and depth of cut. The developed mathematical model succesfully proposed for proper selection of the turning parameters when Ra considered as performance characteristic (Manna, Salodkar, 2008).

Chorng-Jyh Tzeng, Yu-Hsin Lin, Yung-Kuang Yang, Ming-Chang Jeng (2008), have investigated the optimization of CNC turning operation parameters for SKD 11 high carbon high chromium tool steel which is used in the production of dies, plastic injection molding dies, precision gauge, spindle, jigs and fixtures using the Grey relational method. An orthogonal array of $L_9(3^4)$, signal-to-noise ratio and analysis of variance and Grey relational analysis method has been employed. The controlled factors were cutting speed, feed-rate, depth of cut and different cutting fluid concentrations and have 3 levels. Cutting length has been fixed for each experimental run. A TiN coated carbide cutting tool has been employed with part number of TNMG160408-UG. Performance characteristics were Ra; average surface roughness, Rt maximum surface roughness and roundness. It has been found out that the factor depth of cut has the most influence on the Ra, and the factor cutting speed was the most influential factor for Rt and roundness. ANOVA analysis has shown that depth of cut has the major affecting factor sequencely cutting speed, cutting fluid concentration and feed-rate were (Tzeng, Lin, Yang, Jeng, 2008).

M. Nalbant, H. Gökkaya and G. Sur (2007), have used Taguchi method to find the optimal cutting parameters for surface roughness in turning operation. An orthogonal array of $L_9(3^4)$, signal-to-noise ratio and analysis of variance have been employed to study the performance characteristics in turning operations. In this study AISI 1030 steel bars have been employed as workpiece material and P20 grade TiN coated cutting inserts types with TNMG160404-MA, TNMG160408-MA and TNMG160412-MA have been used. The controlled factors were insert radius, depth of cut, feed which have three levels. Ra, surface roughness was the performance characteristic. It has been found out that insert radius and feed are the significant characteristics whic are affecting the surface roughness, directly. The change of the depth of cut in the range defined in the study has an insignificant effect on surface roughness (Nalbant, Gökkaya, Sur, 2007).

M.S. Kartal (2006), has employed an orthogonal array of $L_9(3^4)$, the signal-to-noise ratio (S/N) and the analysis of variance (ANOVA) to investigate the cutting characteristics of St33 and St 52 steel bars using hard mine tüpped pen cutting tool in CNC turning. Controlled factors were cutting speed (120 m/min,150 m/min, 180 m/min), feed-rate (0,1 mm/rev, 0,2 mm/rev, 0,3 mm/rev) and depth of cut (0,5 mm, 1,0 mm, 1,5 mm). Performance characteristics were amount of tool wear and Ra surface roughness. After analysing the collected data, it has been found out that cutting speed is most effective parameter for tool life and feed-rate has has a smaller effect compared with cutting speed. The most effective parameter is feed-rate for surface roughness, cutting speed and depth of cut have smaller effects when compared with feed-rate (Kartal, 2006).

D. Kirby (2006), has used Taguchi method for optimizing surface roughness in CNC turning operation. This study has utilized a standard orthogonal array of $L_8(2^7)$, with an applied noise factor. Controlled factors were spindle speed, feed rate and depth of cut. Controlled factors except feed rate have 2 levels, feed rate has 4 levels. Therefore standard orthogonal array has needed to modify. Noise factor was slightly damaged jaw. The noise factor has considered to increase robustness and applicability in industrial applications. The workpiece material was 6061-T6511 Aluminum Alloy rod with a diameter of 25,4 mm. Tool material was VNE Versa Turn CCGT 432-AF. Performance characteristic was Ra, surface roughness. It has been found out that feed rate has the highest effect on surface roughness, spindle speed has a moderate effect, depth of cut has insignificant effect (Kirby, 2006).

J.A. Ghani, I.A. Choudhury, H.H.Hassan (2004), have applied Taguchi method to optimize cutting parameters for AISI H13 in end milling operation. An orthogonal array of $L_{27}(3^{13})$ has been employed to check the interactions among factors clearly. Controlled factors were assigned as cutting speed, feed and radial depth of cut with 3 levels. Performance characteristics were Ra, surface roughness and cutting force which is measured in three directions. Tool material was TiN coated carbide endmilling cutter inserts. S/N ratio and Pareto ANOVA analysis have been caried out. It has been found out that, in end milling, high cutting speed, low feed-rate and low radial depth of cut have obtained better surface finish, furthermore, low feed rate and low depth of cut have leaded the smaller resultant cutting force (Ghani, Choudhury, Hassan, 2004).

T. Chung-Chen, H. Hong (2002) have applied Taguchi method to investigate the wear of TiCN/TiAlCN PVD coated 6 mm tungsten carbide end mill cutters. This study has utilized a standard orthogonal array of $L_8(2^7)$ with controlled factors different coated deposition, feed-rate, spindle speed, tool material which have 2 levels. Workpiece material was AISI 1045 carbon steel and performance characteristic was the amount of the average side flank wear. After milling the defined total removal volume, S/N ratio and ANOVA have been employed. It has been shown that, tool material is the main parameter among other controllable factors which influence the tool life in milling quenched AISI 1045 carbon steel. The TiCN hard coating deposition has the best performance compared to other hard coated treatments, but has an insignificant effect on performance characteristic. The TiCN coated deposition with K40 tool material has the best wear resistance when machining quenched AISI 1045 carbon steel (Chung-Chen, Hong, 2002).

W.H. Yang and Y.S. Tarng (1998), have used the Taguchi method to optimize cutting parameters for turning operation. An orthogonal array of $L_9(3^4)$, the signal-to-noise ratio (S/N) and the analysis of variance (ANOVA) have been employed to investigate the cutting characteristics of S45C steel bars using grade P10 tungsten carbide cutting tool. Controlled factors were cutting speed, feed and depth of cut. Performance characteristics were tool life, amount of flank wear which is recommended by ISO and Ra surface roughness. After analysing the collected data, it has been found out that cutting speed and feed are most effective parameters for tool life compared with depth of cut. Additionally, feed is most effective parameter compared to cutting speed and depth of cut for surface roughness in turning operation (Yang, Tarng, 1998).

2.3. Tool life and Tool Wear

E. Incal (2007), has investigated the wear resistance of PVD coated HSS drilling tools when reboring C45 steel substrate. The drills, with TiN coating and no coating have been examined by comparing abrasion chracteristics. Cutting speed with a value of 22,4 m/min, feed-rate 0,13 mm/rev, hole depth of 15 mm was employed as cutting parameters during drilling tests. It has been found out that wear amount of coated tools were less than uncoated tools. Cutting speed could be increased for this purpose. The coated tools achived better surface finish compared to uncoated tools (Incal, 2007).

I. Demirayak (2006), has investigated the effects of the cutting parameters and coating layer onto the flank wear and surface roughness of the product have been investigated. Cutting parameter ranges were as for cutting speed 120-160-200 m/min, for feed-rate 0,12-0,18-0,22 mm/rev and depth of cut 1-1,5-2,0 mm. of the cold work steels that are used in the automotive industry, especially in die making industry, DIN 1.2738 (AISI P20) has been machined with various cutting parameters using two different cutting tools, each having the same microstructure but different coating layers. After these operations, the effects of the coating layers were evaluated. The coating layer is T(C,N)+ Al_2O_3 + TiN for ISCAR IC 9007 and TiAlN for ISCAR IC 907, and ISO CNMG 120408 type inserts that are recommended for semi-rough operations were employed. As the results of the experiments, it was observed that TiNAl coated inserts have positive effects on the flank wear and surface quality, compared to the T(C,N)+ Al_2O_3 + TiN coated inserts. Increasing cutting speed has resulted with increased wear rate. Increased feed-rate with increased cutting speed is more effective on wear rate than the effect of cutting speed seperately (Demirayak, 2006).

Y. Kaynak (2006), have investigated the efects of machining parameters, different coatings and drill geometry in order to understand their effect on the cutting temperature and cutting forces. The dry drilling tests were performed on Al 2024 for 10 mm diameters of different coated drills; several spindle speeds, and feed rates.

Regrinded, TiAlN coated, TiN coated, %5 Co coated HSS drills were employed in this study. Cutting parameters were employed with the values of 0,15 mm/rev, 0,20 mm/rev, 0,25 mm/rev feed-rates, 30 m/min, 45 m/min and 60 m/min cutting speeds. Full factorial design has been employed and 45 drilling tests have been carried out. Thermocouple method used in these experiments for measurement of cutting temperature. Dynamometer was also used in order to measure of cutting forces in dry drilling of aluminum alloys. The cutting temperatures and forces were predicted using a numerical calculation with Third Wave AdvantEdge™ 3D version Lagrangian based on explicit finite element analysis software. The experimental and numerical approach have used and the results have shown that cutting temperature and cutting forces have increased with increased feed-rate in dry drilling of Al 2024 aluminum alloy. Additionally point angle of 130° has given better results compared with a point angle of 130°. TiN coated HSS drill has provided best wear characteristic (Kaynak, 2006).

G. Büyüktaş (2005), have investigated the wear process and cutting forces of cutting tools whose surfaces had been modified by using Plasma Immersion Ion Implantation (PI3). In this purpose, N_2 and C ions had been implanted to cutting tools by PI. The cutting tests were performed in accordance to ISO 3685 and in the conditions of 0,3 mm/rev feedrate, 2 mm cutting depth, 180-240-300 m/min cutting speed. As work piece, AISI 4140 steel was used in dimensions of Ø120 x 300 mm. In the force measurements, a straingauge based dynamometer was designed and produced to measure main cutting force (Fc) and feed force (Fa). In the result of investigations, it was observed that tool life of cutting tools whose surfaces had been modified by PI3 increased and cutting forces decreased when cutting speed increased (Büyüktaş, 2005).

K.A. Abou-El-Hossein, Z.Yahya (2005), have investigated the performance of multilayered (TiN/TiCN/TiN) carbide inserts recently developed for end-milling of AISI 304 stainless steels. The length of chip–tool contact is small for these inserts as they contain a chip breaker that restricts the chip–tool contact area. In this study, the possible failure modes of tool wear were discussed and the effect of cutting speed and feed rate variation on tool life and tool wear modes was investigated. An increase in tool wear was noticed with increasing the cutting speed, while at the same time, a decrease in tool wear was observed with increasing the cutting feed. The most optimum cutting parameter for end-milling operation using a single end mill was established in terms of maximum productivity and maximum tool life. It has been reported that, the increase in cutting speed caused a dramatic reduction in tool life, but feed variation at high cutting speeds has small affect on tool life. It has been also reported that, the dominant tool failure mode was notch wear at the flank face and this mode occurred at high feed (Abou-El-Hossein, Yahya, 2005).

Tsann-Rong Lin (2002), have investigate the effect of tool life, surface roughness, tool wear and burr formation in high-speed drilling. Ø 8 mm TiN coated solid carbide drills with curved cutting edge were employed during drilling of SUS 304 Austenitic stainless steel with dimensions of 150 mm x 100 mm x 15 mm. The drilling tests were carried out at peripheral speeds of 65 m/min, 75 m/min and 85 m/min. The applied feed-rates were 0,05 mm/rev, 0,1 mm/rev, 0,15 mm/rev and 0,2 mm/rev. The burr height was measured by a digital caliper with a resolution of 0,01 mm. The tool rejection criterion are maximum flank wear of 0,8 mm, Ra surface roughness of 5,0 μm, excessive outer corner tearing and chipping of the helical flutes. Curved cutting edge have also provided reduced torque and thrust force. It is shown that tool life increases with feed-rates smaller than 0,05 mm/rev. Optimal cutting speed was found at 75 m/min from the standpoint surface roughness or burr height. Burr with a drill cap has been decreased as the feed-rate decreases. Outer corner wear is founded the main cause of the drill failure for high feed-rate for low cuttting speed (Lin, 2002).

A.K. Ghani, I.A. Choudhury, Husni (2002), have studied about tool life, surface finish and vibration while machining nodular cast iron using ceramic tool. A series of cutting tests have been carried out to verify the change in surface finish of the workpiece due to increasing tool wear in a conventional lathe machine. The tests have been done under various combinations of speed, feed and depth of cut. The effects of vibration on the flank wear both in the direction of main cutting force and radial cutting forces have been investigated. The vibration was measured using two accelerometers attached to the tool holder and the parameters used to make the correlation with surface roughness were the amplitude and acceleration of the signals. The results show that the tool life of the alumina ceramic inserts is not satisfactory when machining nodular cast iron. In the speed range 364–685 m/min, maximum tool life achieved was only about 1.5 min. Surface finish was found to be almost constant with the progression of the flank wear under all cutting conditions. It has been observed that for the same flank wear, vibration during cutting decreases as the speed increases. At low depth of cut, vibration remains almost constant with the increase of flank wear (Ghani, Choudhury, Husni, 2002).

W.C. Chen, C.C. Tsao (1999), have experimentally investigated the cutting performance of HSS drills with various coatings. TiN monolayer, TiN-surface multilayer and TiCN-surface mutilayer PVD coated HSS twist drills have been used during experiments. To measure the cutting forces and to investigate the effect of coating layers, fixed spindle speed 485 rpm and feed-rate 0,12 mm/rev have been applied during drilling JIS SS 400 carbon steel for each kind of tool. For further investigation to study the effects of drilling conditions on the cutting force response, spindle speed has been fixed for various feed-rates and feed-rate has been fixed for various spindle speeds. Hole depth has been kept constant about 28 mm. For measuring drill life, fixed feed-rate about 0,12 mm/rev and spindle speeds of 485 rpm, 725 rpm and 1030 rpm have been considered during drilling of 60, 80 and 100 holes. Flank wear has been measured during experiments. 100 x 200 x 32 mm blocks of JIS SS 400 carbon steel have been used as workpiece material. It has been shown that, the coating layers have no significant effect on thrust forces and torque. However, the thrust force and drilling torque have increased with increased feed-rate. And the average thrust force and drilling torque have decreased within a narrow range with increasing spindle speed. Drill life has decreases with an increasing drilled number of holes. Consequently drill life has increased with an increasing spindle speed (Chen, Tsao, 1999).

2.4. Machinability

Y. Isik (2007), have investigated the machinability of tool steels in turning operations. In these test the effects of tool material, type of coating on the insert (for coated tools) and the cutting parameters that affect the machinability were taken into considerations. The cutting force data used in the analyses were gathered by a tool breakage detection system that detects the variations of the cutting forces measured by a three-dimensional force dynamometer. The workpiece materials used in the experiments are cold work tool steel, AISI O2 (90 MnCrV8); hot work tool steel, AISI H10 (X32CrMo33) and mould steel, AISI improved 420 (X42Cr13). The cutting tools used are HSS tools, uncoated WC and coated TiAlN and TiC + TiCN + TiN inserts (ISO P25). The type of inserts is DNMG 150608. No cutting fluid was used during the turning operations. During the experiments cutting forces, flank wear and surface roughness values were measured throughout the tool life and the machining performance of tool steels were compared. It has been reported that feed rate (f) is the most influential parameter on surface roughness, cutting depth (a) is the second most one, and cutting speed (V) is the least influential parameter. The influence of cutting speed is negligible compared with those of the other cutting parameters. It has been also reported that, increases of feed rate and cutting depth affect the surface quality negatively and the increase of cutting speed affects the surface quality positively, but this effect appears to be small (Isik, 2007).

J.A. Paro, T.E. Gustafsson, J. Koskinen (2004), have investigated the suitability of TiN- and TiCN-coated cemented carbide tools in the machining of conventionally produced stainless steel with hot isostatic pressed (HIPed) NiTi coating. Stainless steels were often considered to be poorly machinable materials. In this study drilling tests were carried out by a machining center and machinability was studied by analyzing cemented carbide drills and chips. The effect of feed-rate on chip formation and tool wear have been analyzed. The cutting tests have indicated that cutting speeds of 50 m/min, feed-rate of 0,1-0,2 mm/rev and solid carbide drills could be applied with the point of view machinability. A HIPed pseudo-elastic coatings have decreases machinability. When effective cutting speeds and feed-rates were utilized, optimal tool life was achieved without a decrease in coating properties (Paro, Gustafsson, Koskinen, 2004).

E. Gariboldi (2003), have studied on machinability in drilling operations of a magnesium alloy and the opportunity utilized by the use of coated tools. PVD coated 10 mm HSS twist drills with coatings TiN, CrN and two different ZrN were used during the tests. Each coating was characterised as far as thickness, surface finish and hardness were concerned. The dry drilling tests have consisted of machining holes with depth 40 mm, 60 mm, used uncoated and coated tools. Tool life criterion has considered as excessive vibration on cutting tool. The other performance characteristic was Ra surface roughness. Three sets of experiments were carried out at a fixed peripheral speed of 63 m/min and feeds at 0,27 mm/rev, 0,37 mm/rev, 0,5 mm/rev and 0,7 mm/rev. Workpiece material was AM60B magnesium alloy. The tool life of all tested tools at the minumum feed-rate was very short. For TiN coating intermediate levels of feed-rate achives better performance against tool wear. A further increase of feed-rate up to 0,5 mm/rev has shortened the tool life of uncoated and TiN coated twist drills, increased that of CrN and ZrN have been suggested the higher optimal ranges of feed-rate at higher values for zirconium and chromium nitrides. The second series of tests have been carried out for hole depth of 60 mm for only uncoated and ZrN coated tools. For ZrN coated tools long machined length at feed-rate of 0,5 mm/rev has been achieved. So under heavy machining conditions, tool life of uncoated tools has been reduced with the increased feed-rate (Gariboldi, 2003).

2.5. Microstructure of drilled holes

J.G. Li, M. Umemoto, Y.Todaka, K. Tsuchiya (2007), have investigated the microstructure of the surface of the drilled holes which has generated under different drilling conditions of cutting speeds of 20m/min upto 100 m/min, feed-rate from 0,01 upto 0,05 mm/min by using sintered carbide drills with diameters 2,5 mm and 5 mm. The workpiece material were Fe-0,56 %C steels in ferrite and pearlite, martensite and tempered martensite structures, Fe-0,80 %C steels in martensite, fine lamellar pearlite and coarse lamellar pearlite structures and commercial bearing steel (SUJ) in a tempered martensite structure. It has been found out that, surface microstructure has strongly depended on drill parameters and matrix hardness. White Edge Layer formation has strongly depended on drilling parameters and matrix hardness. Hardness depth profile near the hole surface has changed with the cutting speed and the matrix hardness (Li, Umemoto, Todaka, Tsuchiya, 2007).

3. MATERIAL AND METHOD

3.1. Material

3.1.1. Workpiece Material

In this study C35 MOD BY hot rolled low alloyed medium carbon steel used which is modified from C35 defined in EN 10083-2. The material is defined in DBL 4028 (Daimler Benz Lievervorschrift) by customer for special purpose. Workpieces employed are billets 250 mm length and with a square cross-section of 80 x 80 mm. This is a kind of a raw material for forging process that is used to produce finish product after machining and finally used in Automotive Industry engine unit bearing arm. The Chemical Composition of the workpiece material is given in Table 3.1 by percentage of weight. Also the mechanical properties of subject material are given in Table 3.2.

Table 3.1 Chemical Composition of Workpiece Material by percentage of weight.

C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Al %	Cu %	Sn %
0.37	0.57	0.97	0.013	0.055	0.16	0.01	0.12	0.017	0.22	0.014

Table 3.2 Mechanical Properties of Workpiece Material.

Hardness HB	Yield Strength N/mm^2 (0,2 %)	Tensile Strength N/mm^2	Elongation A %	Reduction of Area Z %
207	569	728	20	66

The deliberate addition of sulphur, lead and tellurium to steels, makes possible increased production rates and improved surface finish. These additives also known as free-machining additives, do not greatly affect the room temperature mechanical properties of the parent metal (Boothroyd, Knight, 2006).

