An Investigation of the Surface Parameters in Self-piloting Deep Hole Machining Using A Developed Methodology of Statistical Design of Experiment

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ABSTRACT

An Investigation of the Surface Parameters in Self-piloting Deep Hole Machining Using A Developed Methodology of Statistical Design of Experiment

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Analytical methods in manufacturing processes for the development of mathematical models are usually unreliable due to the inherent cross influence of the cutting parameters, hence experimental data are widely used. In this case, statistical techniques are usually more suited to analyze the experimental data, which result in reduced cost and time of experimentation. Conclusions of such analysis are also more reliable. Taguchi method for statistical design uses orthogonal arrays instead of factorial and fractional factorial. For optimal values, he relies upon graphs of marginal averages rather than using a mathematical optimization procedure. Unfortunately, this method will not identify optimal conditions, in general, but might identify only conditions that are close to the optimum. A comprehensive analysis of the statistical design of experiment and its application in machining processes has been developed. The applied aspects of the design such as the basic requirements to the criterion of effectiveness, factors selection, and mathematical model formulation, were considered. A special attention is paid to the pre-process decisions. The 2^k factorial experiment, complete block was chosen as the basic type of the design of experiments in machining. The statistical design of experiment is applied successfully to investigate the surface parameters of self-piloting deep hole machining. In order to study the tool life and the cutting forces, using 2^k factorial experiments, the logarithmic coordinate transformations of the Taylor equation in regression form, were proposed. The experimental study of bell mouth in precision hole machining with self-piloting tools is carried out.

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NOMENCLATURE

$E\{y\}$	Mathematical expectation or true average response
y	True parameter of optimization (POO).
x_i	Factors that choosen to be varied in the experiment.
i	Factor number
b_o , b_i , b_{ij}	Selected regression coefficients
β_o , β_i , β_{ij}	Theoretical regression coefficients
y'	Estimation of POO
$\tilde{x}_i$	True value of a factor
Δx_i	Factor interval of variation
N	Number of combinations
K	Number of factors
u	Current point in the design matrix.
r	Number of parallel tests at the same point in the design matrix.
y_u	Average response at a point in the design matrix
s_u^2	Row variance
$s^2\{y\}$	Variance of response
G_{cr}	Critical Cochran number.
m	Number of terms in the obtained model.
s^2_{ad}	Variance of adequateness

$\propto\%$	Significance level
n	Number of points in the design matrix
v	Cutting speed
s	Feed.
Q	Cutting fluid flow rate
c	Radial clearance between the starting bush and the tool
f	Distance between the starting bush and the workpiece faces
a	Distance measured from the face of the workpiece along the bell mouth
T	Index of the tool life.
t	Depth of cut.
P_x, P_y, P_z	Cutting force components

CHAPTER 1

INTRODUCTION

1.1 DEEP HOLE MACHINING

The constant drive for higher accuracy, surface finish and at the same time higher productivity to withstand the economic competition has led to many improvements in the cutting tools and cutting methods. Considering the enormous amount of hole production in a manufacturing activity, the strive for better drilling tools and procedures were always at the forefront of such drives. This constant quest has led to the development of deep hole drilling methods. The type of hole making operation selected usually depends upon the following hole requirements:

1) Diameter of the hole;

2) Depth of the hole;

3) Quality of the hole surface;

4) Size, accuracy, parallelism and straightness.

Machining holes of high length-to-diameter ratios to high standards of size, parallelism, straightness and surface finish, has always presented problems. Since hole straightness deteriorates when the hole length to a diameter ratio exceeds three, conventional drilling tools such as twist drills are inadequate for precision drilling. In case of twist drills, both radial and tangential cutting forces are theoretically balanced. But in reality, due to uneven grinding and material inhomogeneity, these are unbalanced Swarf or chip removal becomes difficult in twist drilling of deeper holes The deeper the hole to be machined, the lower is the rigidity of the tool, since the rigid support is farther away from the cutting edge This phenomenon tends to make the hole making process a difficult task for holes of high length-to-diameter ratios

One of the most significant technological advances made during the past thirty years to help solve the above-mentioned problems has been the development of hole machining with self-piloting tools This machining process uses high pressure coolant and is capable of machining deep holes in a single pass Actually, this process can cover a large range of bore diameters (3 mm to 1500 mm) and can be used for hole depths of up to 150 times the hole diameter

Deep hole drilling processes use a tool having the geometry of the drill head such that the cutting forces generated at the cutting edge are balanced by the reaction forces at the pads situated at approximately 90^0 and 180^0 to it. The pads bear against the wall of the hole being drilled. They have a smoothing and stabilizing effect which improve the surface finish and accuracy of the hole [1].

1.1.1 HISTORICAL BACKGROUND

The deep hole drilling process had its origin in the gun barrel's industry during the period from 16^{th} to 18^{th} centuries. The town of Suhl in Germany was known as a center of deep hole drilling during 1500 - 1750. This technique employed a water mill as a prime driver and spade drill bits as the cutting tool. Two barrels could be drilled simultaneously by two parallel boring spindles. The feed and thrust were provided by an operator. The operator actuated a lever which supplied force amplification, thus enabling him to provide an infinitely variable feed [2] In 1713, a vertical gun drilling machine was built by Martiz. A cutter head mounted on the end of a boring bar was rotated by animal power, and a downward feed was given to the gun barrel.

The first boring machine in which the workpiece was rotated and feed motion was given to the drilling tool appears to have been used about 1758 by J. Verbruggen in collaboration with Ziegler. This was regarded as a first generation of machine tool for engineering applications [3]. The cutting tools used in that machine were spade drills with two cutting edges suitable for drilling a hole into a solid workpiece. Also, counter-boring tools were employed for enlarging and cleaning up existing cast holes. The invention of twist drill in the United States in 1860 pioneered the important steps in drilling. Morse first studied the commercial production of twist drill in 1862. An article published in 1886 by Landis [4] describing gun barrel manufacturing showed that a variety of self-supporting tools were available at this time. But it remains a fact that the foundation of modern deep hole drilling process had been laid down by the first half of 20th century. It was in the 1950s when gun drills were introduced extending the deep hole drilling process to small bores. The extensive use of deep hole drilling in the engineering industry, and with the growth of technology rising exponentially the drilling operation has come quite far since then.