The common way of improving machinability of steel is by adding sulphur. For instance, with the sufficient amount of manganese content with sulphur will form manganese sulphides which deform plastically to produce planes of low strength for crack initiation and propagation required during chip formation. The sulphide functions on tool chip interface as a lubricant (Sandvik Coromant, 1994).

Other common additives are lead, selenium or combination of them with sulphur in carbon steels and stainless steels. The effects of other alloying elements are shown in Annex 2

3.1.2. Cutting Tools

The drilling tools used in these sets of experiments are coated cemented carbide indexable insert drills. Central inserts are 1044 grade, fine grained cemented carbide with an excellent combination of both hardness and toughness. The fine grains contribute to keeping the cutting edge sharp throughout the entire tool life. The carbide is PVD coated with a 3 microns bronze colored TiAlN layer giving excellent edge toughness and resistance against built-up edge. The basic choice for central drilling inserts in all materials (Figure 3.1 a). Peripheral inserts are 4024 grade, have a cemented carbide substrate with a good balance between hardness and toughness. The substrate is coated with a MT-CVD layer of TiCN giving excellent abrasive wear resistance, followed by a layer of Al_2O_3 giving very good high temperature protection. The total thickness is about 9 microns and very universal grade for peripheral inserts in steel, stainless steel and cast iron at medium to high cutting speed (Figure 3.1. b). And U-drilling tool has two internal coolant flutes.

All cemented carbide cutting tools can be used at elevated temperatures compared to high-speed steel, but these materials are relatively brittle and can fracture easily when interrupted cuts are used. The standard classification and properties of cemented carbide tool materials are given in Annex 3 (Boothroyd, Knight, 2006).

(a) (b) (c)

Figure 3.1 (a) Central insert, (b) Peripheral insert, (c) U-drill tool (Sandvik, 2008)

More than 75% of turning operations and more than 40% of milling are performed with coated cemented carbides. The main coating materials are titanium carbide (TiC), titanium nitride (TiN), aluminum oxide-ceramic (Al_2O_3) and titanium carbon nitride (TiCN). Titanium carbide and aluminum oxide are very hard materials, providing wear resistance and chemically inert, providing a chemical and heat barrier between tool and chip. Titanium nitride is not such a hard material, but gives a lower coefficient of friction to the faces of the insert and better cratering resistance (Sandvik Coromant, 1994).

3.1.3. Experimental Equipment

The sets of experiments in this study have been carried out on OKUMA MA-500HB SPACE CENTER horizontal CNC machining center with an OSP E100M controller. The machine has a maximum workpiece size of Ø 800 mm diameter x 1000 mm height. Pallet size and machining range capacity are 500 mm x 500 mm and 700 mm x 900 mm x 700 mm in sequence. Spindle speed range is about 50 to 6000 rpm and infinitely variable. Feed-rate range is about 60000 mm/min. Maximum torque of the machine is 606 Nm and maximum output power of the spindle is 30 kW. During the tests the machine spindle torque has been limited from the controller about 25% of the maximum spindle torque as usual application in CIMSATAS during production. The machine stops and gives an alarm signal if there is an existing override value of the limited spindle power.

The fixture used during tests is shown in figure 3.2. Support console (A), workpiece (B), pallet (C), fixing arms (D), lower supporting blocks (E) and upper adjustable supporting (F) can be seen in figure. Rear side of the workpiece has been machined on a conventional milling machine as preparatory process. It is carried out for eliminating the effects of the tightening forces of the fixing arms.

Figure 3.2 Horizontal CNC Machining Center

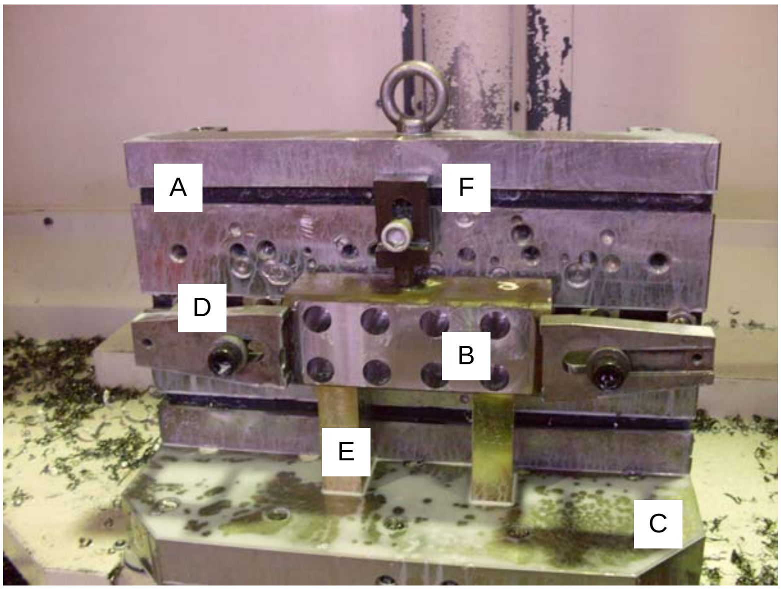


Figure 3.3 Fixture used during tests

Initial start-up checks have been performed before the drilling experiments and can be called as setting up process of the whole process. They have performed in order to minimize and eliminate the variation sources and increase the reliability of the results. Linear positioning accuracy of the machine is checked according to ISO 230-1 at three axes and found about 3 μm. Repeatability of the positioning accuracy of the machine at three axes is found about 1 μm. Spindle speed is checked by SCHENCK VIBRO BALANCER 42 and there is not any deviation detected. Torque-meter is used to tightening the workpiece repeatable and a value of 220 Nm torque. Radial run-out of the drilling tool is checked before every run of experiments. Maximum total run-out of the drilling tool is detected up to 0,05 mm. In order to eliminate the effect of the angular deviation between tool and workpiece, workpiece surface has been milled about 1~2 mm before drilling on the same fixture under same fixed conditions.

3.2. Method

3.2.1. Statistical Design of Experiments (DOE)

The most important benefit from statistically designed experiments is that more information per experiment will be obtained that way than with unplanned experimentation. A second benefit is that statistical design results in an organized approach to the collection and analysis of information. Still another advantage of a statistical planning is the credibility that is given to the conclusions of an experimental program when the variability and source of experimental error are made clear by statistical analysis. Also, an important benefit of statistical design is the ability to discover interactions between experimental variables. (Dieter, 2000)

In any experimental program, to randomize the order in which the specimens are selected for testing, is important. Randomization permits any one of the specimens to have an equal chance of being selected for a given test. This provides minimization of the bias due to uncontrollable second-order variables.

An experimental investigation starts with preliminary familiarization experiments. At this stage earlier results have been gained, and the main aim is to define clearly the problem. Statistical design in this earlier stage is not very applicable. After the goals of the investigation have been defined, the number of variables have been tried to reduce from larger quantity to the most important few ones. As the experimentation moves into the optimization stage, the number of variables has been reduced to only a few. Finally, statistical analysis can assist in choosing between possible models for the process.

The response variables are the data obtained from an experimental run. Responses can be classified as quantitative, qualitative and quantal. A quantitative response is the most common and easiest to work in statistical analysis and can be measured by a continuous scale. Qualitative responses, like color or brightness, can be ranked on an ordinal scale, for example 0 (worst) to 10 (best). Quantal or binary responses produce one of two values, like go or no go, pass or reject.

Factors are experimental variables that are controlled by investigator. The most important part of planning an experimental program is, to identify the most affecting variables for the response and decide how to exploit them. At the analyzing stage support of a statistician is needed. The level of one factor may be independent of the level of the other factors. However, two or more factors may interact with one another, for example, the effect of the response of one variable depends upon the levels of the other variables. Interactions between the factors are determined by varying factors simultaneously under statistical control rather than one at time.

It is important to realize that not all primary factors may be capable of variation with equal facility. Thus, completely randomizing the sequence of testing may be impractical. Often the final experimental plan is a compromise between the information that can be obtained and cost of the information.

It is not necessary to conduct a statistically designed experiment through the completion. There are advantages to conducting the experimental program in stages. That allows changes to be made in later tests based on the information gained from early results. Conducting the experiment in stages is attractive when the optimum response has been searched, and it allows the investigation closer to the optimum at each stage. But, if there are large start-up costs for each stage or if there is a long time delay between preparing the samples and measuring their performance, carrying the designed experiment through to completion may be preferred. (Dieter, 2000)

In general, there are three classes of statistically designed experiments.

Blocking designs, use blocking techniques to remove the effect of background variables from the experimental error. The most common designs are the randomized block plan and the balanced incomplete block, which remove the effect of a single extraneous variable. The Latin square and the Youden square designs remove the effects of two extraneous variables. Greco-Latin square and hyper-Latin square designs remove the effects of three or more extraneous variables.

Factorial designs, are the experiments in which all levels of each factor in an experiment are combined with all levels of every factor. The experimental design consists of making an observation at each of all possible combinations that can be formed for the different levels of the factors. Each different combination is called a treatment combination. Most common type of factorial design is one that uses two levels. A disadvantage is that with only two levels that is not possible to distinguish between linear and higher-order effects. In a 2^n experimental design, factors that are set at the low level are indicated (-) and those at the high level (+). The main effect of the factor is the change in response produced by a change in level of the factor. All treatment combinations have to be used for each estimation of main effect and interaction. The number of treatment combinations in a factorial design increases rapidly with an increase in number of factors. Most of the engineering experimentation can easily involve 6 to 10 factors, so the required number of the experiments can become prohibitive in cost. For considered 6 factors, 2^6 factorial experimental designs require observations of 64 treatment combinations. For considered 4 factors, if three level 3^4 factorial experimental designs require observations of 81 treatment combinations.

Response surface designs, are used to determine the empirical functional relation between the factors (independent variables) and the response (performance variable). The central composite design and rotatable designs are frequently used for this purpose. Response surface methodology has two objectives:

1- To determine with one experiment where to move in the next experiment so as to continually seek out the optimal point on the response surface.
2- To determine the equation of the response surface near the optimal point.

Response surface methodology (RSM) uses two-step procedure aimed at rapid movement from the current operating position into the central region of the optimum. This is followed by the characterization of the response surface in the vicinity of the optimum by a mathematical model. The basic tools used in RSM are two level factorial designs and the method of least squares model and its simpler polynomial forms.

Initially, a small factorial experiment is run over a small area of the response surface where the surface may be considered to be planar. To move most efficiently toward the optimum, a path of steepest ascent along the gradient vector of the surface has to be followed. Experiments are carried out along this path until a maximum is reached. Then another factorial experiment is centered around that point and the new gradient vector is followed.

3.2.2. Taguchi Method

A systematized statistical approach to product and process improvement has developed by Dr. Genichi Taguchi. The technique emphasizes moving the quality issue upstream to the design stage and focusing on prevention of defects by process improvement. Taguchi has placed great emphasis on the importance of minimizing variation as the primary means of improving quality (Dieter, 2000).

Taguchi defines the quality level of a product to be the total loss incurred by society due to the failure of the product to deliver the expected performance and due to harmful side effects of the product, including the operating cost. In the concept some loss is unavoidable from the time a product is served to the customer and smaller loss provides desirable products. It is very important to quantify this loss for comparing various product designs and manufacturing processes. This is done with a quadratic loss function. L(y) is the quality loss when the quality characteristic is y, m is the target value for y and k is the quality loss coefficient.

$$L(y) = k(y - m)^2 \tag{25}$$

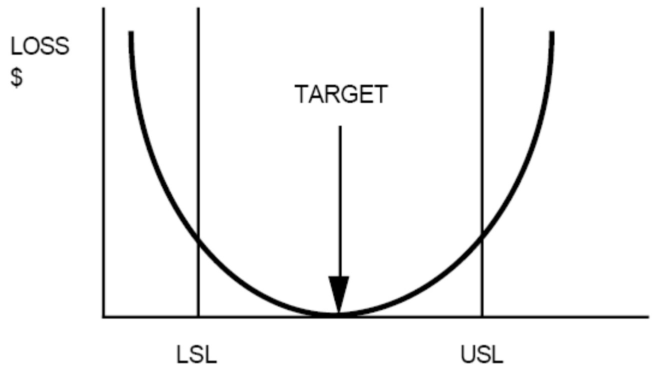


Figure 3.4 The quadratic loss function. (Unal, Dean, 1991)

When y = m the loss is zero and the slope of the loss function is zero, too. The loss increases slowly when y is near m, but by the deviation of y from the target, the loss increases more rapidly. In the usual practice of manufacturing quality control the producer specifies a target value of the performance characteristic and a tolerance interval around that value. Any value of the performance characteristic of which is within the tolerance range about 3σ is defined to be desirable product. With the loss function as a definition of quality the emphasis is on achieving the target value of the performance characteristic and deviations from that value are penalized. The greater deviation from the target value results with a greater quality loss.

The input parameters that affect the quality of the product or process may be classified as design factors and disturbance factors. Design factors are controllable factors by the designer; disturbance factors are the parameters which are uncontrollable or impractical to control. The variability of the input and output parameters plays an important role in Taguchi Methodology. These can be classified into four categories. Output variability, variational noise which is the short-term unit to unit variation due to the manufacturing process and inner noise is the long term change in product characteristics over time due to the deterioration and wear. Input variability, tolerances is the normal variability in design factors and outer noise represents the variability of the disturbance factors that contribute to output variability (Dieter, 2000).

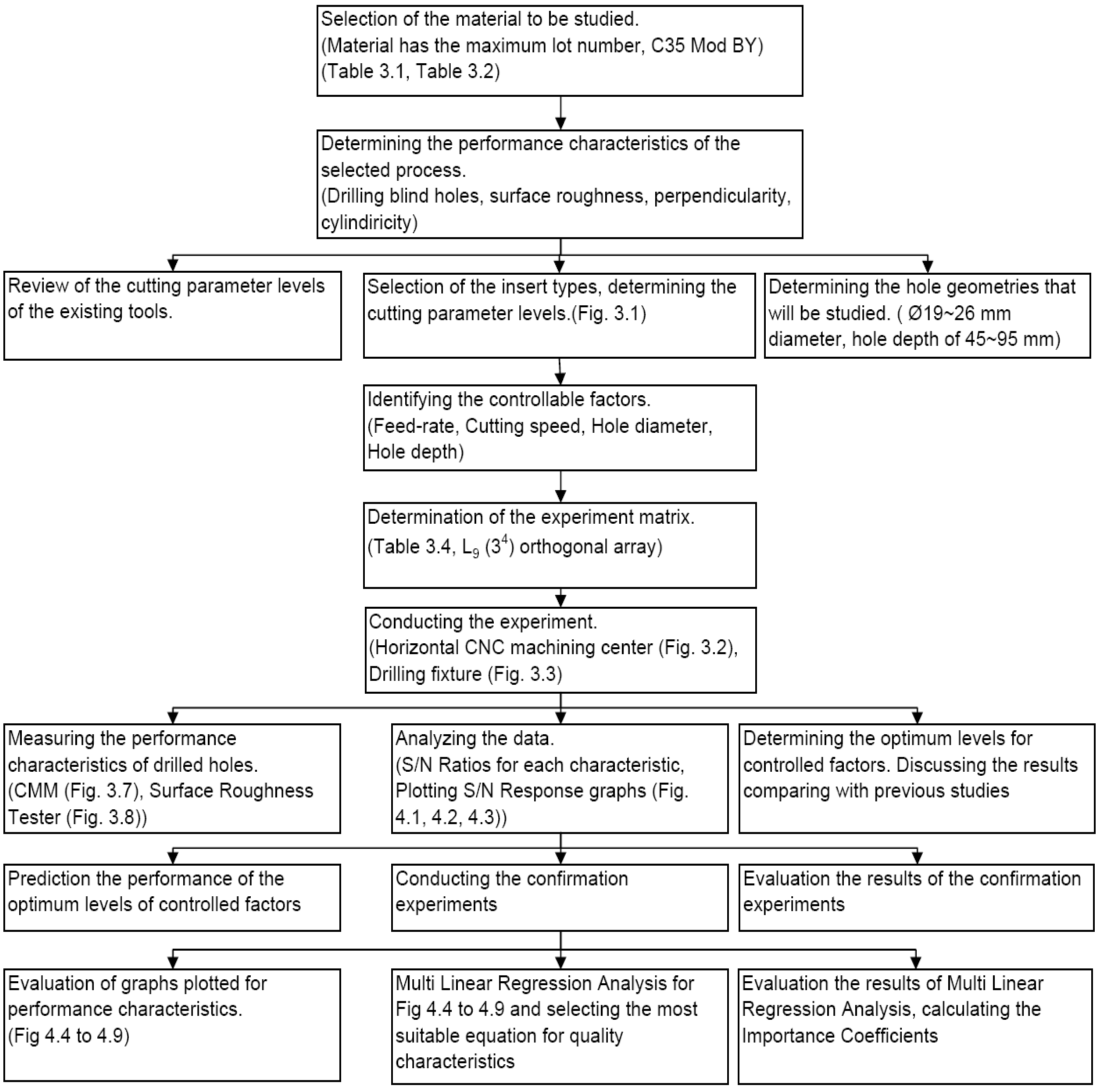


Figure 3.5 Flowchart of the Taguchi Method employed for this study.

Designs of experiments techniques, specifically Orthogonal Arrays (OA), are employed in Taguchi's approach to systematically vary and test the different levels of each of the control factors. Commonly used Orthogonal Arrays include the L_4, L_9, L_{12}, L_{18}, and L_{27}, several of which are shown in figure 3.5. The columns in the Orthogonal Array indicate the factor and its corresponding levels, and each row in the Orthogonal Array constitutes an experimental run which is performed at the given factor settings. For instance, in figure 3.6 b experimental run #3 has Factor 1 at Level 1, Factor 2 at Level 3, Factor 3 at Level 3, and Factor 4 at Level 3. It is up to the experimental designer to establish the appropriate factor levels for each control factor; typically either 2 or 3 levels are chosen for each factor.

	Factors						
Run	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

(a)

	Factors			
Run	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

(b)

Figure 3.6 Some commonly used orthogonal arrays (Simpson).

The Taguchi method utilizes orthogonal arrays from design of experiments theory to study a large number of variables with a small number of experiments. Using orthogonal arrays significantly reduces the number of experimental configurations to be studied. Orthogonal arrays are not unique to Taguchi Method. As shown in the array in figure 3.6 b, the columns are mutually orthogonal. That is, for any pair of columns, all combinations of factor levels occur; and they occur an equal number of times. Here there are four parameters A, B, C, and D, each at three levels. This is called an "L_9" design, with the 9 indicating the nine rows, configurations, or prototypes to be tested. Specific test characteristics for each experimental evaluation are identified in the associated row of the table. Thus, L_9 means that nine experiments are to be carried out to study four variables at three levels. The number of columns of an array represents the maximum number of parameters that can be studied using that array. Note that this design reduces 81 (3^4) configurations to 9 experimental evaluations. There are greater savings in testing for the larger arrays. For example, using an L_{27} array, 13 parameters can be studied at 3 levels by running only 27 experiments instead of 1,594,323 (3^{13}).(Unal, Dean, 1991)

The Taguchi method can reduce research and development costs by improving the efficiency of generating information needed to design systems that are insensitive to usage conditions, manufacturing variation, and deterioration of parts.

As a result, development time can be shortened significantly; and important design parameters affecting operation, performance, and cost can be identified. Furthermore, the optimum choice of parameters can result in wider tolerances so that low cost components and production processes can be used. Thus, manufacturing and operations costs can also be greatly reduced.

To implement robust design, Taguchi advocates the use of an inner array and an outer array approach. The inner array consists of the orthogonal array that contains the control factor settings; the outer array consists of the orthogonal array that contains the noise factors and their settings which are under investigation. The combination of the inner array and outer array constitutes what is called the product array or complete parameter design layout (Simpson).

The product array is used to systematically test various combinations of the control factor settings over all combinations of noise factors after which the mean response and standard deviation may be approximated for each run using the following equations.

$$y_{ave} = \frac{1}{n} \sum_{i=1}^{n} y_i \quad \text{is mean response} \qquad (26)$$

$$S = \sqrt{\sum_{i=1}^{n} \frac{(y_i - y_{ave})^2}{n-1}} \quad \text{is standard deviation} \qquad (27)$$

The preferred parameter settings are then determined through analysis of the signal-to-noise (S/N) ratio where factor levels that maximize the appropriate S/N ratio are optimal. There are three standard types of S/N ratios depending on the desired performance response.

1- Smaller the better, for making the system response as small as possible.

$$SN_S = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \qquad (28)$$

2- Nominal is the best, for reducing the variability around a target..

$$SN_T = 10 \log \left[\frac{y_{ave}^2}{S^2} \right] \qquad (29)$$

3- Larger the better, for making the system response as large as possible.

$$SN_L = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right] \tag{30}$$

These S/N ratios are derived from quadratic loss function and are expressed in decibel scale. After all of the S/N ratios have been computed for each run of an experiment, Taguchi advocates a graphical approach to analyze the data. In the graphical approach, the S/N ratios and average responses are plotted for each factor against each of its levels. The graphs are then examined to pick the winner, i.e., pick the factor level which (1) best maximize S/N and (2) bring the mean on target (or maximize or minimize the mean, as the case may be). Using this information, the control factors can also be grouped as follows (Simpson).

1. Factors that affect both the variation and the average performance of the product.
2. Factors that affect the variation only.
3. Factors that affect the average only.
4. Factors that do not affect either the variance or the average.

Factors in the first and second groups can be utilized to reduce the variations in the system, making it more robust. Factors in the third group are then used to adjust the average to the target value. Lastly, factors in the fourth group are set to the most economical level. Finally, confirmation tests should be run at the optimal product settings to verify that the predicted performance is actually realized.

3.2.3. Identifying the Controlled Factors and Selecting The Performance Characteristics

Generally the factors which affect the performance of several machining processes are feed rate, cutting speed, depth of cut, workpiece material, tool geometry, the amount of material to be removed and machining process or processes. Selecting the optimum parameters for a specific product heavily depends on those factors. Traditionally, the selection of cutting conditions for metal cutting is left to the machine operator. In such cases, the experience of the operator plays a major role, but even for a skilled operator it is very difficult to attain the optimum values each time (Aggarwal, Singh, 2005). In today’s manufacturing industry this has became a demanding area for process engineers who have the responsibility of determining the optimum cutting conditions.

In this study, only a specific kind of workpiece material called as C35 Mod BY is considered, so workpiece material will have no effect to the variations of responses. Although few diameters will be considered for the desired holes, tool geometries are all the same geometry and are in the same grade. Only drilling operation will be considered and sets of experiment will be carried out on the same machine, so machine and process have no effect on the variation of responses. Tool wear is an important factor on cutting forces. Flank wear and crater wear on tools were observed after every sets of experiments and no wear has been detected on cutting tools. Therefore, chatter effect has no effect on variations of responses.

Remaining factors can be called as our controlled factors, which are cutting speed and feed-rate. Additionally hole diameter will be taken as a controlled factor instead of depth of cut, because in drilling, depth of cut is equal to the half of the diameter. Finally hole depth will be considered because of being a constraint in drilling process in today’s machining applications.

So, controlled factors and their levels can be listed as follows.

Table 3.3 Controlled factors and levels

Factor codes	Factors	Units	Level 1	Level 2	Level 3
A	Hole diameter	mm	19	23	26
B	Hole depth	mm	45	68	95
C	Feed-rate	mm/rev	0,06	0,09	0,12
D	Cutting speed	m/min	140	160	180

A L_9 (3^4) orthogonal array will be employed for these sets of experiments. The design of experiment is shown in table 3.4.

Table 3.4 L_9 (3^4) orthogonal array and experiment matrix

Run # / Trial #	Level	Factor A Hole diameter (mm)	Level	Factor B Hole depth (mm)	Level	Factor C Feed-rate (mm/rev)	Level	Factor D Cutting speed (m/min)
1	1	19	1	45	1	0,06	1	140
2	1	19	2	68	2	0,09	2	160
3	1	19	3	95	3	0,12	3	180
4	2	23	1	45	2	0,09	3	180
5	2	23	2	68	3	0,12	1	140
6	2	23	3	95	1	0,06	2	160
7	3	26	1	45	3	0,12	2	160
8	3	26	2	68	1	0,06	3	180
9	3	26	3	95	2	0,09	1	140

Surface roughness Ra, perpendicularity of hole, cylindiricity are the performance characteristics which will be used to optimize the cutting conditions in production.

3.2.4. Measuring Equipment

3.2.4.1. Coordinate Measuring Machine

CNC controlled coordinate measuring machine (CMM) is used to measure the perpendicularity and cylindiricity of the holes during the experiments. The machine is ZEISS ACCURA CMM with a measuring range of 900 mm x 1500 mm x 700 mm. The machine has equipped with multi sensor rack (MSR) for automated measuring without manually changing probes for different purposes and has passive scanning option.

Figure 3.7 Coordinate Measuring Machine (CMM)

The linear measuring uncertainty of the CMM is 2,2 + (L/300) μm and form uncertainty of roundness is 1,7 μm during scanning with VAST XXT scanning probe. The machine has calibrated every year periodically according to the VDI/VDE 2617-2 to check whether it is within the specified tolerances or not. During experiments linear and scanning uncertainty of the machine has been verified with linear and round standard gauge blocks.

3.2.4.2. Surface Roughness Tester

A stylus contact type device MITUTOYO SJ 301 Surface Roughness Tester is used to measure the surface roughness of the holes during the experiments. Roughness tests have been carried out according to DIN 1990. Gauss filter is used during measuring "P" profile. Ra average roughness parameter has been selected as output parameter. The λ_c cut-off length is 0,8 mm and λ_S the evaluated profile length is 4,0 mm. Five cut-off length has been scanned and three of them filtered. The measuring speed is 5 mm/sec. The device verified every day before use with a standard roughness specimen. Before measuring each part the device has verified.

Figure 3.8 MITUTOYO Roughness Tester

3.2.4.2.(1). Surface Roughness

Every part surface has two important aspects that must be defined and controlled. The first concerns the geometric irregularities and the second concerns the metallurgical alterations of the surface and surface layer. This second aspect has been termed as surface integrity. Surface finish concerned with only the geometric irregularities of surfaces of solid materials and the characteristic to be measured is roughness. Surface texture is defined in terms of roughness, waviness, lay and flaws (ASM, 1995).

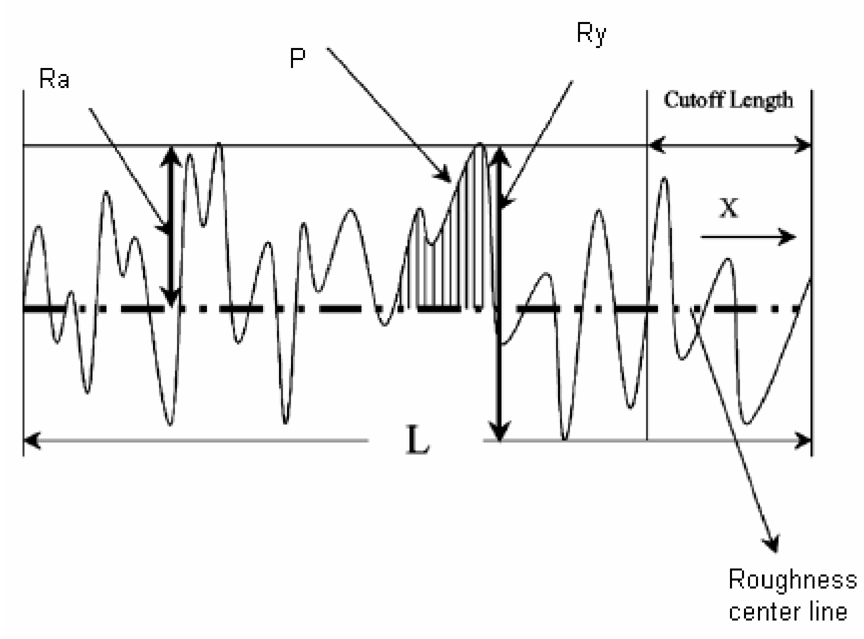


Figure 3.9 Surface Roughness Profile (Nalbant, Gökkaya, Sur, 2007)

Ra is the average roughness of the profile, Rp is the root mean square roughness, Ry maximum peak-to-valley roughness. L is the sampling length of the subject profile.

The average roughness Ra, is the area between roughness profile and its mean line. It can be defined as the integral of the absolute value of the roughness profile height over the evaluation length. Ra is specified by the following equation:

$$Ra = \frac{1}{L} \int [Y(x) dx, \qquad (31)$$

Ra is the arithmetic average deviation from the mean line, L is the sampling length and Y is the ordinate of the profile curve.

4. RESULTS AND DISCUSSIONS

The employed L_9 (3^4) orthogonal array for this study is shown in table 4.1.

Table 4.1 L_9 (3^4) orthogonal array and experiment matrix

Run # / Trial #	Level	Factor A Hole diameter (mm)	Level	Factor B Hole depth (mm)	Level	Factor C Feed-rate (mm/rev)	Level	Factor D Cutting speed (m/min)
1	1	19	1	45	1	0,06	1	140
2	1	19	2	68	2	0,09	2	160
3	1	19	3	95	3	0,12	3	180
4	2	23	1	45	2	0,09	3	180
5	2	23	2	68	3	0,12	1	140
6	2	23	3	95	1	0,06	2	160
7	3	26	1	45	3	0,12	2	160
8	3	26	2	68	1	0,06	3	180
9	3	26	3	95	2	0,09	1	140

During this study by each of the experimental run, 10 pieces of holes were drilled on the experiment samples. The three performance characteristics, surface roughness, perpendicularity and cylindiricity were measured for each of the drilled holes.

Table 4.2 S/N ratio and average performance characteristics table for each experimental run

Run #	Average Surface Roughness (µm)	S/N Ratios Surface Roughness (dB)	Average Perpendicularity (mm)	S/N Ratios Perpendicularity (dB)	Average Cylindiricity (mm)	S/N Ratios Cylindiricity (dB)
1	1,21	-1,693	0,0061	43,528	0,0325	29,6196
2	1,44	-3,270	0,0106	38,877	0,0727	22,5651
3	1,80	-5,279	0,0182	33,862	0,0479	26,3535
4	2,40	-6,578	0,0085	40,082	0,0278	31,0535
5	2,62	-10,174	0,0150	35,242	0,0394	18,5163
6	2,58	-5,319	0,0113	35,749	0,0265	25,0493
7	1,21	-1,748	0,0095	39,816	0,0261	31,3278
8	0,80	1,779	0,0121	37,719	0,0483	25,9372
9	1,26	-2,037	0,0259	30,409	0,0485	25,8253
S/N Total		-34,319		335,283		236,248
S/N Average		-3,813		37,254		26,250

The results calculated from the measured data for three performance characteristics, surface roughness, perpendicularity and cylindiricity are shown in Table 4.2.

Table 4.3 Total variations and Standard deviations for performance characteristics table for each experimental run

Run #	Ave. Surface Roughness (μm)	Total Var. Ra (μm)	St. Dev. Ra (μm)	Ave. Perp. (mm)	Total Var. Perp. (mm)	St. Dev. Perp. (mm)	Ave. Cyl. (mm)	Total Var. Cyl. (mm)	St. Dev. Cyl. (mm)
1	1,21	± 0,215	0,149	0,0061	± 0,004	0,003	0,0325	± 0,011	0,006
2	1,44	± 0,35	0,214	0,0106	± 0,007	0,004	0,0727	± 0,028	0,017
3	1,80	± 0,435	0,373	0,0182	± 0,013	0,009	0,0479	± 0,008	0,004
4	2,40	± 0,565	0,320	0,0085	± 0,009	0,005	0,0278	± 0,005	0,004
5	2,62	± 0,52	0,451	0,0150	± 0,012	0,008	0,0394	± 0,005	0,004
6	2,58	± 0,39	0,237	0,0113	± 0,012	0,009	0,0265	± 0,005	0,003
7	1,21	± 0,23	0,164	0,0095	± 0,007	0,004	0,0261	± 0,012	0,008
8	0,80	± 0,225	0,152	0,0121	± 0,008	0,005	0,0483	± 0,023	0,015
9	1,26	± 0,01	0,061	0,0259	± 0,023	0,016	0,0485	± 0,025	0,017

4.1. Analyzing the Data For Surface Roughness

Table 4.4 S/N Response table for surface roughness

S/N Response Table for Surface Roughness					
		Mean S/N Ratio (dB)			
Symbol	Factors	Level 1	Level 2	Level 3	Difference
A	Hole Diameter	-3,414	-7,36	-0,669	6,689
B	Hole Depth	-3,340	-3,888	-4,212	0,872
C	Feed-rate	-1,744	-3,962	-5,734	3,990
D	Cutting Speed	-4,635	-3,446	-3,359	1,275

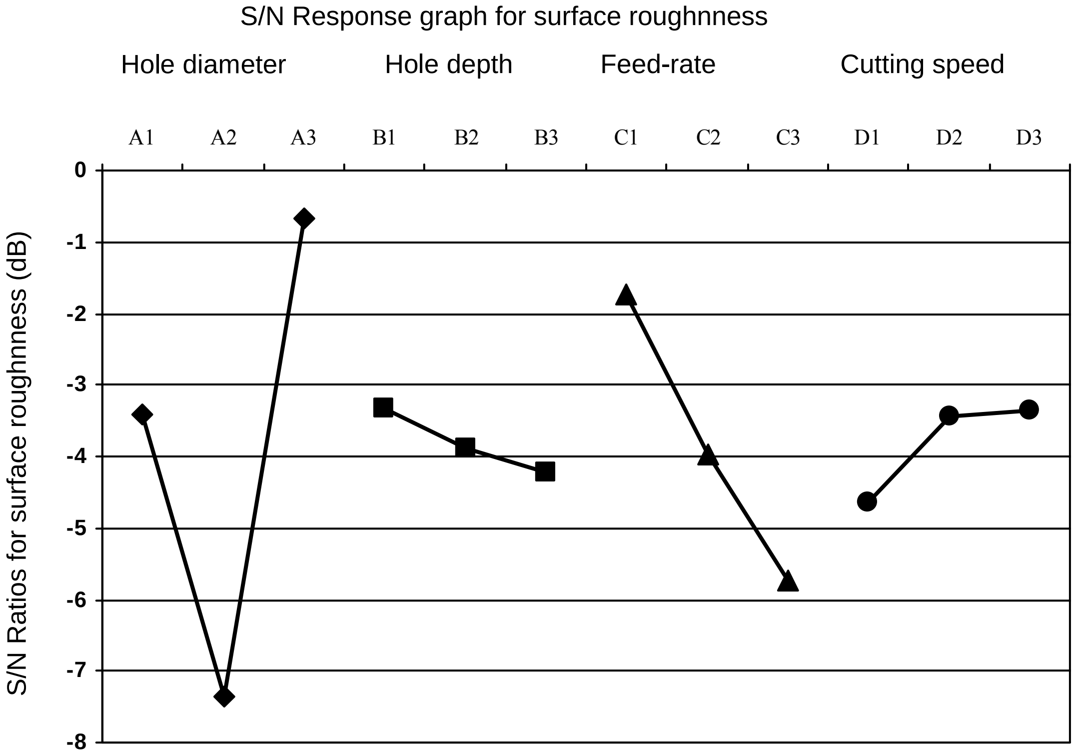


Figure 4.1 S/N response graph of surface roughness

For surface roughness, the average S/N Ratio of controlled factors affecting the surface roughness were determined in Table 4.4 and Figure 4.1. Maximum levels of the S/N ratios of each controlled factors will give the optimum performance characteristic. As seen in Table 4.4 and Figure 4.1, maximum levels can be determined as A3, B1, C1 and D3 which are hole diameter of 26 mm, hole depth of 45 mm, feed-rate of 0,06 mm/rev and cutting speed of 180 m/min. With optimum levels of controlled factors the predicted S/N ratio for surface roughness can be calculated from the following formula.

$$\mu_{A3,B1,C1,D3} = \left[\frac{(-1{,}748 + 1{,}779 + -2{,}037)}{3} + \frac{(-1{,}693 + -6{,}578 + -1{,}748)}{3} + \frac{(-1{,}693 + -5{,}319 + 1{,}779)}{3} + \frac{(-5{,}279 + -6{,}578 + 1{,}779)}{3}\right] - (3 \cdot -3{,}813)$$

$$= 2{,}3279979 \text{ dB}$$

Table 4.5 Analysis of Variance for surface roughness

Results of Analysis of Variance for Surface Roughness					
Source of Variation		Degree of freedom	Sum of Squares	Mean Square	Contribution %
A	Hole Diameter	2	67,8224	33,911	70,64
B	Hole Depth	2	1,1657	0,5828	1,21
C	Feed-rate	2	23,9766	11,988	24,97
D	Cutting Speed	2	3,0485	1,5243	3,18
	Total	8	96,013		100

As seen in Table 4.5, the most important variable affecting the surface roughness is hole diameter by a percentage contribution of % 70,64. By the change in hole diameter in range from 19 mm up to 26 mm, maximum deviation in surface roughness value has been detected. It can be explained as the power need changes during drilling by the change of hole diameter. In solid drilling depth of cut is explained with half of the diameter of the drilled hole. Also feed-rate has a significant effect on surface roughness with a percentage contribution of % 24,97. This means that these two factors must be considered when an optimizing study will be planned for the given range of the parameters in Table 4.1. Cutting speed and hole depth have no significant effects on surface roughness for the given range in Table 4.1 compared with feed-rate as a cutting parameter. This can be explained as follows. Cutting speeds have been kept constant during experiments, so revolution numbers have been changed by the changes of hole diameters. Therefore, the effects of feed-rate and cutting speed on surface roughness will be examined at the end of this section separately.

J.A. Ghani, I.A. Choudhury, H.H.Hassan (2004), have found out that, in end milling, high cutting speed, low feed-rate and low radial depth of cut have obtained better surface finish, furthermore, low feed rate and low depth of cut have leaded the smaller resultant cutting force. A. Manna and S. Salodkar (2008), have reported that cutting speed is the most effecting parameter on Ra surface roughness compared to feed and depth of cut. But optimum feed-rate level has been detected minumum level of 0,16 mm/rev employed during the experiments as in my study. Y. Isik (2007), has reprted that feed rate (f) is the most influential parameter on surface roughness, cutting depth (a) is the second most one, and cutting speed (V) is the least influential parameter. The influence of cutting speed is negligible compared with those of the other cutting parameters. M. Nalbant, H. Gökkaya and G. Sur (2007), have found that insert radius and feed-rate are the significant characteristics which are affecting the surface roughness, directly. The improvement of surface roughness from initial cutting parameters to the optimal cutting parameters were % 335. W.H. Yang and Y.S. Tarng (1998), have found out that cutting speed, feed-rate and depth of cut are significant characteristics but feed-rate has the most significant effect. D. Kirby (2006), has reported that feed-rate has the most significant effect on surface roughness. He has also reported that spindle speed has a moderate effect and depth of cut has insignificant effect on surface roughness. From that point of view, an examination independent from hole diameter in my study become neccesary. M.S. Kartal (2006), has reported that feed-rate has the most significant effect on surface roughness when compared with cutting speed and depth of cut in CNC turning. E. Incal (2007), has found out that TiN coated tools achieve better surface finish compared to uncoated HSS tools. He also reported that wear amount of coated tools is less than uncoated tools. This can be explained as coated tools are more strength against cutting forces compared to uncoated tools. From the data obtained from Table 4.4 and Figure 4.1 confirmation test has been carried out. 10 pieces of holes drilled on the experiment specimen with determined parameters. The S/N ratio of the confirmation test has been calculated as $\mu_{A3,B1,C1,D3}$, -0,71 dB.