1.1.2 DEEP HOLE MACHINING SYSTEM

The deep hole machining system consists of:

I. Machine

The extreme nature of conditions imposed during the deep hole machining operation necessitate special considerations for building a machine and its structure. Deep hole machines are very robust and of unusual stiff and sturdy design, equipped with comparatively high-powered feed and main drives.

The deep hole drilling machine contains the following features to ensure economically satisfactory performance [5]:

1) Spindle with ample power;

2) Feed drive unit;

3) Special coolant supply system;

4) Swarf filtration system;

5) Starting bush;

6) Rigid structure; and

7) Accessories.

A schematic representation of a typical deep hole machining system is illustrated in Figure 1.1.

The spindle and feed drive assembled over a rigid structure who determines the capability of the machine. The design and performance of these units are similar to such units of other machine tools. The next most important component of any deep hole machining system is the coolant supply system. The primary functions of the coolant in deep hole machining process are:

1) Lubrication of contact surfaces in the machining and burnishing zone;

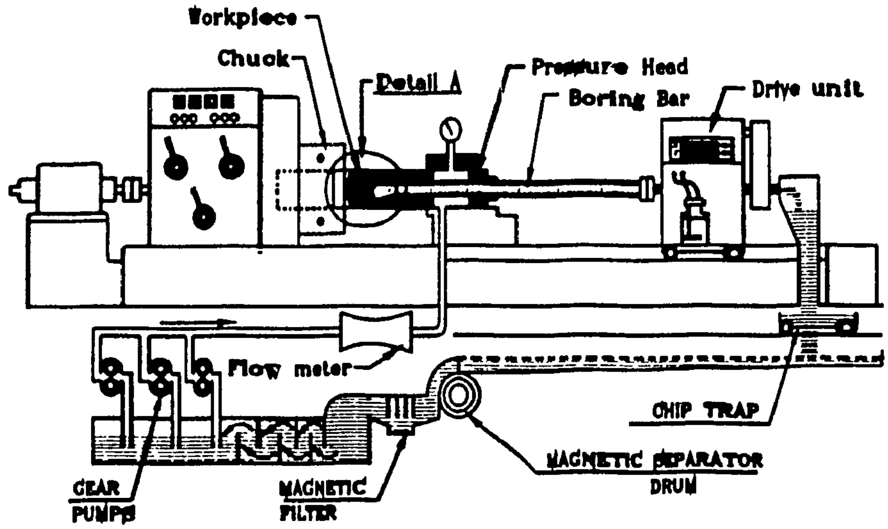


Figure 1.1 Deep hole machining system

2) Heat removal from the contact areas,

3) Transportation of chips from the machining zone to the chip collection area

The difficulty in supplying the coolant to the cutting zone and the need to remove the chip from the machining zone to the swarf filtration system over great lengths calls for special high pressure coolant supply system in deep hole machining system Coolant is pumped by heavy duty pumps, completes with non-return and pressure relief valves, through the pressure head to the point of cutting Swarf returns along the center of the boring bar to a chip basket where the bulk of the chips is removed.

The pressure head is mounted on the guide side of the deep hole boring machine and is one of the most important components in a successful boring operation The pressure head has three main functions

1) Transferring the cutting forces at the starting of the machining operation to the machine bed through the starting bush;

2) Directing the coolant flow into the machining zone via the tool head at high pressure,

3) Acts as a seal in preventing the coolant leakage

II. Tools

Numerous names have been given to similar deep hole drilling tools This interchangeable use of generic names for the same type of tools is confusing In the most general case, the tools of this type are classified by the method of the coolant supply. It can be gundrill-type tools, BTA-type tools, Ejector-type tools [6].

A) Gundrill Type Tools

Gun drills are single-lip, end cutting tools which drill or bore a hole in a single pass. A gun drill has approximately two-thirds of a circular cross section solid, and one-third V-grooved. The typical gun drill consists of a cutting tip, hollow shank and a driver as shown in Figure 1.2. The cutting tip is brazed to the shank, and at the other end a driver is provided.

The function of drill shank is to provide the torsional stiffness to allow a reasonable continuous feed during machining [2]. The shank has a kidney shaped cross section forming a V-groove which serves as the passage for swarf from the cutting head to the disposal point (external chip removal). The coolant is pumped through one of the three possible types of tip orifices and flows over the cutting zone (internal coolant supply). The swarf is carried through the external chip removal channel created by the V-flute and the bore wall, the principle of gundrill is shown in Figure 1.3.a. The tool head may be made of solid carbide, or have carbide tips brazed on steel body for larger diameters.

B) BTA Type Tools

BTA type tools [7] are single or multi-edge, end cutting tools with external cutting fluid supply through the annular channel between the boring bar and the bore walls and internal chip removal along the inner surface of the boring bar. The principle of BTA deep-hole machining is shown in Figure 1.3.b.