The predicted S/N ratio is 1,779 dB, but when compared with S/N ratios from Table 4.2, a significant improvement has been employed. The mean S/N ratio of the experiments is -3,813 dB. The improvement ratio is % 81,4 when mean S/N ratio has been considered.

4.2. Analyzing the Data For Perpendicularity

For perpendicularity, the average S/N Ratio of controlled factors affecting the surface roughness were determined in Table 4.6 and Figure 4.2. Maximum levels

Table 4.6 S/N Response table for surface roughness

S/N Response Table for Perpendicularity					
		Mean S/N Ratio (dB)			
Symbol	Factors	Level 1	Level 2	Level 3	Difference
A	Hole Diameter	38,755	37,02	35,981	2,774
B	Hole Depth	41,142	37,279	33,340	7,802
C	Feed-rate	38,999	36,456	36,307	2,692
D	Cutting Speed	36,393	38,148	37,221	1,755

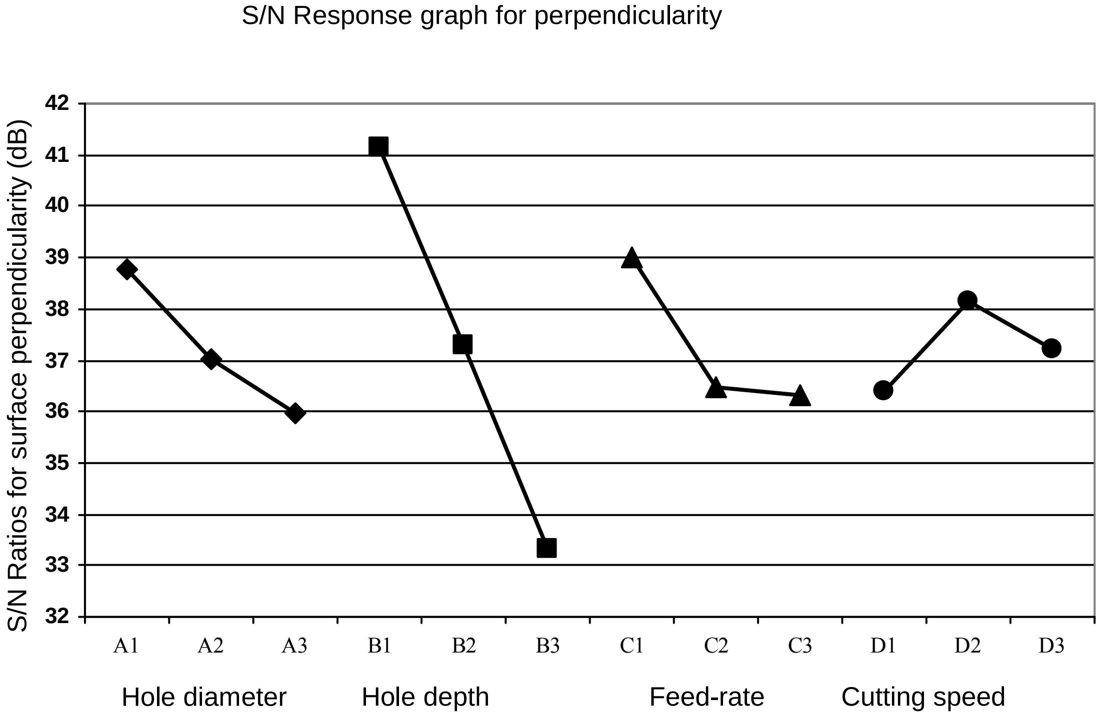


Figure 4.2 S/N response graph of perpendicularity

of the S/N ratios of each controlled factors will give the optimum performance characteristic. As seen in Table 4.6 and Figure 4.2, maximum levels can be determined as A1, B1, C1 and D2 which are hole diameter of 19 mm, hole depth of 45 mm, feed-rate of 0,06 mm/rev and cutting speed of 160 m/min. With optimum levels of controlled factors the predicted S/N ratio for perpendicularity can be calculated from the following formula.

$$\mu_{A1,B1,C1,D2} = \left[\frac{(43{,}528 + 38{,}877 + 33{,}682)}{3} + \frac{(43{,}528 + 40{,}082 + 39{,}816)}{3} + \frac{(43{,}528 + 35{,}749 + 37{,}719)}{3} + \frac{(38{,}877 + 35{,}749 + 39{,}816)}{3}\right] - (3 \cdot 37{,}254)$$

$$= 45{,}282494 \text{ dB}$$

Table 4.7 Analysis of Variance for perpendicularity

Results of Analysis of Variance for Perpendicularity					
Source of Variation		Degree of freedom	Sum of Squares	Mean Square	Contribution %
A	Hole Diameter	2	11,780	5,890	9,70
B	Hole Depth	2	91,307	45,653	75,18
C	Feed-rate	2	13,756	6,868	11,31
D	Cutting Speed	2	4,624	2,312	3,81
	Total	8	121,446		100

As seen in Table 4.7, the most important variable affecting the perpendicularity is hole depth by a percentage contribution of % 75,18. By the change in hole depth in range from 45 mm up to 95 mm, maximum deviation in perpendicularity value has been detected. It can be explained as tool deflection increases by the hole depth in drilling. Also this might be a reason of the chip removing capability. The chip control has become an important factor when the chip removing distance increases. Hole diameter and feed-rate have significant effects on perpendicularity with a percentage contribution of % 9,70 and % 11,31 . This means that three of these four factors must be considered when an optimizing study will be planned for the given range of the parameters in Table 4.1. Cutting speed has insignificant effect on perpendicularity with a percentage contribution of % 3,81 under the conditions of this experiments. This can be explained as follows. Cutting speeds have been kept constant during experiments, so revolution numbers have been changed by the changes of hole diameters.

From the data obtained from Table 4.6 and Figure 4.2 confirmation test has been carried out. 10 pieces of holes drilled on the experiment specimen with determined parameters. The S/N ratio of the confirmation test has been calculated as $\mu_{A1,B1,C1,D2}$, 31,90 dB.

The predicted S/N ratio is 45,282 dB, but when compared with S/N ratios from Table 4.2, the predicted value can not be reached. But mean perpendicularity value is 0,0240 mm. Target deviation value of perpendicularity was considered about 0,05 mm during planning stage of this study. The improvement ratio is % 52 when target perpendicularity value is considered.

4.3. Analyzing the Data For Cylindiricity

For cylindiricity, the average S/N Ratio of controlled factors affecting the cylindiricity were determined in Table 4.8 and Figure 4.3. Maximum levels of the S/N ratios of each controlled factors will give the optimum performance characteristic. As seen in Table 4.8 and Figure 4.3, maximum levels can be determined as A3, B1, C1 and D3 which are hole diameter of 26 mm, hole depth of 45 mm, feed-rate of 0,06 mm/rev and cutting speed of 180 m/min. With optimum levels of controlled factors the predicted S/N ratio for cylindiricity can be calculated from the following formula.

Table 4.8 S/N Response table for cylindiricity

S/N Response Table for Cylindiricity					
		Mean S/N Ratio (dB)			
Symbol	Factors	Level 1	Level 2	Level 3	Difference
A	Hole Diameter	26,179	24,87	27,697	2,824
B	Hole Depth	30,667	22,340	25,743	8,327
C	Feed-rate	26,869	26,481	25,399	1,469
D	Cutting Speed	24,654	26,314	27,781	3,128

As seen in Table 4.9, the most important variable affecting the cylindiricity is hole depth by a percentage contribution of % 77,72. By the change in hole depth in range from 45 mm up to 95 mm, maximum deviation in cylindiricity value has been detected. It can be explained as tool deflection increases by the hole depth in drilling. Also this might be a reason of the chip removing capability. The chip control has

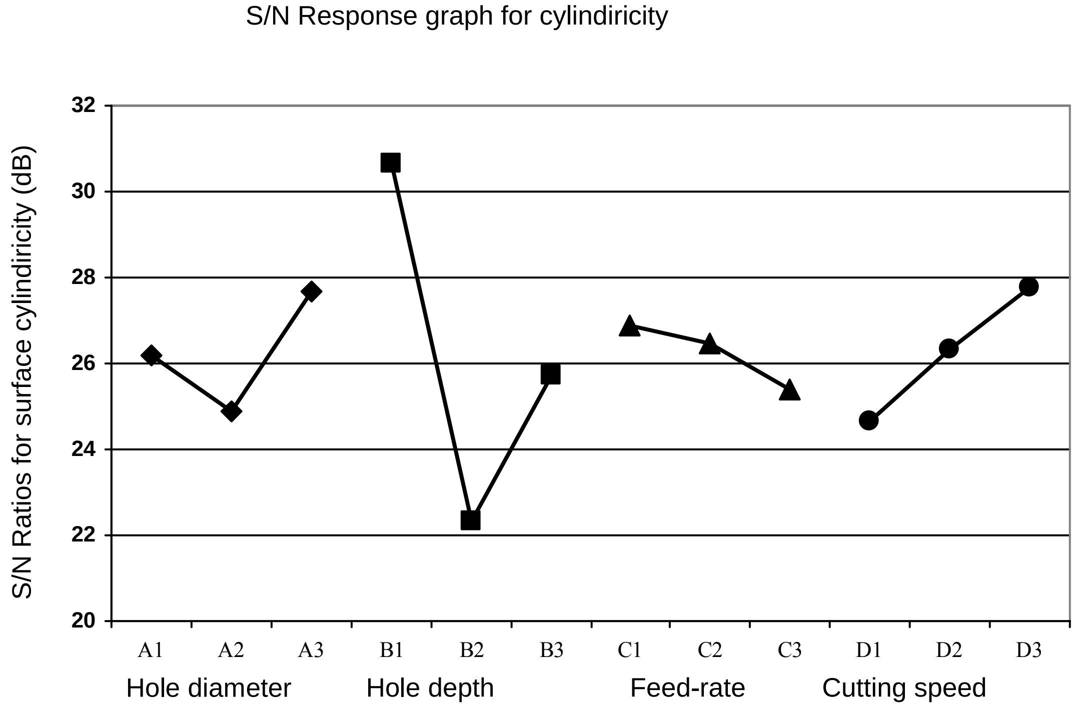


Figure 4.3 S/N response graph of cylindiricity

$$\mu_{A3,B1,C1,D3} = \left[\frac{(31{,}328 + 25{,}937 + 25{,}825)}{3} + \frac{(29{,}620 + 31{,}054 + 31{,}328)}{3} + \frac{(29{,}620 + 25{,}049 + 25{,}937)}{3} + \frac{(26{,}354 + 31{,}054 + 25{,}937)}{3}\right] - (3 \,.\, 26{,}25)$$

$$= 34{,}265 \text{ dB}$$

Table 4.9 Analysis of Variance for cylindiricity

Results of Analysis of Variance for Cylindiricity					
Source of Variation		Degree of freedom	Sum of Squares	Mean Square	Contribution %
A	Hole Diameter	2	11,982	5,9912	8,85
B	Hole Depth	2	105,176	52,588	77,72
C	Feed-rate	2	3,480	1,7402	2,57
D	Cutting Speed	2	14,692	7,346	10,86
	Total	8	135,331		100

become an important factor when the chip removing distance increases. Also hole diameter and cutting speed have significant effects on cylindiricity with a percentage contribution of % 8,85 and % 10,86. It can be explained as the power need changes during drilling by the change of hole diameter. In solid drilling depth of cut is explained with half of the diameter of the drilled hole. Feed-rate has insignificant effect on cylindiricity with a percentage contribution of % 2,57 under the conditions of this experiments.

W.C. Chen, C.C. Tsao (1999), have reported that the thrust force and drilling torque have increased with increased feed-rate. And the average thrust force and drilling torque have decreased within a narrow range with increasing spindle speed. E. Gariboldi (2003), has reported that cutting speed is the most affecting factor for roundness. Roundness is a form deviation and also can give idea for cylindiricity. G. Büyüktaş (2005), has reported that cutting forces decreased when cutting speed increased. . I. Demirayak (2006), has observed that TiNAl coated inserts have positive effects on the flank wear and surface quality, compared to the T(C,N)+ Al_2O_3 + TiN coated inserts. Increasing cutting speed has resulted with increased wear rate. Increased feed-rate with increased cutting speed is more effective on wear rate than the effect of cutting speed separately. From this point of view it can be commented that in future studies feed-rate and cutting speed have to be considered as factors have the main effects, and also the interaction between these parameters will be needed to be examined.

From the data obtained from Table 4.8 and Figure 4.3 confirmation test has been carried out. 10 pieces of holes drilled on the experiment specimen with determined parameters. The S/N ratio of the confirmation test has been calculated as $\mu_{A3,B1,C1,D3}$, 34,720 dB.

The predicted S/N ratio is 34,265 dB. The S/N ratio of the confirmation test for cylindiricity is higher than the predicted value. The predicted S/N ratio value has been reached nearly. The improvement ratio is % 40 when mean S/N Ratio of 26,520 dB has been considered.

4.4. Analyzing The Effects of Feed-rate and Cutting Speed

4.4.1. Effects of Feed-rate and Cutting Speed on Surface Roughness

To compare the effects of feed-rate and cutting speed independently from hole diameter, an additional graphical analyze has been carried out. As shown in Figure 4.4, feed-rate has a direct correlation with surface roughness for the diameter range 19 mm up to 26 mm. As shown in Figure 4.5, when hole depths were considered, the same correlation could not be detected. From this point of view, it can be said that, hole diameter has a significant effect on surface roughness with feed-rate under the conditions of this experiment.

Multi Linear Regression Analysis has been carried out with Data Analysis tool of Microsoft Excel for Figures 4.4. and 4.5. for the data range given in Table 4.1. The most suitable formulation for surface roughness under the given conditions for this experiment is:

$$Ra = 25{,}40\ f - 0{,}011\ Vc + 0{,}049\ D \qquad (32)$$

$$R^2 = 0{,}9207$$

The coefficient of determination, $\boldsymbol{R^2}$ is used in the context of statistical models whose main purpose is the prediction of future outcomes on the basis of other related information. It is the proportion of variability in a data set that is accounted for by the statistical model. It provides a measure of how well future outcomes are likely to be predicted by the model. is the multi coefficient of determination is an indicator for selecting the most suitable equation for defining the dependent variable (response). R^2 is often interpreted as the proportion of response variation "explained" by the regressors in the model. Thus, $R^2 = 1$ indicates that the fitted model explains all variability in y, while $R^2 = 0$ indicates no 'linear' relationship (for straight line regression, this means that the straight line model is a constant line, slope=0, intercept = y_{ave}) between the response variable and regressors. An interior value such as $R^2 = 0.7$ may be interpreted as follows: Approximately seventy percent of the variation in the response variable can be explained by the explanatory variable. The remaining thirty percent can be explained by unknown, lurking variables or inherent variability.

As shown in Table 4.1 the range of the selected parameters are f 0,06 ~ 0,12 mm/rev, Vc 140 ~ 180 m/min and D 19 ~ 26 mm. From Equation 32, it can be written as:

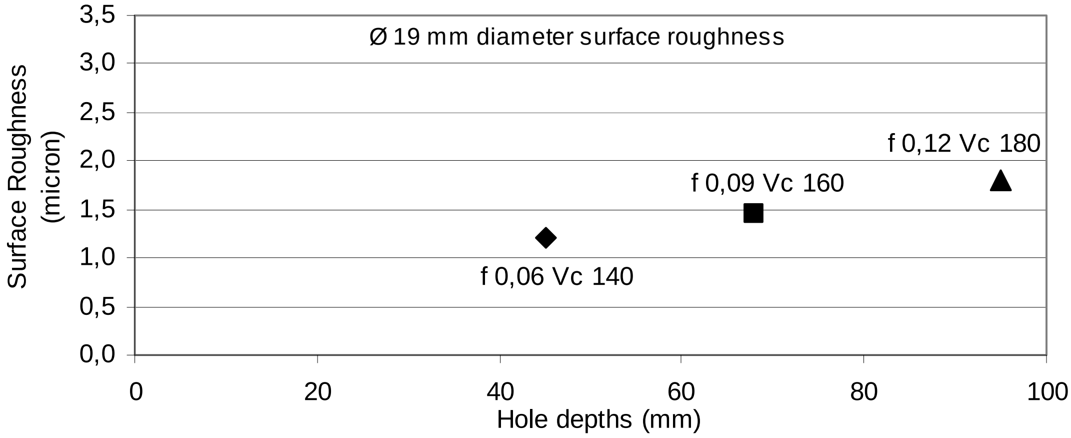
$$Ra = 25{,}40\ (0{,}06 \sim 0{,}12) - 0{,}011\ (140 \sim 180) + 0{,}049\ (19 \sim 26) \quad (33)$$

$$Ra = (1{,}524 \sim 3{,}048) - (1{,}54 \sim 1{,}98) + (0{,}931 \sim 1{,}274)$$

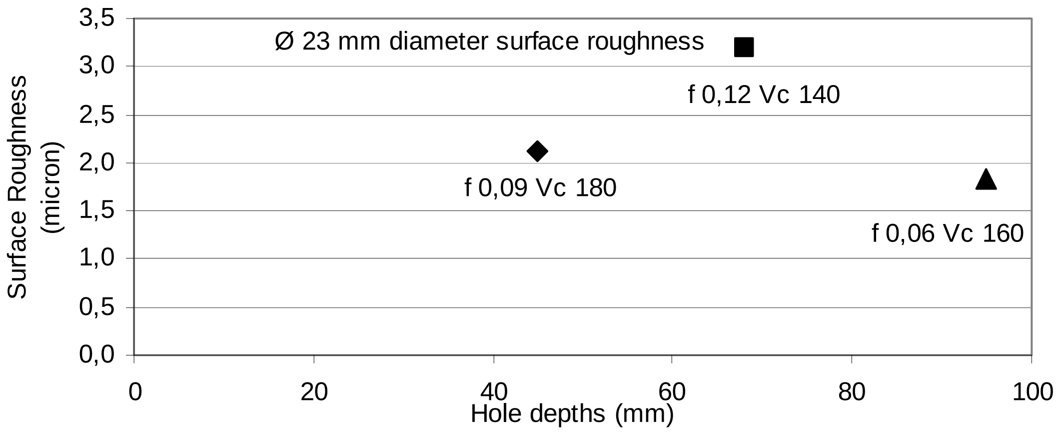
$$Ra = (0{,}915 \sim 2{,}342)$$

From the absolute values of the terms of the given parameters, the importance coefficients of the parameters for surface roughness can be calculated as follows:

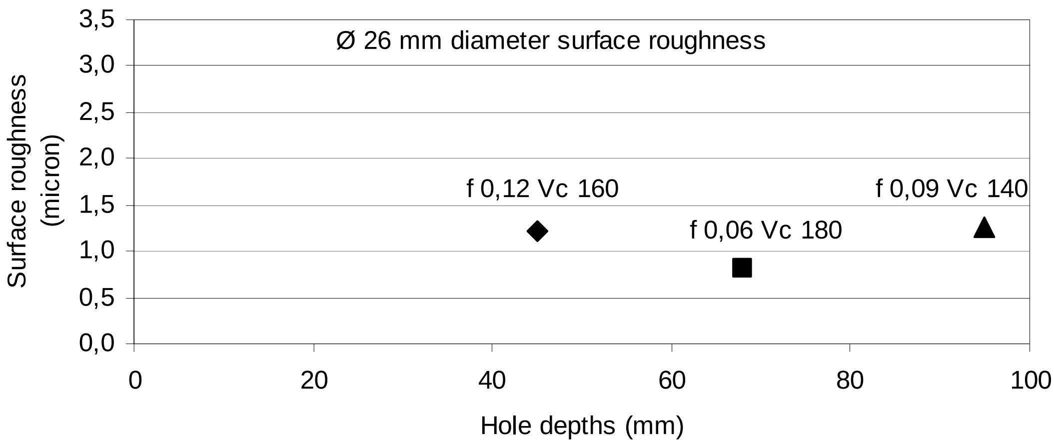
IC_f = [(1,524 / 3,995) , (3,048 / 6,302)] = (% 38,15 ~ % 48,37)
IC_{Vc} = [(1,54 / 3,995) , (1,98 / 6,302)] = (% 31,42 ~ % 38,55)
IC_D = [(0,931 / 3,995) , (1,274 / 6,302)] = (% 23,30 ~ % 20,21)



(a)

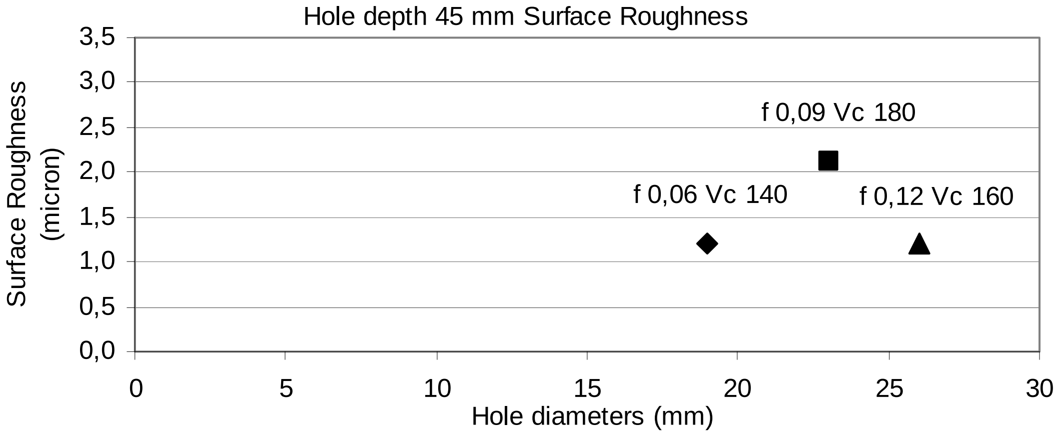


(b)

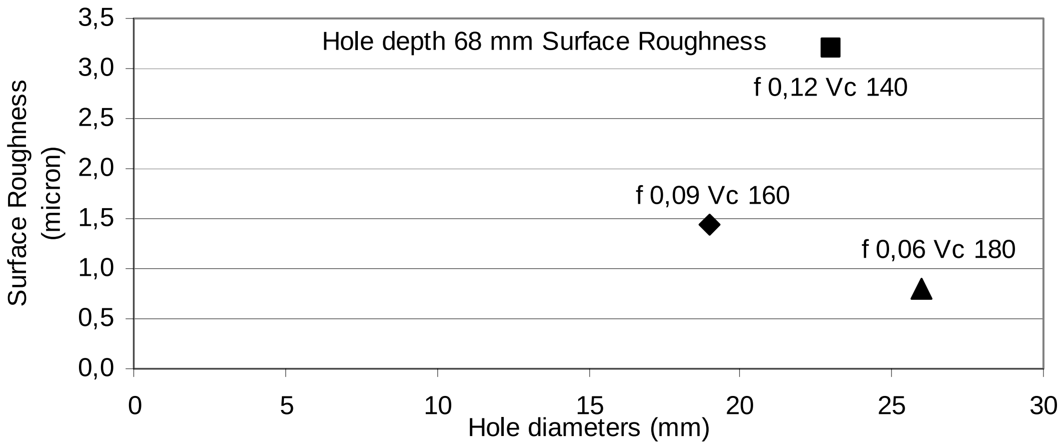


(c)

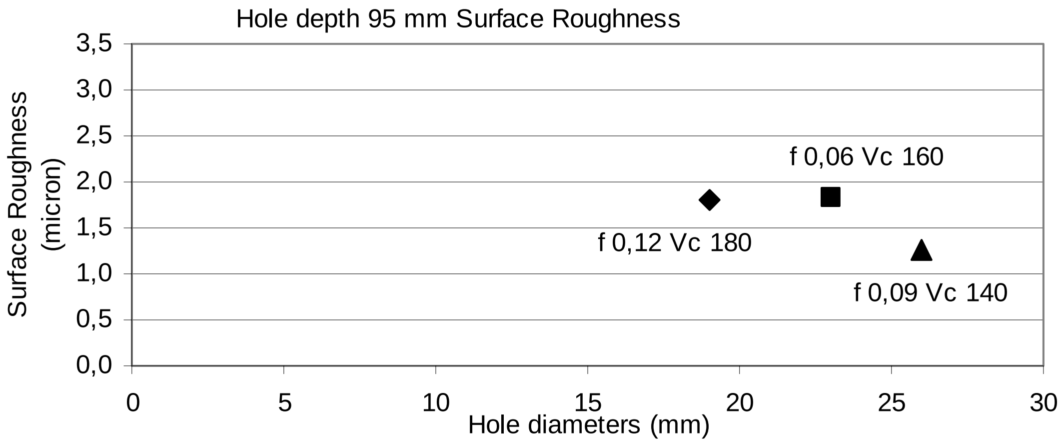
Figure 4.4 a, b, c Mean surface roughness values for three hole depths for hole diameters 19 mm, 23 mm and 26 mm



(a)



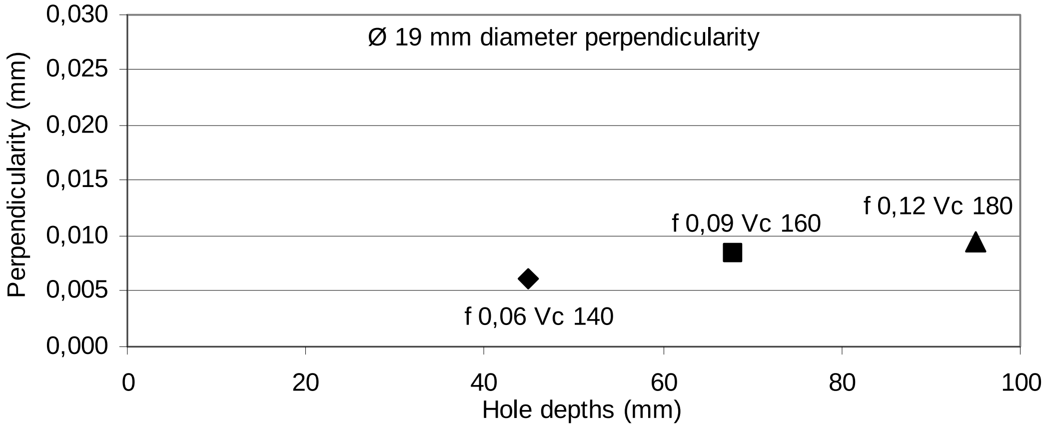
(b)



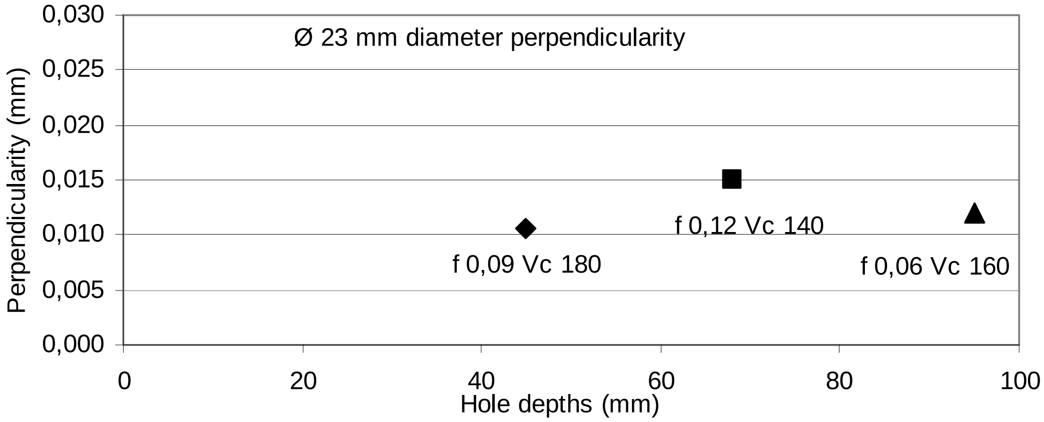
(c)

Figure 4.5 a, b, c Mean surface roughness values for three hole diameters for hole depths 45 mm, 68 mm and 95 mm

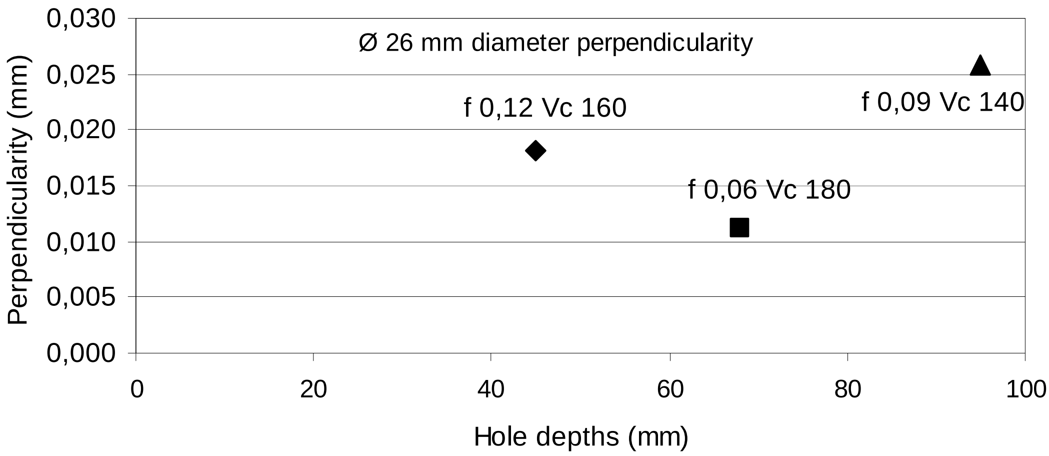
4.4.2. Effects of Feed-rate and Cutting Speed on Perpendicularity



(a)

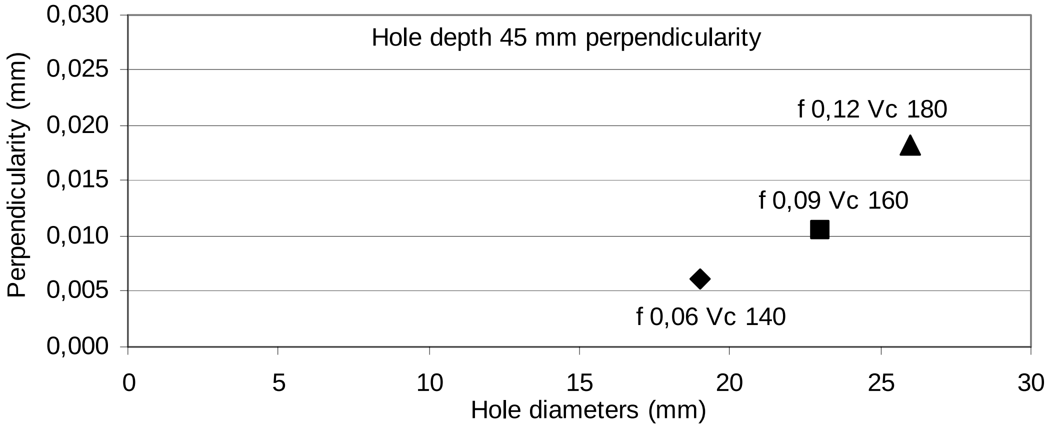


(b)

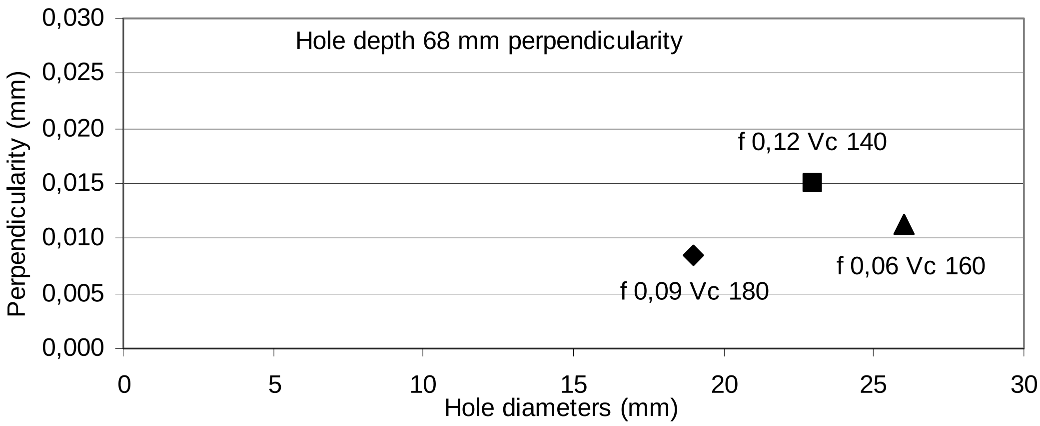


(c)

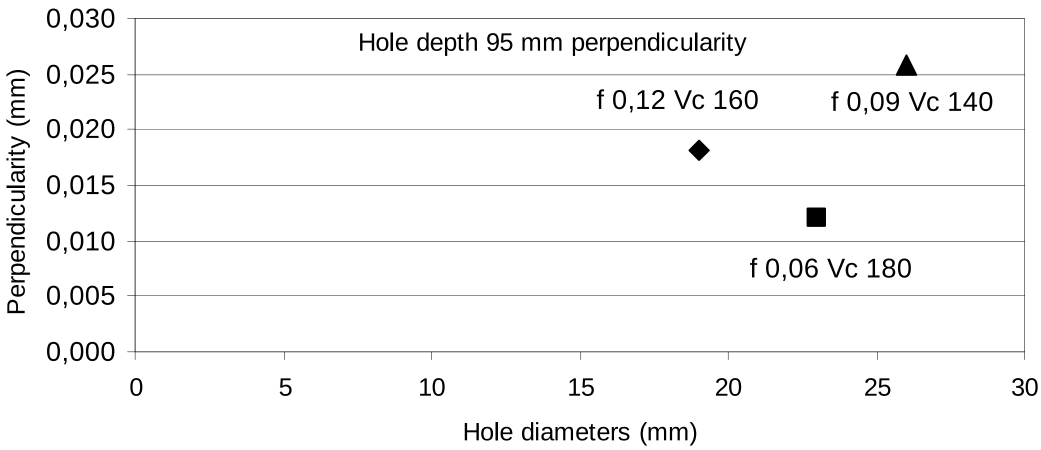
Figure 4.6 a, b, c Mean perpendicularity values for three hole depths for hole diameters 19 mm, 23 mm and 26 mm



(a)



(b)



(c)

Figure 4.7 a, b, c Mean perpendicularity values for three hole diameters for hole depths 45 mm, 68 mm and 95 mm

In Figure 4.6.a, it can be seen that for diameter of 19 mm, perpendicularity increases with increasing cutting speed and increasing feed-rate, but as seen in Figures 4.6.b and 4.6.c, increasing feed-rate is not only the affecting parameter for perpendicularity. As seen in Figure 4.7.a increasing feed-rate and cutting speed, increase the perpendicularity value. But, as seen in Figures 4.7.b and 4.7.c, it can be mentioned that there is an interaction between feed-rate and cutting speed existing. This interaction between feed-rate and cutting speed has to be investigated during further studies.

4.4.3. Effects of Feed-rate and Cutting Speed on Cylindiricity

As seen in Figure 4.8.b, a direct correlation can be mentioned between feed-rate and cylindiricity. But, Figures 4.8.a and 4.8.c does not support this interpretation. As seen in Figure 4.9.a and 4.9.b, a reverse correlation between cutting speed and cylindiricity can be mentioned under the conditions of this experiment. But, as seen in Figure 4.9.c the trend is not similar to as shown in Figures 4.9.a and 4.9.b. For the cutting speed values of 140 m/min and 160 m/min have nearly the same cylindiricity values. From this point of view the interaction between feed-rate and cutting speed have to be investigated during further studies. This can be seen from the calculated R^2 value of the most suitable formulation for cylindiricity under the given conditions for this experiment. The equation is as follows:

$$\text{Cylindiricity} = 0{,}3289\ f + 0{,}00016\ Vc - 0{,}0016\ D \qquad (33)$$

$$R^2 = 0{,}7258$$

As shown in Table 4.1 the range of the selected parameters are f 0,06 ~ 0,12 mm/rev, Vc 140 ~ 180 m/min and D 19 ~ 26 mm. From Equation 33, it can be written as:

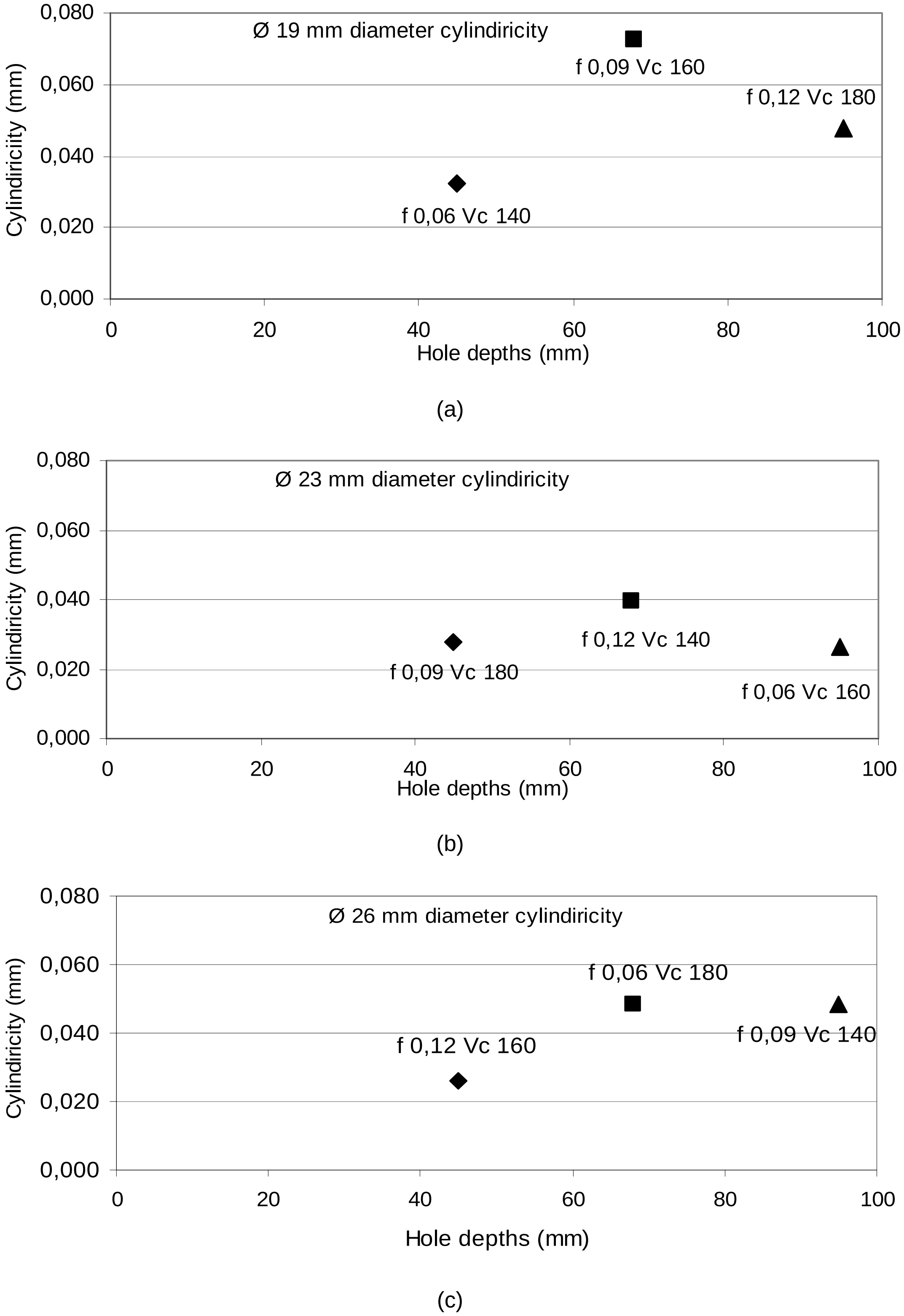


Figure 4.8 a, b, c Mean cylindiricity values for three hole depths for hole diameters 19 mm, 23 mm and 26 mm