C) Ejector Type Tools

The ejector deep hole drilling method developed by Sandvik Coromant, overcomes

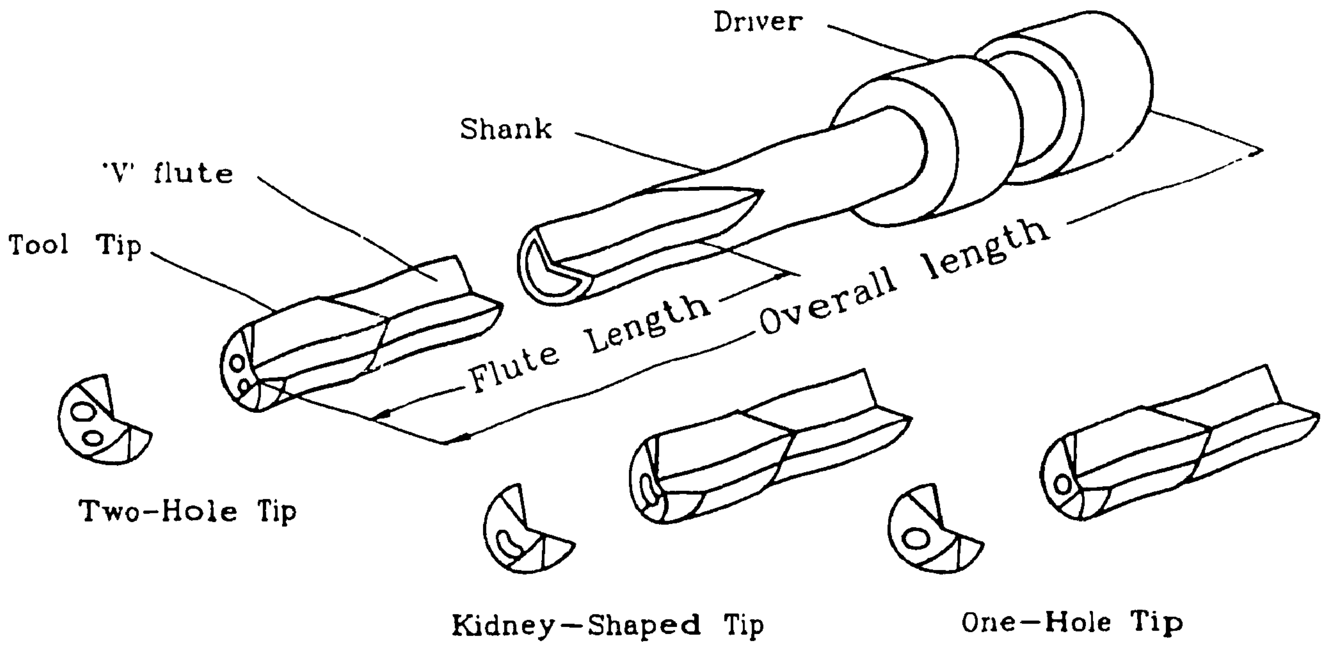


Figure 1.2 Typical gundrill

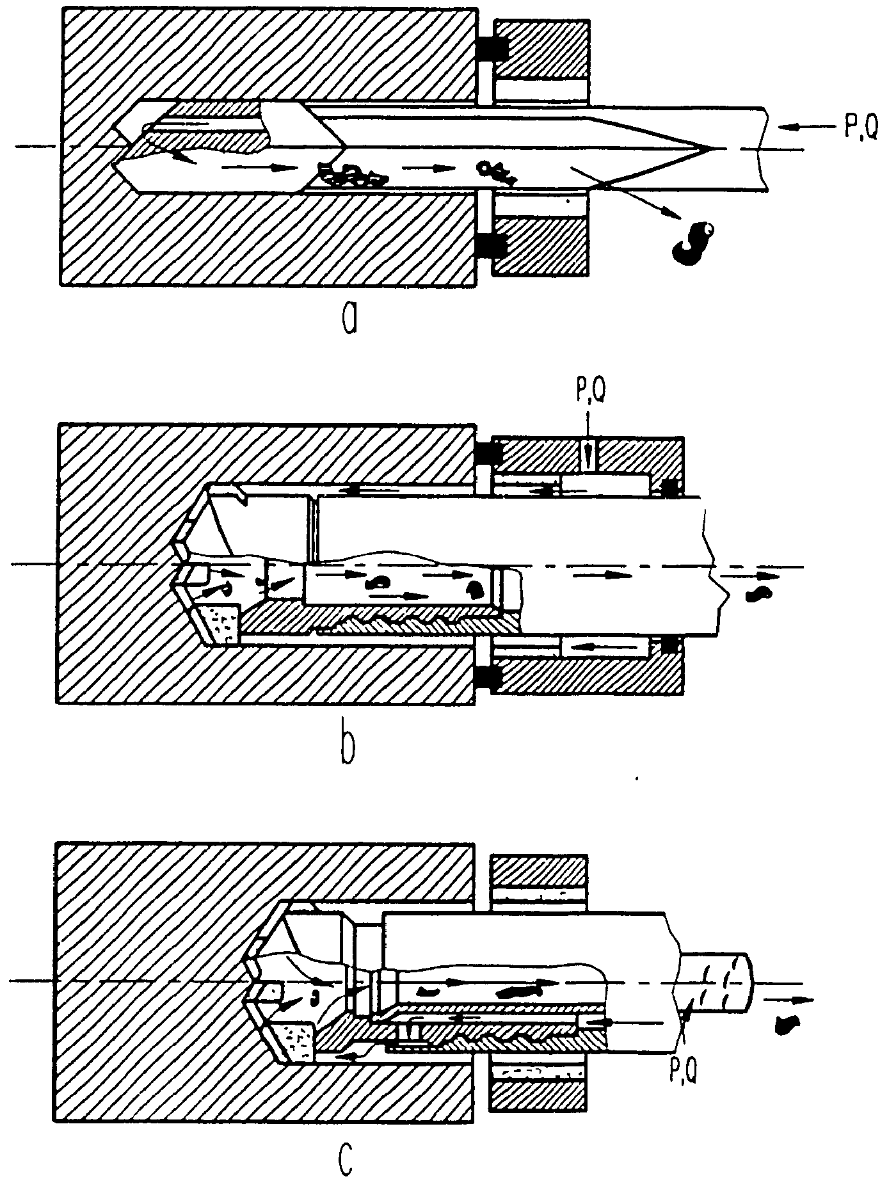


Figure 1.3 Types of self-piloting tools (a) Gundrill (b) BTA drill (c) Ejector drill

problems inherent with BTA drilling system, the sealing being probably the most serious one Two concentric drilling tubes are employed Ejector type tools are usually multi-edge, end cutting tools with internal coolant supply (between the boring bar and the inner tube), and internal chip removal (through the inner tube) The inlet and outlet channels connected by the ejector nozzle and part of the pumped coolant is drawn off through this nozzle to set up a partial vacuum in the inner tube that provides better conditions for swarf removal (Figure 1.3.c)

The term deep hole drilling has grown to mean that in the drilling process the cutting forces generated on one side of the centre line of the drill head are balanced on the other side by equal and opposite forces, created by supporting pads which bear against the bore of the drill hole So the deep hole drill guides itself in the pilot bush and then in the hole being drilled, and as such is self-piloted (Astakhov et al 1979, Griffiths, 1979, 1982, 1993, Griffiths and Grieve 1993). Currently, multi-edge and multi inserts tools also utilize the same principal of self-piloting and it is suggested that the term self-piloting drilling which conveys the idea of the drill guiding or steering itself during a drill operation could replace the widely used terms as gundrill, BTA, or Ejector drill which reflect, as mentioned above, methods of coolant supply only. There are gundrills with an ejector nozzle, ejector drills with external coolant supply etc (Astakhov et al 1979a, 1984) So, this can only be stated about self-piloting tools for deep hole drilling and this term (self-piloting) really reflects the main design concept of these drills

1.2 SOME OBSERVATIONS OF SURFACE INTEGRITY OF DEEP HOLE DRILLING.

Surface integrity is defined as the inherent or enhanced condition of a surface produced in a machining or other surface generation operation. The term surface integrity has become widely accepted and is now used extensively in technical literature [8] Surface integrity has two distinct aspects The first is surface topography, which is concerned with surface finish roughness, form and texture The second aspect is surface metallurgy which is concerned with the nature of the surface and sub-surface layers. B.J Griffiths (1982) has done extensive studies on this subject

Three of the most important surface parameters are roughness, roundness and bell mouth

I. ROUNDNESS

Roundness is a condition of a surface of revolution, such as a cylinder, cone or sphere, where all points of the surface intersected by any plane, (I) perpendicular to a common axis(cone cylinder) or (ii) passing through a common center (sphere) are equidistant from the axis Simply roundness can be defined as the radial uniformity of a work surface measured from the center line of the workpiece.

The perfect roundness is very important In the first place, the circular cross section is the most frequently used basic shape in engineering design. Secondly, the quality of roundness enters into the proper functioning of most kinds of machinery. Following from the points just considered, the conditions of roundness, external and internal, demand the most attention of any form or shape measurement. Roundness measurement falls into two basic systems which depend upon the choice of the datum surface from which the measurement is taken. These two methods are presented in appendix A, with an example on calculating the out of roundness in a machined hole [10]

II. ROUGHNESS

Surface metrology may be broadly defined as the measurement of the difference between what the surface actually is and what it is intended to be. It is treated separately from length measurement because length measurement is concerned with the relationship of two surfaces on a workpiece, whereas surface measurement is involved with the relationship of a surface on the workpiece to a reference which is not actually on the workpiece.

By far the most common aspect of surface metrology is the measurement of surface roughness as an average deviation from a mean center line. At the present time some 90 percent of the surface measurements made in the United States today are measurements of this average roughness height.

Many of concepts of surface metrology are defined in ASA Standard B46.1-1962, "Surface Texture,". Roughness consists of the finer irregularities in the surface texture, usually including those irregularities which result from the inherent action of the production process. These are considered to include traverse feed marks and other irregularities within the limits of the roughness-width cutoff. Roughness-width cutoff is the greatest spacing of repetitive surface irregularities to be included in the measurement of average roughness height. It is possible to give the surface texture a numerical value in one of several different ways. These ways are presented in appendix B [11].

III. BELL MOUTH

An inherent disadvantage of self-piloting tools especially of drills and boring tools, is so called the bell mouth. The bell mouth is the tapered hole entrance which maximum diameter is usually out of hole tolerance in machining of the precise holes. This diameter is located at the workpiece face and the burr a round the hole entrance occurs as a result of the bell mouth formation (Figure 1.4). The surface finish within the bell mouth is characterized by deep groves that make it unacceptable for many cases. When high diameteral accuracy is required, the bell mouth becomes an issue that cannot be neither ignored nor tollerated. To improve the hole quality, it is necessary to make the workpiece initially longer and subsequently machine off the bell mouth.

The bell mouth formation is another important aspect of the pads role in the deep hole drilling process, and it illustrates the need to be a ware of pads contribution to the hole form. The guide pads bear against the bore wall of the pilot bush and the cutting starts as the tip penetrates the workpiece. When the pads touch the workpiece the burnishing action commences. During the first few revolutions of the burnishing, the hole diameter is maximum. As the depth of penetration increases the area of the work material contacting the pads also increases. Consequently, the work material offers more resistance to plastic deformation and the hole diameter gradually becomes smaller as the bell mouth is formed. The oversize at the start of the bell mouth depends on the tool clearance in the pilot bush, and