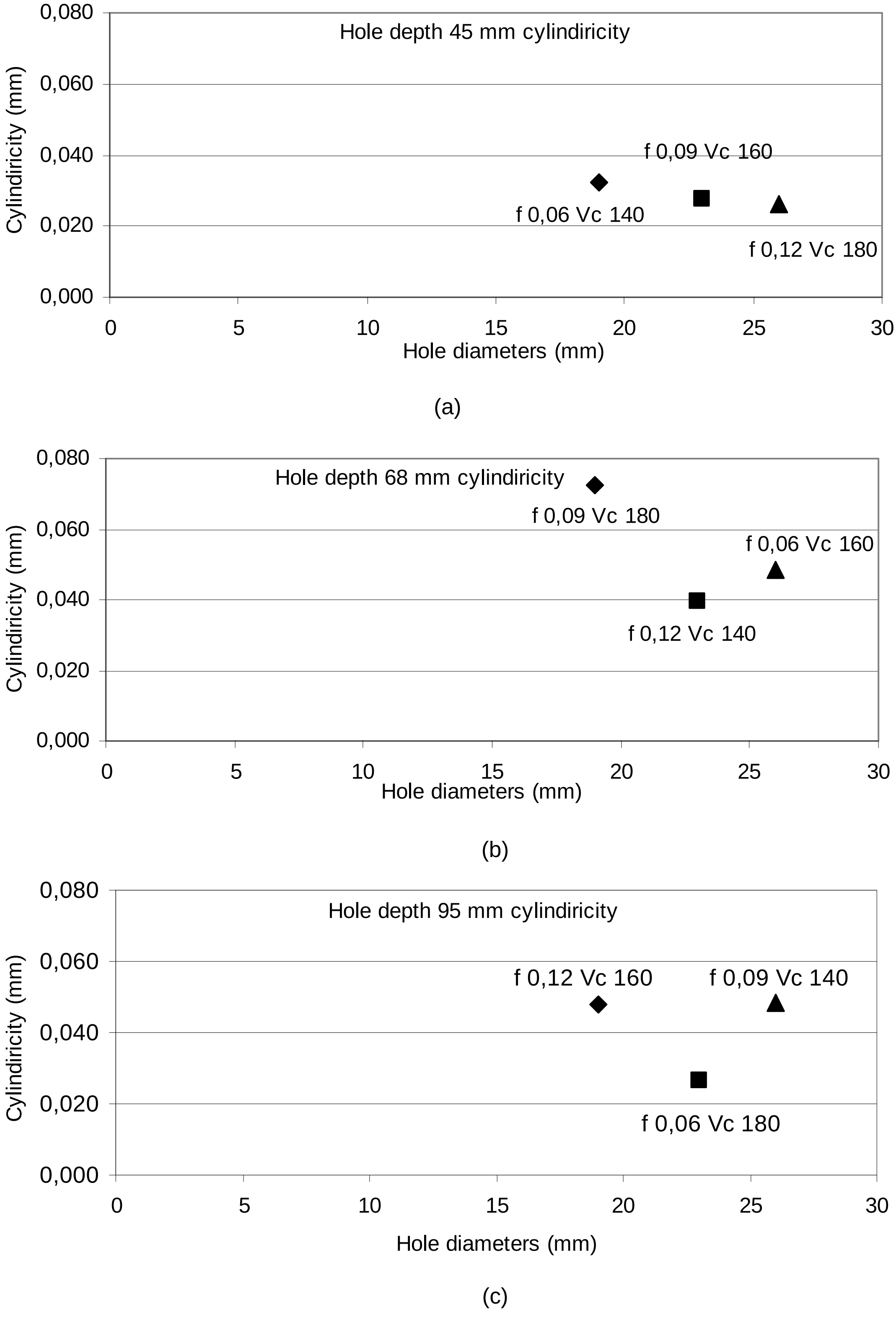


Figure 4.9 a, b, c Mean cylindiricity values for three hole diameters for hole depths 45 mm, 68 mm and 95 mm

Cylindiricity = 0,3289(0,06 ~0,12) + 0,00016(140 ~180) - 0,0016(19 ~26)

Cylindiricity = (0,0197 ~0,0395) + (0,0224 ~ 0,0288) - (0,0304 ~0,0416)

Cylindiricity = (0,0117 ~0,0267)

From the absolute values of the terms of the given parameters, the importance coefficients of the parameters for cylindiricity can be calculated as follows:

IC_f = [(0,0197 / 0,0725) , (0,0395 / 0,1099)] = (% 27,17 ~ % 35,94)

IC_{Vc} = [(0,0224 / 0,0725) , (0,0288 / 0,1099)] = (% 26,21 ~ % 30,90)

IC_D = [(0,0304 / 0,0725) , (0,0416 / 0,1099)] = (% 37,85 ~ % 41,93)

5. CONCLUSIONS

In this study, taguchi method has been employed to optimize the performance characteristics in drilling. A L_9 (3^4) orthogonal array has been employed in this study. The controlled factors were hole diameter, hole depth, feed-rate and cutting speed. As shown in this study, Taguchi Method provides an efficient methodology for the parameter optimization of cutting parameters with far less effect than would be required for most optimization techniques. This methodology also decreases the number of experimental runs, therefore, time saving, quick response and cost saving can be utilized.

It has been shown that surface roughness, perpendicularity and cylindiricity can be improved significantly when target values were considered and compared at the design stage. The confirmation experiments were carried out to verify the optimal cutting parameters.

1. Taguchi's robust orthogonal array design method provides a simple, systematic and efficient methodology for the optimization of process parameters such as feed-rate, cutting speed, hole diameter and hole depth for selected quality characteristics surface roughness, perpendicularity and cylindiricity for drilling operation.
2. The experimental results demonstrate that hole diameter is the most significant factor for surface roughness. It can be explained that the source of the variations of the surface roughness values is hole diameter, therefore, the power need changes during drilling by the change of hole diameter. In solid drilling depth of cut is explained with half of the diameter of the drilled hole.
3. Feed-rate has a significant effect on surface roughness with a percentage contribution of % 24,97 . This means that these two factors must be considered when an optimizing study will be planned for the given range of the parameters in Table 4.1.
4. Cutting speed and hole depth have no significant effects on surface roughness for the given range in Table 4.1 compared with feed-rate as a cutting parameter.

Cutting speeds have been kept constant during experiments, so revolution numbers have been changed by the changes of hole diameters.

5. The most important variable affecting the perpendicularity is hole depth by a percentage contribution of % 75,18. By the change in hole depth in range from 45 mm up to 95 mm, maximum deviation in perpendicularity value has been detected. It can be explained as tool deflection increases by the hole depth in drilling. Also this might be a reason of the chip removing capability. The chip control has become an important factor when the chip removing distance increases.
6. Hole diameter and feed-rate have significant effects on perpendicularity with a percentage contribution of % 9,70 and % 11,31. This means that three of these four factors must be considered when an optimizing study will be planned for the given range of the parameters in Table 4.1.
7. Cutting speed has insignificant effect on perpendicularity with a percentage contribution of % 3,81 under the conditions of this experiments. Cutting speeds have been kept constant during experiments, so revolution numbers have been changed by the changes of hole diameters.
8. The most important variable affecting the cylindiricity is hole depth by a percentage contribution of % 77,72. By the change in hole depth in range from 45 mm up to 95 mm, maximum deviation in cylindiricity value has been detected. It can be explained as tool deflection increases by the hole depth in drilling. Also this might be a reason of the chip removing capability. The chip control has become an important factor when the chip removing distance increases.
9. Hole diameter and cutting speed have significant effects on cylindiricity with a percentage contribution of % 8,85 and % 10,86. It can be explained as the power need changes during drilling by the change of hole diameter. In solid drilling depth of cut is explained with half of the diameter of the drilled hole.
10. Feed-rate has insignificant effect on cylindiricity with a percentage contribution of % 2,57 under the conditions of this experiments.

11. Tool wear is an important factor on cutting forces. Flank wear and crater wear on tools were observed after every sets of experiments and no wear has been detected on cutting tools. Therefore, chatter effect has no effect on variations of responses.
12. For diameter of 23 mm drilling application in CIMSATAS, from the Figures 4.1 to 4.3, optimum parameters can be selected as C1 and D3 for minimum variation of the performance characteristics surface roughness, perpendicularity and cylindiricity. The parameter levels are C1 of feed-rate 0,06 mm/rev and D3 of cutting speed 180 m/min. Drilling time of the diameter 23 mm and depth 100 mm, of hole has been reduced by % 33,6 (60,6 sec to 40,27 sec).
13. The interaction between feed-rate and cutting speed have to be investigated during further studies for affecting the surface roughness, perpendicularity and cylindiricity.

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CHAPTER III, A review of Taguchi methods,.

AUTOBIOGRAPHY

Evren KABAKLI was born in İzmir, in 20 march 1974. He has started primary school in 1980 in İzmir. He has started secondary school in 1985. He has graduated from 60th Year Anatolia High School in 1992, in İzmir. He has registered Istanbul Technical University Mechanical Engineering Department in 1992, and graduated in 1997. After he has completed his military service as a reserve officer in 2000. He has worked in BMC San. Ve Tic. A.Ş. for one and half year. During this period he has married with Tevhide KABAKLI in 2001. Then he has located in Mersin and has started to work in CİMSATAS in 2002. He has a doughter at 4 years old Sezin Ege KABAKLI. He has started his MSc degree in Cukurova University Mechanical Engineering Department in 2006 and still working in CİMSATAS as a Machining Quality Engineer.

Some of his hobies are playing football, tennis, swimming, reading, listening music, following automotive magazines, motorsports and also Formula1.

ANNEX-1 Possible tool wear types and solutions.

Tool Wear	Possible cause	Remedy
Flank and notch wear (a). Rapid flank wear causing poor surface texture or inconsistency in tolerance. (b, c). Notch wear causing poor surface texture and risk of edge breakage.	(a). Cutting speed too high or insufficient wear resistance. (b/c). Oxidation. (b/c). Attrition. (c). Oxidation.	Reduce cutting speed. Select a more wear resistant grade. Select an aluminium oxide coated grade for steel machining. For work-hardening materials, select a smaller entering angle or a more wear resistant grade. Reduce the cutting speed but when machining heat resistant material with ceramics, increase cutting speed.
Crater wear Excessive crater wear causing a weakened edge. Cutting edge break through on the trailing edge causes poor surface texture.	Diffusion wear due to too high cutting temperatures on the rake face.	Select an aluminium oxide coated grade Select positive insert geometry. First, reduce the speed to obtain a lower temperature and secondly, the feed.
Plastic deformation Plastic deformation (edge depression (a) or flank impression (b)) leading to poor chip control and poor surface texture. Risk of excessive flank wear leading to insert breakage.	Cutting temperature too high combined with a high pressure.	Select a harder grade with better resistance to plastic deformation. (a) Reduce cutting speed (b) Reduce feed

ANNEX-1 Possible tool wear types and solutions.

Tool Wear	Possible cause	Remedy
Built-up edge Built-up edge causing poor surface texture and cutting edge frittering when the BUE is torn away.	Smearing workpiece material is welded to the insert due to: Low cutting speed. Negative cutting geometry. Very sticky material, such as certain stainless steels and pure aluminium.	Increase cutting speed or change to coated, tougher P35 grade. Select a positive geometry. Increase cutting speed considerably. If tool-life turns out to be short, apply coolant in large quantities.
Mechanical fatigue cracking Cracks running mainly parallel to cutting edge.	Excessive load variations on edge. Heavy start of cut shock or vibrations.	Select a tougher grade. Reduce feed rate. Change tool approach. Improve stability.
Chipping Small cutting edge chipping causing poor surface texture and excessive flank wear.	Grade too brittle. Insert geometry too weak. Built-up edge.	Select tougher grade. Select an insert with a stronger geometry (bigger chamfer for ceramic inserts). Increase cutting speed or select a positive geometry. Reduce feed at beginning of cut. Improve stability.

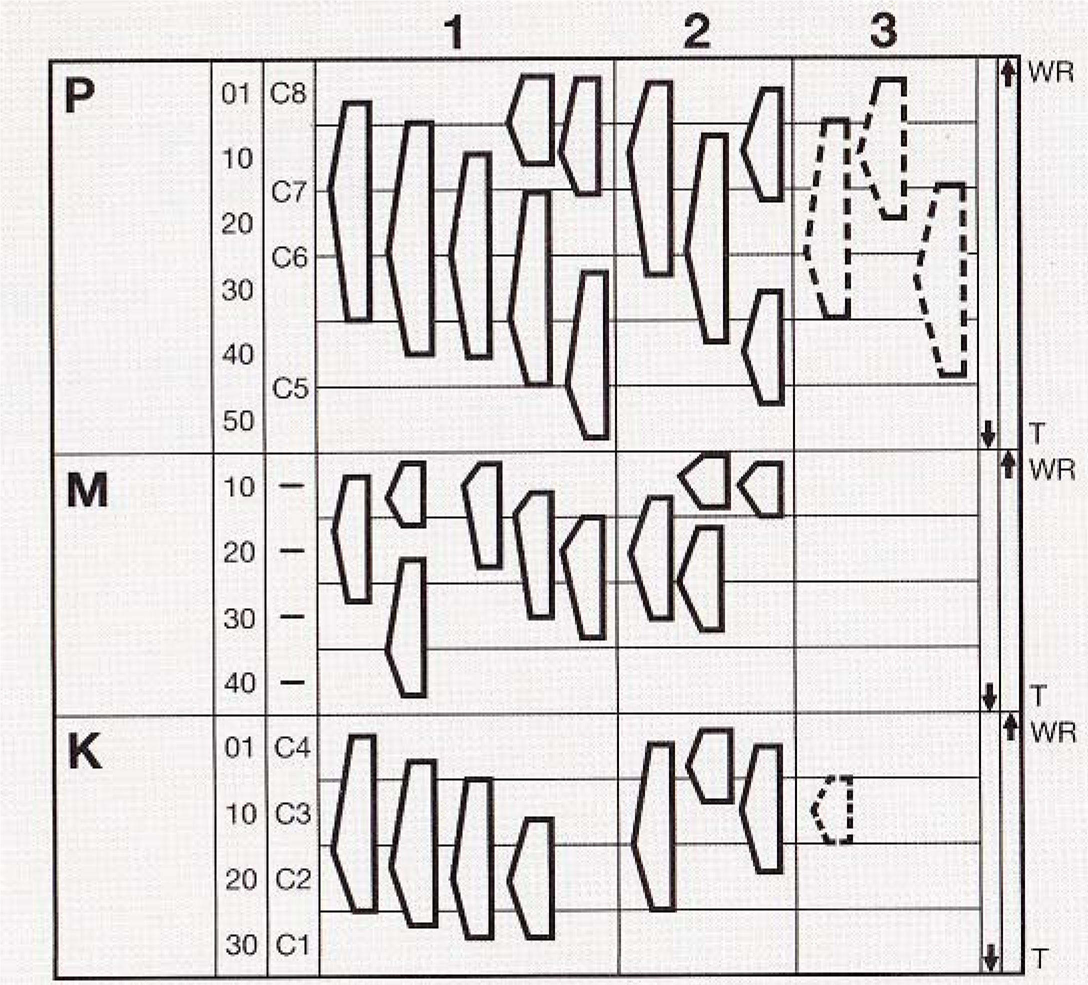
ANNEX-1 Possible tool wear types and solutions.

Tool Wear	Possible cause	Remedy
Thermal cracks Small cracks perpendicular to the cutting edge causing chipping and poor surface texture	Thermal cracks from excessive temperature variations caused by: Intermittent machining. Varying coolant supply.	Select a tougher grade with better resistance to thermal shocks. Coolant should be applied copiously or not at all. Select a tougher grade.
Fracture Insert fracture that damages not only the insert but also the shim and workpiece.	Grade too brittle. Excessive load on the insert. Insert geometry too weak. Insert too small.	Reduce feed and/or depth of cut. Select a stronger geometry, preferably a single sided insert. Select a thicker/larger insert. Improve stability.
Horisontal fracture on ceramic inserts	Grade too brittle. Insert geometry too weak.	Reduce feed. Select a tougher grade. Use an insert with stronger corner angle. Select an insert with smaller chamfer. Improve stability
Chipping from chip hammering Cutting edge, not in cut, is damaged through chip hammering. Both the top side and the support for the insert, can be damaged.	The chips are of an excessive length and directed in the wrong direction against the cutting edge.	Change the feed slightly. Select an alternative geometry. Select a tougher grade. Change the entering angle.

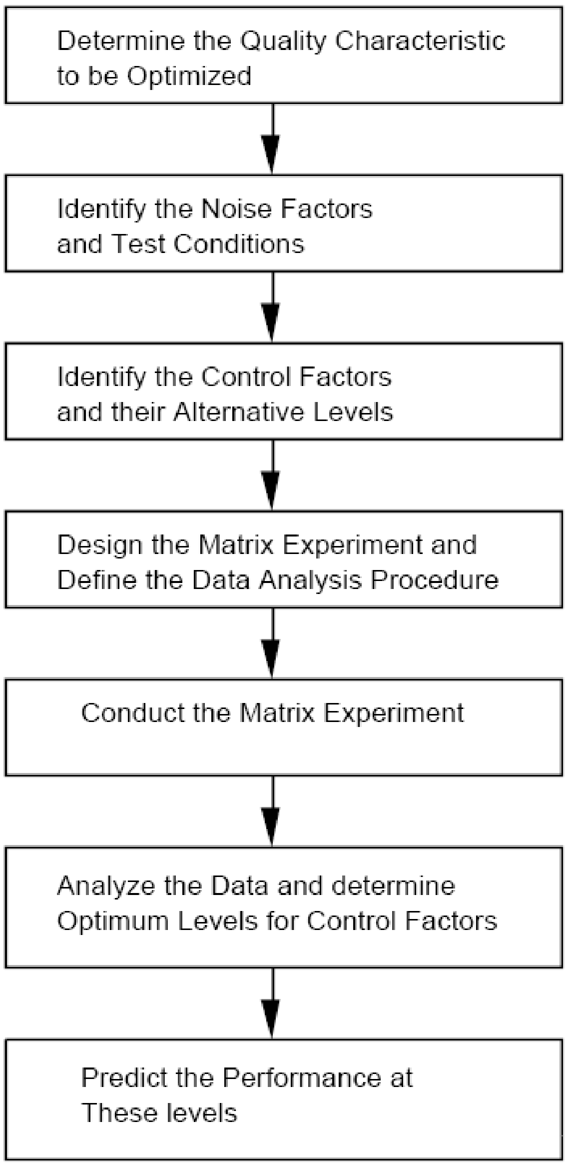
ANNEX-2 Main alloying elements and their effects on machinability.

Negatively:	Positively:
Mn	
Ni	Pb
Co	S
Cr	P
V	
C < 0.3%	C 0.3-0.6%
C > 0.6%	
Mo	
Nb	
W	

ANNEX-3 Typical range of cemented carbide grades set to cover the various operations that occur throughout the ISO P, M and K areas.



ANNEX-4 Flowchart of Taguchi Method



ANNEX-5 Results of experiments and calculated values for S/N Ratios

Run 1 — Hole Diameter Ø 19 mm; Hole Depth 45 mm; Feed rate 0,06 mm/rev; Cutting Speed 140 mm/min

Hole Number	Surface Roughness Ra (µm)		Perpendi-cularity (mm)	Cylindiricity (mm)	Cylindric Diameter (mm)
1	1,01	1,010	0,0086	0,0363	19,2351
2	1,39	1,390	0,0055	0,0266	19,2382
3	1,32	1,320	0,0009	0,0289	19,2381
4	1,25	1,250	0,0089	0,0303	19,2366
5	1,05	1,050	0,0090	0,0327	19,2389
6	1,13	1,130	0,0040	0,0392	19,2407
7	1,16	1,160	0,0040	0,0442	19,2408
8	1,26	1,260	0,0039	0,0320	19,2426
9	1,06	1,060	0,0071	0,0220	19,2426
10	1,44	1,440	0,0090	0,0327	19,2389
MEAN		1,207	0,0061	0,0325	19,2393
ST. DEV		0,1485	0,002847	0,0063194	0,002446426
S/N		-1,69	43,52764	29,619599	77,9131212
MIN BEST					NOM BEST
		10	10	10	10
		1,4767	0,000044	0,001092	370,148746

Run 2 — Hole Diameter Ø 19 mm; Hole Depth 68 mm; Feed rate 0,09 mm/rev; Cutting Speed 160 mm/min

Hole Number	Surface Roughness Ra (µm)		Perpendi-cularity (mm)	Cylindiricity (mm)	Cylindric Diameter (mm)
1	1,04	1,040	0,0068	0,0579	19,2073
2	1,28	1,280	0,0168	0,0591	19,2043
3	1,41	1,410	0,0106	0,0704	19,2081
4	1,74	1,740	0,0184	0,0700	19,2079
5	1,65	1,650	0,0124	0,0727	19,2090
6	1,37	1,370	0,0042	0,0480	19,2132
7	1,51	1,510	0,0068	0,0800	19,2068
8	1,68	1,680	0,0095	0,0946	19,2006
9	1,29	1,290	0,0092	0,0697	19,2134
10	1,46	1,460	0,0111	0,1044	19,2059
MEAN		1,443	0,0106	0,0727	19,2077
ST. DEV		0,2136	0,0044194	0,0169097	0,003812042
S/N		-3,27	38,876833	22,565116	74,04633037
MIN BEST					NOM BEST
		10	10	10	10
		2,1233	0,000130	0,005540	368,933832

Run 3 — Hole Diameter Ø 19 mm; Hole Depth 95 mm; Feed rate 0,12 mm/rev; Cutting Speed 180 mm/min

Hole Number	Surface Roughness Ra (µm)		Perpendi-cularity (mm)	Cylindiricity (mm)	Cylindric Diameter (mm)
1	1,27	1,270	0,0286	0,0498	19,1845
2	1,30	1,300	0,0069	0,0471	19,1778
3	1,27	1,270	0,0087	0,0437	19,1747
4	2,11	2,110	0,0321	0,0462	19,1758
5	2,02	2,020	0,0132	0,0403	19,1644
6	2,03	2,030	0,0205	0,0521	19,1701
7	1,81	1,810	0,0187	0,0470	19,1771
8	2,14	2,140	0,0068	0,0491	19,1715
9	1,95	1,950	0,0180	0,0478	19,1668
10	2,12	2,120	0,0287	0,0563	19,1678
MEAN		1,802	0,0182	0,0479	19,1731
ST. DEV		0,3726	0,0093695	0,00438411	0,00608189
S/N		-5,28	33,861814	26,3534734	69,973046
MIN BEST					NOM BEST
		10	10	10	10
		3,372	0,000411	0,002316	367,605880

Run 4 — Hole Diameter Ø 23 mm; Hole Depth 45 mm; Feed rate 0,09 mm/rev; Cutting Speed 180 mm/min

Hole Number	Surface Roughness Ra (µm)		Perpendi-cularity (mm)	Cylindiricity (mm)	Cylindric Diameter (mm)
		1			
1	2,19	2,190	0,0129	0,0322	23,3231
2	1,92	1,920	0,0066	0,0231	23,3281
3	1,49	1,490	0,0032	0,0339	23,3226
4	1,93	1,930	0,0083	0,0271	23,3189
5	2,62	2,620	0,0070	0,0288	23,3191
6	1,97	1,970	0,0033	0,0251	23,3109
7	2,34	2,340	0,0108	0,0249	23,3118
8	2,44	2,440	0,0205	0,0245	23,3104
9	2,01	2,010	0,0030	0,0300	23,3159
10	2,20	2,200	0,0093	0,0285	23,3100
MEAN		2,111	0,0085	0,0278	23,3171
ST. DEV		0,3195	0,005381	0,0035288	0,006304813
S/N		-6,58	40,08167	31,0535	71,36003911
MIN BEST					NOM BEST
		10	10	10	10
		4,5482	0,000098	0,000785	543,686256

Run 5 — Hole Diameter Ø 23 mm; Hole Depth 68 mm; Feed rate 0,12 mm/rev; Cutting Speed 140 mm/min

Hole Number	Surface Roughness Ra (µm)		Perpendi-cularity (mm)	Cylindiricity (mm)	Cylindric Diameter (mm)
1	3,31	3,310	0,0203	0,0441	23,2738
2	3,65	3,650	0,0134	0,0374	23,2728
3	2,61	2,610	0,0021	0,0421	23,2814
4	2,76	2,760	0,0088	0,0360	23,2790
5	2,89	2,890	0,0151	0,0431	23,2786
6	3,90	3,900	0,0258	0,0345	23,2746
7	3,09	3,090	0,0217	0,0384	23,2726
8	3,65	3,650	0,0065	0,0411	23,2765
9	3,40	3,400	0,0204	0,0343	23,2813
10	2,72	2,720	0,0158	0,0427	23,2753
MEAN		3,198	0,0150	0,0394	23,2766
ST. DEV		0,4506	0,0074468	0,0037032	0,00331443
S/N		-10,17	35,241633	18,516342	76,9302109
MIN BEST					NOM BEST
		10	10	10	10
		10,41	0,000299	0,014072	541,799652

Run 6 — Hole Diameter Ø 23 mm; Hole Depth 95 mm; Feed rate 0,06 mm/rev; Cutting Speed 160 mm/min

Hole Number	Surface Roughness Ra (µm)		Perpendi-cularity (mm)	Cylindiricity (mm)	Cylindric Diameter (mm)
1	1,94	1,940	0,0022	0,0233	23,3217
2	1,63	1,630	0,0021	0,0230	23,3218
3	1,46	1,460	0,0142	0,0278	23,3214
4	1,92	1,920	0,0143	0,0277	23,3210
5	1,57	1,570	0,0111	0,0252	23,3114
6	1,72	1,720	0,0113	0,0280	23,3110
7	1,84	1,840	0,0043	0,0263	23,3129
8	1,95	1,950	0,0039	0,0218	23,3131
9	2,04	2,040	0,0266	0,0302	23,3040
10	2,24	2,240	0,0225	0,0320	23,3163
MEAN		1,831	0,0113	0,0265	23,3155
ST. DEV		0,2365	0,0084864	0,00325953	0,0060152
S/N		-5,32	35,749437	25,0492657	71,7678741
MIN BEST					NOM BEST
		10	10	10	10
		3,4029	0,000266	0,003127	543,610708

ANNEX-5 Results of experiments and calculated values for S/N Ratios

				Run 7		
		Hole Diameter Ø 26 mm		Hole Depth 45 mm	Feed rate 0,12 mm/rev	Cutting Speed 160 mm/min
Hole Number	Surface Roughness Ra (µm)			Perpendi-cularity (mm)	Cylindiricity (mm)	Cylindiric Diameter (mm)
1	0,94		0,940	0,0081	0,0245	26,0998
2	1,28		1,280	0,0052	0,0202	26,1000
3	1,27		1,270	0,0093	0,0304	26,0896
4	1,35		1,350	0,0078	0,0326	26,0904
5	1,31		1,310	0,0079	0,0360	26,0902
6	1,38		1,380	0,0070	0,0212	26,0963
7	1,33		1,330	0,0186	0,0384	26,0936
8	1,16		1,160	0,0147	0,0182	26,0681
9	1,19		1,190	0,0083	0,0148	26,0682
10	0,92		0,920	0,0078	0,0245	26,0646
MEAN			1,213	0,0095	0,0261	26,0861
ST. DEV			0,1637	0,004033	0,0079168	0,013725062
S/N			-1,75	39,81645	31,327836	65,57788999
MIN BEST						NOM BEST
			10	10	10	10
			1,4955	0,000104	0,000737	680,483739

				Run 8		
		Hole Diameter Ø 26 mm		Hole Depth 68 mm	Feed rate 0,06 mm/rev	Cutting Speed 180 mm/min
Hole Number	Surface Roughness Ra (µm)			Perpendi-cularity (mm)	Cylindiricity (mm)	Cylindiric Diameter (mm)
1	1,01		1,010	0,0060	0,0324	26,0760
2	0,79		0,790	0,0056	0,0337	26,0724
3	0,83		0,830	0,0145	0,0236	26,0714
4	0,79		0,790	0,0126	0,0643	26,0700
5	0,80		0,800	0,0107	0,0613	26,0674
6	1,11		1,110	0,0098	0,0702	26,0662
7	0,68		0,680	0,0176	0,0544	26,0661
8	0,68		0,680	0,0221	0,0550	26,0627
9	0,67		0,670	0,0083	0,0392	26,0628
10	0,66		0,660	0,0133	0,0490	26,0600
MEAN			0,802	0,0121	0,0483	26,0675
ST. DEV			0,1515	0,0051513	0,0154419	0,004975049
S/N			1,78	37,718949	25,937217	74,38604065
MIN BEST						NOM BEST
			10	10	10	10
			0,6639	0,000169	0,002548	679,514579

				Run 9		
		Hole Diameter Ø 26 mm		Hole Depth 95 mm	Feed rate 0,09 mm/rev	Cutting Speed 140 mm/min
Hole Number	Surface Roughness Ra (µm)			Perpendi-cularity (mm)	Cylindiricity (mm)	Cylindiric Diameter (mm)
1	1,29		1,290	0,0230	0,0526	26,0613
2	1,29		1,290	0,0067	0,0463	26,0539
3	1,34		1,340	0,0048	0,0490	26,0507
4	1,16		1,160	0,0218	0,0361	26,0485
5	1,21		1,210	0,0501	0,0411	26,0566
6	1,26		1,260	0,0395	0,0356	26,0495
7	1,21		1,210	0,0512	0,0314	26,0469
8	1,36		1,360	0,0266	0,0367	26,0452
9	1,25		1,250	0,0149	0,0742	26,0440
10	1,26		1,260	0,0202	0,0821	26,0462
MEAN			1,263	0,0259	0,0485	26,0503
ST. DEV			0,0607	0,0163426	0,01705523	0,00549501
S/N			-2,04	30,40888	25,8252615	73,5168816
MIN BEST						NOM BEST
			10	10	10	10
			1,5985	0,000910	0,002615	678,617115

ANNEX-6 Results of confirmation tests and calculated values for S/N Ratios.

		Confirmation test results for surface roughness				
		Hole		Hole	Feed rate	Cutting
		Diameter		Depth		Speed
		Ø 26 mm		45 mm	0,06 mm/re	180 mm/min
Hole Number	Surface Roughness Ra (µm)			Perpendi-cularity (mm)	Cylindiricit (mm)	Cylindiric Diameter (mm)
1	0,85		0,850	0,0391	0,0300	26,1453
2	0,95		0,950	0,0309	0,0288	26,1436
3	0,98		0,980	0,0221	0,0449	26,1440
4	0,75		0,750	0,0158	0,0336	26,1425
5	0,96		0,960	0,0172	0,0388	26,1408
6	1,14		1,140	0,0441	0,0342	26,1389
7	1,45		1,450	0,0386	0,0276	26,1398
8	1,25		1,250	0,0267	0,0312	26,1382
9	1,33		1,330	0,0222	0,0368	26,1388
10	0,99		0,990	0,0131	0,0284	26,1381
MEAN			1,065	0,0270	0,0334	26,1410
ST. DEV			0,2213	0,010803	0,005476	0,002655811
S/N			-0,71	30,79375	29,41366	79,86249999
MIN BEST						NOM BEST
			10	10	10	10
			1,1783	0,000833	0,001145	683,351887

		Confirmation test results for cylindricity				
		Hole		Hole	Feed rate	Cutting
		Diameter		Depth		Speed
		Ø 26 mm		45 mm	0,06 mm/re	180 mm/min
Hole Number	Surface Roughness Ra (µm)			Perpendi-cularity (mm)	Cylindiricit (mm)	Cylindiric Diameter (mm)
1	1,72		1,720	0,0128	0,0175	26,1390
2	1,65		1,650	0,0071	0,0172	26,1358
3	1,71		1,710	0,0030	0,0192	26,1351
4	1,41		1,410	0,0054	0,0184	26,1350
5	1,43		1,430	0,0121	0,0180	26,1348
6	1,73		1,730	0,0145	0,0183	26,1329
7	1,38		1,380	0,0069	0,0180	26,1327
8	1,51		1,510	0,0038	0,0214	26,1313
9	1,59		1,590	0,0111	0,0177	26,1318
10	1,45		1,450	0,0199	0,0176	26,1308
MEAN			1,558	0,0097	0,0183	26,1339
ST. DEV			0,1384	0,005346	0,001216	0,002501022
S/N			-3,88	39,24329	34,71959	80,38174083
MIN BEST						NOM BEST
			10	10	10	10
			2,4446	0,000119	0,000337	682,981780

ANNEX-6 Results of confirmation tests and calculated values for S/N Ratios.

		Confirmation test results for perpendicularity				
		Hole		Hole	Feed rate	Cutting
		Diameter		Depth		Speed
		Ø 19 mm		45 mm	0,06 mm/rev	160 mm/min
		Surface		Perpendi-	Cylindiricity	Cylindiric
Hole		Roughness		cularity		Diameter
Number		Ra (µm)		(mm)	(mm)	(mm)
1	2,27		2,270	0,0279	0,0373	19,2833
2	2,49		2,490	0,0229	0,0403	19,2589
3	1,88		1,880	0,0050	0,0488	19,2782
4	2,34		2,340	0,0345	0,0467	19,2526
5	1,88		1,880	0,0161	0,0453	19,2544
6	1,95		1,950	0,0306	0,0472	19,2543
7	2,65		2,650	0,0223	0,0418	19,2479
8	2,53		2,530	0,0262	0,0385	19,2526
9	2,42		2,420	0,0229	0,0554	19,2493
10	2,12		2,120	0,0320	0,0513	19,2516
MEAN			2,253	0,0240	0,0453	19,2583
ST. DEV			0,2817	0,008606	0,00580521	0,012254745
S/N			-7,12	31,90725	26,8218771	63,92627781
MIN BEST						NOM BEST
			10	10	10	10
			5,147	0,000645	0,002079	370,882639

ANNEX-7 Table of results determined for Multi Linear Regression Analysis.