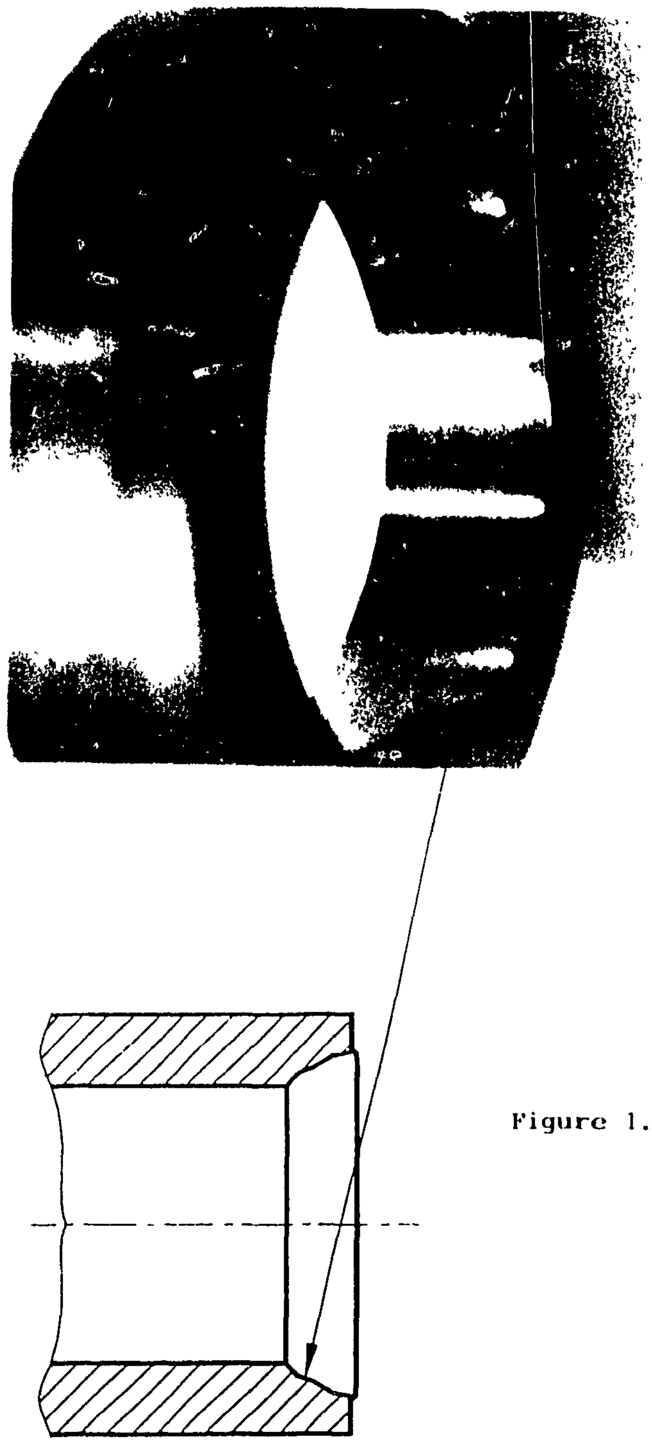


Figure 1.4 : Bell mouth formed at the hole entrance

on other parameters will be discussed later. This is a simplified explanation and in practice the phenomenon is more complex [9].

A deep hole machined surface generally consists of grooves and the spacing between these grooves corresponds to the feed rate. The surface topography did not alter during the various combinations of speed and feed. The study of literature published by various researchers (Griffiths, 1982, Sakuma et al, 1980) can be draw following conclusions:

1) Increase of drilling feed results in:

   a) increasing surface roughness;

   b) decreasing surface finish quality;

   c) increasing depth of plastic deformation.

2) Increase of drilling speed:

   a) negligible change in surface roughness;

   b) negligible change in surface finish quality;

   c) increasing depth of plastic deformation.

El-Khabeery, 1991 concludes that the surface roughness decreases with increasing the cutting speed. He found that the surface roughness decreases with a decrease in feed rate. This occurs because feed affects the suitable chip form and produces small broken chip. Decreasing of feed rate also leads to an increase in tool life which, in turn, decreases the surface roughness and improves the surface. The surface roughness was also found by El-Khabeery to decrease with an increase in speed. An increase in cutting speed leads to a decrease in the built-up edge and also an acceptable chip form [12].

Ramakrishna and Shunmugam, 1987 have shown the variation of surface finish parameters with speed and feed rate. Higher values of roughness at low speed is due to the tearing or work material which in t· rn deteriorates the finish. Tearing occurs when ductile metals are cut at low cutting speeds (Bothroyd, 1985). Also the low cutting speed in deep drilling with carbide tools may cause the formation of the built-up edge (Griffiths 1975, Sakuma et al 1978). The presence of a built-up edge also affects the surface finish. The quality of finish improves remarkably with an increase in speed

Ramakrishna showed that at low speeds there is not a large variation in size. However at increased speeds, an appreciable size variation can be observed. His work shows also that BTA drilling sometimes results in an undersized hole. This may be due to elastic deformation of the workpiece during tool passage and the spring-back phenomenon after that. Also, the temperature rise due to cutting makes the workpiece expand during machining and cooling after drilling shrinks the machined hole (Sakuma et al 1980). With higher feed values oversized holes are produced as a result of the heavy load on the guide pads. A deviation of tool axis as a result of the cutting force, the oil pressure and a vibratory movement of tool axis may also enlarge the hole diameter. Sometimes, as observed by Sakuma et al (1980), the projected part of the built-up edge on the cutting edge makes the hole diameter larger than the tool diameter [13].

The formation of multi-cornered hole profiles in BTA drilling is related to the position of guide pads and is caused by the vibrating movement of the tool axis. This mechanism of formation of multi-cornered hole is explained by Sakuma et al (1981). Ramakrishna has showed that roundness error at entry is high on account of unstable entry of the tool. Self-guiding action stabilizes at larger depths of hole resulting in smaller values of roundness error

Ramakrishna and Shunmugam found that the maximum roundness and straightness errors increase with speed This is mainly due to the vibratory displacements of the tool which is predominant at higher spindle speeds and results in dynamic instability. The maximum roundness error shows increasing trend with feed

They have shown also that the quality of finish is improved by an increase in feed In conventional machining, any increase in the feed value increases the roughness In BTA drilling, the improvemert in the finish is due to the burnishing action of guide pads which produces a plastically deformed surface layer When the feed is increased further, there is an increase of load on the pads Heavy loads may not always make surface quality good in burnishing (Sakuma et al, 1980) and there is therefore an intermediate feed at which the finish reaches an optimum value

Previous investigations showed that a better finish can be achieved at higher speeds, others showed that speed has negligible effect on surface quality. Also, they showed that roughness increases with increasing feed rate, but others showed that the quality of finish is improved by an increase in feed and talked about an intermediate feed at which the finish reaches an optimum value So, it can be thought that the contradiction in their results is due to some reasons they did not properly design the experiments using statistical approaches, they considered machining as a process without interactions between the factors affecting the objective under study, and they varied one factor at a time which increased the error in the obtained results Experimental investigation for surface finish should start with well based properly conducted experiments and provide a mathematical model describing the objective under study, find an optimal setting for the considered factors and conduct an experiment using the obtained setting to verify the obtained mathematical model. Nowadays, high quality achievements is a result of statistical design of experiments[14].

1.3 STATISTICAL DESIGN OF EXPERIMENT

The history of industrial development records a few outstanding instances in which a startling new improvement in material usage, operating method or product design was the outcome of an accidental phenomenon, upon men with sharp eye and keen mind seized to create a new invention. But such event are very rare. Most discovery is the result of well-planned, carefully performed and competently analyzed experimentation. In recent years the consumers have demand products of highest quality and reliability. As a result of this the analysis and understanding of the manufacturing processes are required. Statistical methods can be used to provide insight to many complex manufacturing processes that cannot be satisfactorily explained by the mathematical equations. We need to find out how to make products better, statistical design and analysis is one area where we could immediately do better with methods for improving products and processes that are easier to use and more efficient.

Squeezing the most information from the outcomes of experiments is primarily a function of good statistical analysis. Equipped with this evaluation, the management, engineering and production personnel concerned can then translate the experimental outcomes into meaningful interpretations and improvements. Statistical methodology encompasses the acquisition, review and analysis of data, thereby becoming a useful tool wherever the outcomes of the experiments, the data collected from trials and tests need study, evaluation and interpretation. One cannot begin to meaningfully interpret the results of experiments without a grasp of certain fundamentals of statistical analysis. Variations in data from experiments occur no matter how carefully the experiments are performed. Sometimes, variability in test results may be so large as to obscure completely the effects of factors and factor levels and even cause incorrect conclusions to be drawn.

Statistical experimental design was invented in the early 1920s by R. A. Fisher in England. In her biography, Joan Fisher Box (1978) describes the work of Fisher. In 1919 he went to work at a small, at that time not very well known, agricultural research station called Rothamsted about forty miles north of London. The workers at Rothamsted were interested in finding out the best way to grow wheat, potato, and other crops. They could have conducted their experiments in a greenhouse, carefully controlling the temperature and humidity, making artificial soil that was uniform, and keeping out the birds. By doing so they would have produced results that applied to plants grown under these very artificial conditions. However, the results would most likely have been entirely useless in deciding what would happen on a farmer's field.

The question, then, was how to run experiments in the noisy and imperfectly controlled conditions of the real world. It was gradually realized that Fisher's work on experimental method constituted a major step forward in human progress. He showed for the first time how experimentation could be moved out of the laboratory. His methods quickly produced relevant, practical findings in a multitude of important fields, including medicine, education and biology. In particular, his ideas were suitably developed for the industrial setting, and over the years many statistically designed experiments have been run in industry in the United States, Great Britain, and many other countries [14] Nowadays, one of the well known methods for design of experiment is Taguchi method

1.3.1 TAGUCHI METHODS

Taguchi's quality engineering ideas and statistical procedures have been used in Japan for decades, but it was the mid-1980s when the Western world became aware of his views toward process control and quality improvement in general, and the set of tools that he advocates

The central component of the approach consists of a statistical optimization methodology. This methodology is nowadays routinely employed in Japanese industry Taguchi method is to characterize the dependance of the response on the control factors by conducting orthogonal array experiments. The control factors are then set so as to provide an optimal mean response The Taguchi method groups variables with influence on a particular quality characteristic into controllable factors and disturbance or noise factors Instead of trying to find and monitor the noise factors in the ongoing production process (on-line control), Taguchi proposes a three-stage-design based on what is called off-line control In the first stage, the stage of system design, the process is designed in a way to ensure that it is able to fulfill the given task. In the second stage, the stage of parameter design, one then tries to find those levels of the controllable factors for which the quality characteristic of interest is leased influenced by noise factors. In Taguchi-method the parameter design plays the key role. Its goal is to design systems (products and processes) which are robust against noise and disturbances. Finally, at the third stage, the stage of tolerance design, one determines whether the tolerance ranges of the involved factors need to be tightened [15]. An example on design of experiment using Taguchi method is given in appendix A. In the Anglo-Saxon literature the Taguchi-method was first presented in Taguchi-Wu (1979). A didactically revised presentation is given by Ross (1988) and Ryan (1989). Rayan in his book on quality improvement [16], made a comparison between using the orthogonal arrays and factorial design, this comparison explains the superiority of factorial design over the orthogonal arrays, also he discussed the optimization technique used in Taguchi method. Taguchi's approach is to conduct experiments allowing estimation of only the main effects of the control factors. However, ignoring interaction effects can result in a bias in the experiment if any such interactions are important, this can cause mis-estimation of the optimal setting of the control factors. Taguchi's approach uses orthogonal arrays instead of factorial and fractional factorial which are well known and understood. And, to maximize or minimize, it is logical to attempt to do so using known mathematical optimization procedure rather than trying to rely upon graphs of marginal averages [16].

Taguchi's main contribution appears to be in focusing our attention on new objectives in achieving quality improvement. The statistical tools for accomplishing these objectives will likely continue to be developed.

1.4 OBJECTIVE OF THIS WORK

Metal cutting including deep hole machining is mostly an experimental science.