Hole Dia. D	Surface Rough. Ra	Perp. Perp.	Cylin. Cylin.	Feed Rate f	Cutting Speed V	Hole Depth L	Hole Depth L	Surface Rough. Ra	Perp. Perp.	Cylin. Cylin.	Feed Rate f	Cutting Speed V	Hole Dia. D
19	1,01	0,0086	0,0363	0,06	140	45	45	1,01	0,0086	0,0363	0,06	140	19
19	1,39	0,0055	0,0266	0,06	140	45	45	1,39	0,0055	0,0266	0,06	140	19
19	1,32	0,0009	0,0289	0,06	140	45	45	1,32	0,0009	0,0289	0,06	140	19
19	1,25	0,0089	0,0303	0,06	140	45	45	1,25	0,0089	0,0303	0,06	140	19
19	1,05	0,0090	0,0327	0,06	140	45	45	1,05	0,0090	0,0327	0,06	140	19
19	1,13	0,0040	0,0392	0,06	140	45	45	1,13	0,0040	0,0392	0,06	140	19
19	1,16	0,0040	0,0442	0,06	140	45	45	1,16	0,0040	0,0442	0,06	140	19
19	1,26	0,0039	0,0320	0,06	140	45	45	1,26	0,0039	0,0320	0,06	140	19
19	1,06	0,0071	0,0220	0,06	140	45	45	1,06	0,0071	0,0220	0,06	140	19
19	1,44	0,0090	0,0327	0,06	140	45	45	1,44	0,0090	0,0327	0,06	140	19
19	1,04	0,0068	0,0579	0,09	160	68	45	2,19	0,0129	0,0322	0,09	180	23
19	1,28	0,0168	0,0591	0,09	160	68	45	1,92	0,0066	0,0231	0,09	180	23
19	1,41	0,0106	0,0704	0,09	160	68	45	1,49	0,0032	0,0339	0,09	180	23
19	1,74	0,0184	0,0700	0,09	160	68	45	1,93	0,0083	0,0271	0,09	180	23
19	1,65	0,0124	0,0727	0,09	160	68	45	2,62	0,0070	0,0288	0,09	180	23
19	1,37	0,0042	0,0480	0,09	160	68	45	1,97	0,0033	0,0251	0,09	180	23
19	1,51	0,0068	0,0800	0,09	160	68	45	2,34	0,0108	0,0249	0,09	180	23
19	1,68	0,0095	0,0946	0,09	160	68	45	2,44	0,0205	0,0245	0,09	180	23
19	1,29	0,0092	0,0697	0,09	160	68	45	2,01	0,0030	0,0300	0,09	180	23
19	1,46	0,0111	0,1044	0,09	160	68	45	2,20	0,0093	0,0285	0,09	180	23
19	1,27	0,0286	0,0498	0,12	180	95	45	0,94	0,0081	0,0245	0,12	160	26
19	1,30	0,0069	0,0471	0,12	180	95	45	1,28	0,0052	0,0202	0,12	160	26
19	1,27	0,0087	0,0437	0,12	180	95	45	1,27	0,0093	0,0304	0,12	160	26
19	2,11	0,0321	0,0462	0,12	180	95	45	1,35	0,0078	0,0326	0,12	160	26
19	2,02	0,0132	0,0403	0,12	180	95	45	1,31	0,0079	0,0360	0,12	160	26
19	2,03	0,0205	0,0521	0,12	180	95	45	1,38	0,0070	0,0212	0,12	160	26
19	1,81	0,0187	0,0470	0,12	180	95	45	1,33	0,0186	0,0384	0,12	160	26
19	2,14	0,0068	0,0491	0,12	180	95	45	1,16	0,0147	0,0182	0,12	160	26
19	1,95	0,0180	0,0478	0,12	180	95	45	1,19	0,0083	0,0148	0,12	160	26
19	2,12	0,0287	0,0563	0,12	180	95	45	0,92	0,0078	0,0245	0,12	160	26
D	Ra	Perp.	Cylin.	f	V	L	L	Ra	Perp.	Cylin.	f	V	D
23	2,19	0,0129	0,0322	0,09	180	45	68	1,04	0,0068	0,0579	0,09	160	19
23	1,92	0,0066	0,0231	0,09	180	45	68	1,28	0,0168	0,0591	0,09	160	19
23	1,49	0,0032	0,0339	0,09	180	45	68	1,41	0,0106	0,0704	0,09	160	19
23	1,93	0,0083	0,0271	0,09	180	45	68	1,74	0,0184	0,0700	0,09	160	19
23	2,62	0,0070	0,0288	0,09	180	45	68	1,65	0,0124	0,0727	0,09	160	19
23	1,97	0,0033	0,0251	0,09	180	45	68	1,37	0,0042	0,0480	0,09	160	19
23	2,34	0,0108	0,0249	0,09	180	45	68	1,51	0,0068	0,0800	0,09	160	19
23	2,44	0,0205	0,0245	0,09	180	45	68	1,68	0,0095	0,0946	0,09	160	19
23	2,01	0,0030	0,0300	0,09	180	45	68	1,29	0,0092	0,0697	0,09	160	19
23	2,20	0,0093	0,0285	0,09	180	45	68	1,46	0,0111	0,1044	0,09	160	19
23	3,31	0,0203	0,0441	0,12	140	68	68	3,31	0,0203	0,0441	0,12	140	23
23	3,65	0,0134	0,0374	0,12	140	68	68	3,65	0,0134	0,0374	0,12	140	23
23	2,61	0,0021	0,0421	0,12	140	68	68	2,61	0,0021	0,0421	0,12	140	23
23	2,76	0,0088	0,0360	0,12	140	68	68	2,76	0,0088	0,0360	0,12	140	23
23	2,89	0,0151	0,0431	0,12	140	68	68	2,89	0,0151	0,0431	0,12	140	23
23	3,90	0,0258	0,0345	0,12	140	68	68	3,90	0,0258	0,0345	0,12	140	23
23	3,09	0,0217	0,0384	0,12	140	68	68	3,09	0,0217	0,0384	0,12	140	23
23	3,65	0,0065	0,0411	0,12	140	68	68	3,65	0,0065	0,0411	0,12	140	23
23	3,40	0,0204	0,0343	0,12	140	68	68	3,40	0,0204	0,0343	0,12	140	23
23	2,72	0,0158	0,0427	0,12	140	68	68	2,72	0,0158	0,0427	0,12	140	23
23	1,94	0,0022	0,0233	0,06	160	95	68	1,01	0,0060	0,0324	0,06	180	26
23	1,63	0,0021	0,0230	0,06	160	95	68	0,79	0,0056	0,0337	0,06	180	26
23	1,46	0,0142	0,0278	0,06	160	95	68	0,83	0,0145	0,0236	0,06	180	26
23	1,92	0,0143	0,0277	0,06	160	95	68	0,79	0,0126	0,0643	0,06	180	26
23	1,57	0,0111	0,0252	0,06	160	95	68	0,80	0,0107	0,0613	0,06	180	26
23	1,72	0,0113	0,0280	0,06	160	95	68	1,11	0,0098	0,0702	0,06	180	26
23	1,84	0,0043	0,0263	0,06	160	95	68	0,68	0,0176	0,0544	0,06	180	26
23	1,95	0,0039	0,0218	0,06	160	95	68	0,68	0,0221	0,0550	0,06	180	26
23	2,04	0,0266	0,0302	0,06	160	95	68	0,67	0,0083	0,0392	0,06	180	26
23	2,24	0,0225	0,0320	0,06	160	95	68	0,66	0,0133	0,0490	0,06	180	26

ANNEX-7 Table of results determined for Multi Linear Regression Analysis.

Hole	Surface			Feed	Cutting	Hole	Hole	Surface			Feed	Cutting	Hole
Dia.	Rough.	Perp.	Cylin.	Rate	Speed	Depth	Depth	Rough.	Perp.	Cylin.	Rate	Speed	Dia.
D	Ra	Perp.	Cylin.	f	V	L	L	Ra	Perp.	Cylin.	f	V	D
D	Ra	Perp.	Cylin.	f	V	L	L	Ra	Perp.	Cylin.	f	V	D
26	**0,94**	0,0081	0,0245	0,12	160	45	95	**1,27**	0,0286	0,0498	0,12	180	19
26	**1,28**	0,0052	0,0202	0,12	160	45	95	**1,30**	0,0069	0,0471	0,12	180	19
26	**1,27**	0,0093	0,0304	0,12	160	45	95	**1,27**	0,0087	0,0437	0,12	180	19
26	**1,35**	0,0078	0,0326	0,12	160	45	95	**2,11**	0,0321	0,0462	0,12	180	19
26	**1,31**	0,0079	0,0360	0,12	160	45	95	**2,02**	0,0132	0,0403	0,12	180	19
26	**1,38**	0,0070	0,0212	0,12	160	45	95	**2,03**	0,0205	0,0521	0,12	180	19
26	**1,33**	0,0186	0,0384	0,12	160	45	95	**1,81**	0,0187	0,0470	0,12	180	19
26	**1,16**	0,0147	0,0182	0,12	160	45	95	**2,14**	0,0068	0,0491	0,12	180	19
26	**1,19**	0,0083	0,0148	0,12	160	45	95	**1,95**	0,0180	0,0478	0,12	180	19
26	**0,92**	0,0078	0,0245	0,12	160	45	95	**2,12**	0,0287	0,0563	0,12	180	19
26	**1,01**	0,0060	0,0324	0,06	180	68	95	**1,94**	0,0022	0,0233	0,06	160	23
26	**0,79**	0,0056	0,0337	0,06	180	68	95	**1,63**	0,0021	0,0230	0,06	160	23
26	**0,83**	0,0145	0,0236	0,06	180	68	95	**1,46**	0,0142	0,0278	0,06	160	23
26	**0,79**	0,0126	0,0643	0,06	180	68	95	**1,92**	0,0143	0,0277	0,06	160	23
26	**0,80**	0,0107	0,0613	0,06	180	68	95	**1,57**	0,0111	0,0252	0,06	160	23
26	**1,11**	0,0098	0,0702	0,06	180	68	95	**1,72**	0,0113	0,0280	0,06	160	23
26	**0,68**	0,0176	0,0544	0,06	180	68	95	**1,84**	0,0043	0,0263	0,06	160	23
26	**0,68**	0,0221	0,0550	0,06	180	68	95	**1,95**	0,0039	0,0218	0,06	160	23
26	**0,67**	0,0083	0,0392	0,06	180	68	95	**2,04**	0,0266	0,0302	0,06	160	23
26	**0,66**	0,0133	0,0490	0,06	180	68	95	**2,24**	0,0225	0,0320	0,06	160	23
26	**1,29**	0,0230	0,0526	0,09	140	95	95	**1,29**	0,0230	0,0526	0,09	140	26
26	**1,29**	0,0067	0,0463	0,09	140	95	95	**1,29**	0,0067	0,0463	0,09	140	26
26	**1,34**	0,0048	0,0490	0,09	140	95	95	**1,34**	0,0048	0,0490	0,09	140	26
26	**1,16**	0,0218	0,0361	0,09	140	95	95	**1,16**	0,0218	0,0361	0,09	140	26
26	**1,21**	0,0501	0,0411	0,09	140	95	95	**1,21**	0,0501	0,0411	0,09	140	26
26	**1,26**	0,0395	0,0356	0,09	140	95	95	**1,26**	0,0395	0,0356	0,09	140	26
26	**1,21**	0,0512	0,0314	0,09	140	95	95	**1,21**	0,0512	0,0314	0,09	140	26
26	**1,36**	0,0266	0,0367	0,09	140	95	95	**1,36**	0,0266	0,0367	0,09	140	26
26	**1,25**	0,0149	0,0742	0,09	140	95	95	**1,25**	0,0149	0,0742	0,09	140	26
26	**1,26**	0,0202	0,0821	0,09	140	95	95	**1,26**	0,0202	0,0821	0,09	140	26

ANNEX-8 Multi Linear Regression Analysis sheet for surface roughness.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0,959523536
R Square	0,920685416
Adjusted R Square	0,877773225
Standard Error	0,233200756
Observations	30

ANOVA

	df	SS	MS	F	ignificance F
Regression	3	17,04441	5,681469	104,4722	1,26E-14
Residual	27	1,46833	0,054383		
Total	30	18,51274			

	Coefficients	'andard Err	t Stat	P-value	Lower 95%	Upper 95%	.ower 95,0%	Ipper 95,0%
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
f	25,39586777	1,377102	18,44153	7,88E-17	22,57029	28,22145	22,57029	28,22145
V	-0,01107438	0,002158	-5,13282	2,13E-05	-0,0155	-0,00665	-0,0155	-0,00665
Diameter	0,048909091	0,016422	2,978357	0,006058	0,015215	0,082603	0,015215	0,082603

RESIDUAL OUTPUT

Observation	Predicted Ra	Residuals	ıdard Residuals
1	1,443	-0,403	-1,8216
2	1,443	-0,163	-0,73678
3	1,443	-0,033	-0,14916
4	1,443	0,297	1,342472
5	1,443	0,207	0,935662
6	1,443	-0,073	-0,32997
7	1,443	0,067	0,302847
8	1,443	0,237	1,071266
9	1,443	-0,153	-0,69158
10	1,443	0,017	0,076842
11	2,622	-0,062	-0,28025
12	2,622	0,218	0,985383
13	2,622	0,208	0,940182
14	2,622	0,458	2,070209
15	2,622	0,278	1,25659
16	2,622	0,158	0,714177
17	2,622	-0,302	-1,36507
18	2,622	-0,482	-2,17869
19	2,622	-0,172	-0,77746
20	2,622	-0,302	-1,36507
21	0,802	0,208	0,940182
22	0,802	-0,012	-0,05424
23	0,802	0,028	0,126563
24	0,802	-0,012	-0,05424
25	0,802	-0,002	-0,00904
26	0,802	0,308	1,392193
27	0,802	-0,122	-0,55145
28	0,802	-0,122	-0,55145
29	0,802	-0,132	-0,59665
30	0,802	-0,142	-0,64186

PROBABILITY OUTPUT

Percentile	Ra
1,666667	0,66
5	0,67
8,333333	0,68
11,66667	0,68
15	0,79
18,33333	0,79
21,66667	0,8
25	0,83
28,33333	1,01
31,66667	1,04
35	1,11
38,33333	1,28
41,66667	1,29
45	1,37
48,33333	1,41
51,66667	1,46
55	1,51
58,33333	1,65
61,66667	1,68
65	1,74
68,33333	2,14
71,66667	2,32
75	2,32
78,33333	2,45
81,66667	2,56
85	2,78
88,33333	2,83
91,66667	2,84
95	2,9
98,33333	3,08

ANNEX-9 Multi Linear Regression Analysis sheet for cylindiricity.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0,851924
R Square	0,725774
Adjusted R	0,694132
Standard E	0,01093
Observatio	30

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	3	0,00822	0,00274	22,9374252	1,79E-07
Residual	26	0,003106	0,000119		
Total	29	0,011326			

	Coefficients	*tandard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*.ower 95,0%*	*Jpper 95,0%*
Intercept	-1,638394	0	65535	#NUM!	-1,638394	-1,638394	-1,638394	-1,638394
f	0,328944	0	65535	#NUM!	3,289443	3,289443	3,289443	3,289443
V	0,000157	0	65535	#NUM!	0,015743	0,015743	0,015743	0,015743
L	-0,001623	0,002117	-7,669486	3,8659E-08	-0,020583	-0,011882	-0,020583	-0,011882

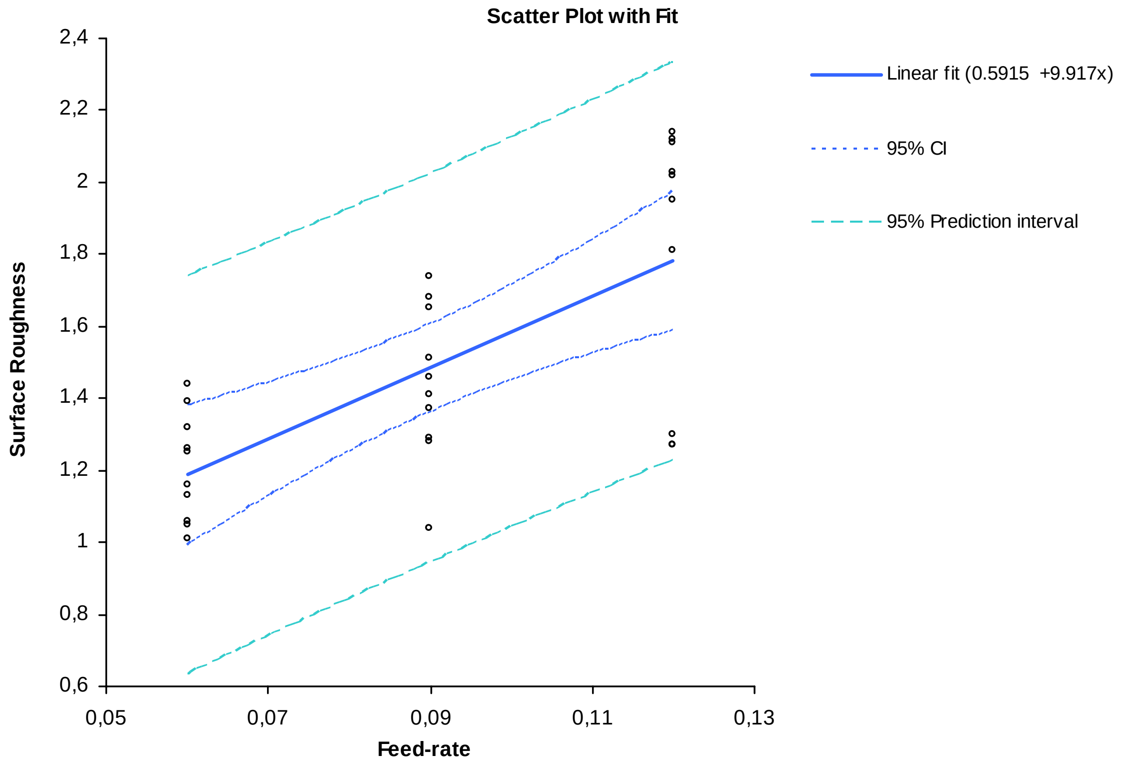
RESIDUAL OUTPUT

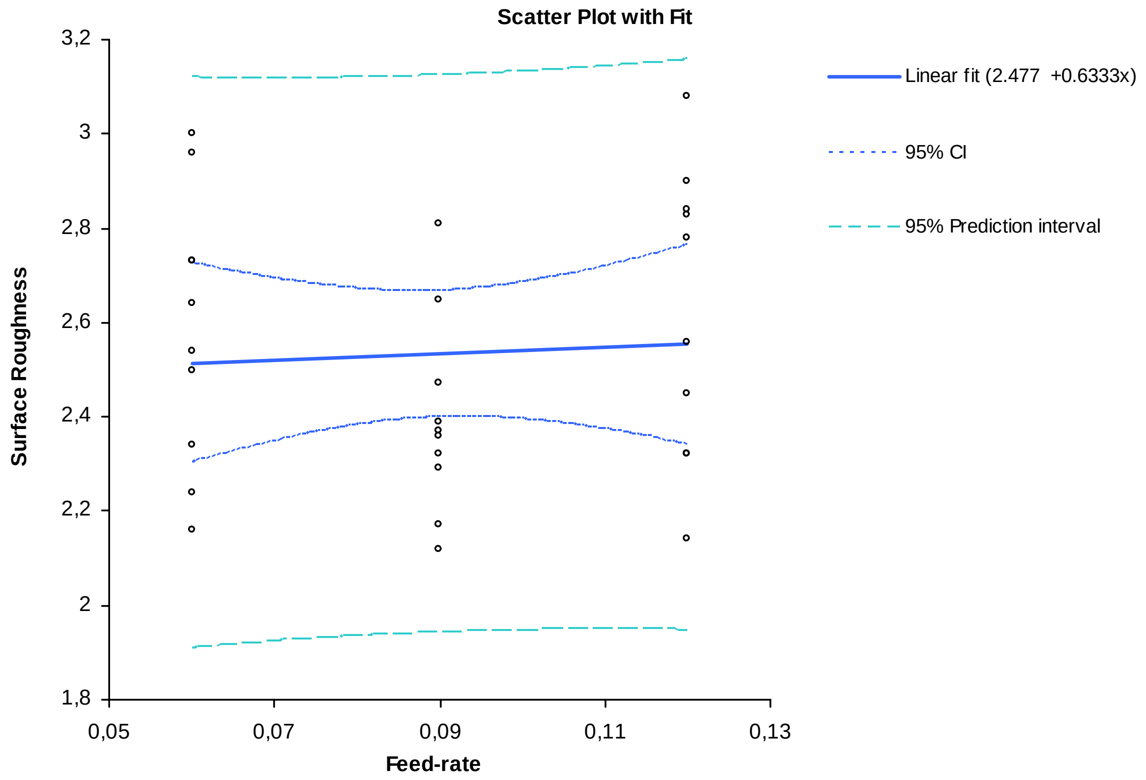
Observation	*redicted Cyl.*	*Residuals*	*ıdard Residuals*
1	0,03249	0,00381	0,368158
2	0,03249	-0,00589	-0,569147
3	0,03249	-0,00359	-0,346899
4	0,03249	-0,00219	-0,211618
5	0,03249	0,00021	0,020292
6	0,03249	0,00671	0,648383
7	0,03249	0,01171	1,131529
8	0,03249	-0,00049	-0,047348
9	0,03249	-0,01049	-1,013641
10	0,03249	0,00021	0,020292
11	0,07268	-0,01478	-1,428181
12	0,07268	-0,01358	-1,312226
13	0,07268	-0,00228	-0,220315
14	0,07268	-0,00268	-0,258967
15	0,07268	2E-05	0,001933
16	0,07268	-0,02468	-2,384811
17	0,07268	0,00732	0,707326
18	0,07268	0,02192	2,118114
19	0,07268	-0,00298	-0,287955
20	0,07268	0,03172	3,065081
21	0,04794	0,00186	0,17973
22	0,04794	-0,00084	-0,081169
23	0,04794	-0,00424	-0,409708
24	0,04794	-0,00174	-0,168135
25	0,04794	-0,00764	-0,738248
26	0,04794	0,00416	0,401978
27	0,04794	-0,00094	-0,090832
28	0,04794	0,00116	0,11209
29	0,04794	-0,00014	-0,013528
30	0,04794	0,00836	0,807821

PROBABILITY OUTPUT

Percentile	*Cylin.*
1,666667	0,022
5	0,0266
8,333333	0,0289
11,66667	0,0303
15	0,032
18,33333	0,0327
21,66667	0,0327
25	0,0363
28,33333	0,0392
31,66667	0,0403
35	0,0437
38,33333	0,0442
41,66667	0,0462
45	0,047
48,33333	0,0471
51,66667	0,0478
55	0,048
58,33333	0,0491
61,66667	0,0498
65	0,0521
68,33333	0,0563
71,66667	0,0579
75	0,0591
78,33333	0,0697
81,66667	0,07
85	0,0704
88,33333	0,0727
91,66667	0,08
95	0,0946
98,33333	0,1044

ANNEX-10 Linear Regression Analysis of effect of feed-rate against surface roughness.





ANNEX-10 Linear regression analysis of effect of feed-rate against surface roughness.