Machining processes in general are very complicated, and they are different from other processes because of factors interactions which make them complex and hard to study Therefore, well based and properly conducted test is the first requirement in metal cutting studies. There is a lack of information dealing with test methodology and data evaluation in metal cutting experiments. Designed experiments using a developed methodology were used to study roughness and roundness in deep hole machining in order to obtain mathematical models describing the effect of the considered factors and their interaction. Several researchers have mentioned the bell mouth formation in deep hole machining with self-piloting tools The existence of this phenomenon was recognized by Griffiths in his Ph D thesis Some practical recommendation to reduce the bell mouth are provided by Astakhov, Galitsky, and Osman [17] Unfortunately, little is known about the bell mouth formation, and the main factors affecting this phenomenon are still unclear. There is no study made to understand the influence of the tool design and the process parameters on the bell mouthing Even though this phenomenon has a great importance in deep hole accuracy, but it is the least studied phenomenon in self piloting machining. This can be explained by its complexity, changing appearance from working method to another, from one set of technological parameters to another, etc Therefore, the main objective of the present work is to establish the mechanics of the bell mouth formation using a modified method of statistical design of experiment in order to achieve a better control over this process A comprehensive theoretical and experimental study of bell mouth is carried out to achieve the objective

Summary and conclusions are given and some recommendation for future work are made.

CHAPTER 2

STATISTICAL DESIGN OF EXPERIMENTS IN MACHINING PROCESSES

Most machining processes are complex and involve a large number of variables affecting the performance of these processes. With the growth in technology, manufacturing engineers are often faced with the problem of how accurately estimate and control the process variability in order to achieve improved product quality and higher productivity. For this purpose new methods of experimentation and analysis are needed to replace the old ineffective methods [18].

Optimization of machining processes is important in the present day automated mass and batch manufacturing systems. Due to the complexity of the machining process, analytical methods for the development of mathematical models are difficult, hence experimental investigations are widely used. Statistical techniques have been widely used to analyze machining processes because of the reduced cost and time of experimentation and also because conclusions can be drawn with the required reliability [19].

The application of the modern technique of DOE originates from Fisher [20]. One widely used Japanese quality-improvement method, the Taguchi method, has statistical design of experiments as its core. This experimental method is used to determine process conditions for achieving the target value and to identify factors that can be controlled to reduce variation. Regardless of the large number of studies done in this field [21-25], the mathematical theory of experiments and DOE are far from completeness, and DOE methodology, especially its applied aspects, has to be developed

It is important to note that methods to design experimentation are receiving great publicity and being highly promoted primarily because of the renewed emphasis on product and service quality improvement as means to attain a competitive advantage The statistical design method discussed in this thesis can be used to determine desired factor settings so that the process responses are close to the target and the variability is as small as possible.

2.1 Design of experiment in machining processes: terminology and requirements.

The statistical design of experiment (DOE) is the process of planning the experiment so that appropriate data will be collected, which are suitable for the further statistical analysis resulting in valid and objective conclusions [26] All factors included in the experiment are varied simultaneously The influence of unknown or non-included factors is minimized by properly randomizing the experiment. Mathematical methods are used not only at the final stage of study, when the evaluation and analysis of experimental data are conducted, but also through all stages of DOE, i e , from the formalization of the *priori* information till the decision making stage Therefore, the mathematical methods play an active role Such methodology provides the answers to important questions "What is the minimum number of tests that should be conducted? Which parameters should be taken into consideration? Which method(s) is better to use for the experimental data evaluation and analysis?"

The problem of the mathematical model selection for the subject under investigation requires the formulation of the clear objective(s) of the study This problem occurs in any study, but the mathematical model selection in DOE requires the quantitative formulation of the objective(s) Such an objective is named *the parameter of optimization* (POO), which is the result of the process under study, its output or response [27]

The process under study may be characterised by several important output parameters but only one generalised parameter should be chosen as POO. To reduce the set of possible POOs, the estimation of their mutual correlations plays an important role. When the correlation coefficient between two parameters is quite high, any one of these two parameters may be excluded from consideration, but it is better to exclude those that are difficult to measure with the required accuracy The correct choice of POO is a very important stage in DOE.

POO must satisfy certain requirements . Firstly, POO should be the effective one in order to reach the final aim of the study Secondly, POO should be easily measured. If there is no method for the quantitative measurement of POO, then the response ranging at least at two levels is possible It should be mentioned here, that the ranging approach is less sensitive than the quantitative methods and restricts the study Thirdly, POO should be a single-valued function of the chosen process parameters Fourthly, because in DOE the relation between the mean value (as an estimator) of POO and the factors has to be established, the statistical effectiveness of POO plays an important role Practically it means that the number of possible states of POO in its range should be as large as possible For example, in study of machinability index of metals, their hardness is a statistically ineffective POO because of low measurement accuracy of hardness. It is better to choose another POO, for example, ultimate tensile stress, which is directly related to the hardness, and can be measured precisely

Input variables are called *factors* In DOE, it is necessary to include into consideration all essential factors. Unconsidered factors change arbitrary and increase the error of tests. Even when a factor does not change arbitrary but is fixed at a certain level, the false idea about the optimum can be obtained because there is no guarantee that the fixed level is the optimal. The consideration of a complete set of factors involved in the process is necessary Such a way helps not to miss the essential factors and to exclude the factors which do not affect the process.

The factors can be quantitative or qualitative but both should be *controllable*. Practically this means that the chosen level of factor(s) can be set up and maintained within a certain accuracy in a test. The chosen factors should affect the process under investigation directly and should not be functions of other factors. For example, the cutting temperature cannot be chosen as a factor because it is not a controllable parameter and depends on the other factors of the cutting process (the cutting regime, the materials properties, the tool geometry, etc.).

The factors combinations should be *compatible*, i.e., all required factors combinations should be realizable. For example, it is impossible to choose the upper level of the cutting regime while cutting an inflammable material, when the cutting temperature exceeds the inflame temperature of the work material.

2.2 The model selection

One of the important stages in the DOE is the selection of the mathematical model Mathematically, the problem of DOE can be formulated as follows: define the estimation of the response surface which can be represented by the function:

$$E\{y\} = \phi(x_1, x_2, \ldots, x_k) \tag{2.1}$$

where y is POO (the process response) under study (for example, the tool life, the hole accuracy, the productivity, etc), x_i, i $1,2, \ldots ,k$ are the factors, which can be varied within a test (for example, the design and geometry parameters of the cutting tool, the parameters of the cutting regime, the properties of the work material, etc.)

The mathematical model (2.1) is used to define the gradient, i.e., the direction in which POO changes quicker than in any other The mathematical model (2.1) represents the response surface which is assumed to be continuous, two times differentiable, and having only one extreme. Under these assumptions, the procedure to define the optimum includes the following steps:

- formulation of the mathematical model using the results of a short experimental study
- estimation of the model gradient, i e., define the direction for further tests;
- conduction of the full-range of experimental study only in the direction defined at the previous stage.

The use of such methodology enables one to reach the stationary region [27].

In general, the study is conducted under insufficient knowledge about the considered phenomenon Naturally, the particular kind of the mathematical model is unknown, but in order to solve the extremal problem, a certain approximation of the model can be found. A good approximation in this case is a power series. The accuracy of the approximation by a power series, which in this context appears as a polynomial, depends upon the order (power) of the series. Therefore, the mathematical description of an unknown response function by a polynomial is convenient. To reduce the number of tests at the first stage of experimental study, a polynomial of first order or a linear model is more suitable. Such a model is successfully used to calculate the

POO gradient, thus, to reach the stationary region. Also, this model is sufficient to describe a process in a certain "narrow" range of factors variations.

When the stationary region is reached then a polynomial containing terms of the second, and sometimes, the third order may be employed. The chosen mathematical model should be adequate to the process, i.e., should predict the process results with a certain accuracy. The experience shows that in metal cutting studies, the model containing linear terms and interactions of the first order can be used successfully [28]. Such a model can be represented as:

$$E\{y\} = \beta_0 + \sum_i \beta_i x_i + \sum_{ij} \beta_{ij} x_i x_j \qquad (2.2)$$

The coefficients of eq.(2.2) should be defined from the tests. Using the experimental results, it is possible to define the regression coefficients b_0, b_i, b_{ij}, which are estimations of the theoretical regression coefficients β_0, β_i, β_{ij}. Thus, the regression equation, received as a result of tests, is different from theoretical Equation (2.2) and has the following format:

$$\hat{y} = b_0 + \sum b_i x_i + \sum b_{ij} x_i x_j \qquad (2.3)$$

Here $\hat{y}$ is the estimation of response $E\{y\}$.

After the regression coefficients are defined, the influence of included factors on the process under study, their interactions, and the direction of the optimal region become clear. When moving to the stationary region, it is not necessary to investigate the detailed relationship between POO and factors. Therefore, the response surface within the limited factorial space can be approximated by a hyperplane. When the stationary region, or, at least, its close neighbourhood, is reached, the problem is considered to be solved. After this, the polynomials of higher orders can be used in DOE, when the detailed analysis of the stationary region is required.

2.3 Pre-process decisions

Each factor has a certain global range of variation. Within this range, the local sub-range which will be used in DOE has to be defined. Practically, it is necessary to define the limits of each factor included in the experiment. In order to do this, available information such as experience, results of previous study, etc., can be used. Using available information, the approximate combination of factors which gives the best results should be defined. Mathematically, the defined combination can be thought as a point in the multi-dimensional factorial space. The coordinates of this point are called the *basic (zero) level of factors*, and the point itself is termed as the *zero point* [20,25].

The interval of factor variation is the number which when is added to the zero level gives the upper limit and when is subtracted from the zero level gives the lower limit. The value of this interval is chosen as the unit of a new scale of a factor. To simplify the notation of the experiment conditions and procedure of the experimental data analysis, this new scale is chosen so that the upper limit corresponds to *+1*, lower - to *-1*, and the basic level - to *0*. For the factors with a continuous domain, the simple transformation formula is used:

$$x_i = \frac{\tilde{x}_i - \tilde{x}_0}{\Delta \tilde{x}_i} . \qquad (2.4)$$

Here x_i is a new (so called "code") value of factor, $\tilde{x}_i$ is the true value of factor, Δx_{io} is the interval of the factor variation (in true units), often called the scale unit; i is the factor number Therefore, the origin of the factorial space is shifted to a new position corresponding to the basic levels of factors, and factors themselves are measured using a new scale [20].

As it is seen, the choice of intervals of the factors variation is a non-formalized stage of DOE and is carried out according to the experience and intuition of the experimentalist. The accuracy of factor setting at the chosen level, the degree of influence (correlation) of each factor on POO, and the accuracy of POO measurements should be also considered. Such considerations enable an experimentalist to avoid the situation when the chosen interval(s) of factor(s) variation is (are) not wide enough to detect the factor(s) influence on POO

It is useful to have at least approximate ideas about the curvature of a response surface When this surface is non-linear then the contradiction between the accuracy of factors setting (require increasing in a scale unit) and the curvature of a response surface (require reducing in a scale unit) becomes significant

It is also important to account the stage of an experimental study When the optimization problem is under consideration then at the first stage of experiment a scale unit should be chosen to provide the step-by-step approaching to the optimal region. When the problem of mathematical description of a process is under consideration, a scale unit should cover the whole factors range chosen for study.

As stated above, an interval of factor variation is a part of the factor range. If this interval is chosen to be no more than *10 %* of the factor range then such interval is called narrow Intervals of no more than *30%*, and of more than *30%* of the range are called medium and wide, respectively.

The minimum number of factors levels used in experiment is determined by the maximum order of the interpolation polynomial and should be bigger than this order by one.

The most useful in metal cutting study is DOE at two levels, which provides either the process approximation by a linear model with interaction terms, or the direction of movement toward the stationary region. Thus, the two factor values corresponding to the upper and lower limits of the interval of variation are used. These values are called the upper and lower levels and are designated "*+1*" and "*-1*" (or even simpler, "+" and "-"). When two factor levels are used in DOE, the design plan is designated as 2^k, where k is the number of involved factors [25].

2.4 2^k factorial experiment, complete block

Experiments are conducted in order to investigate the effects of one or more factors on a response. When an experiment involves two or more factors, the factors can influence the response individually or jointly. Often, as in the case of one factor-at-a time experimentation, an experimental design does not allow one to properly assess the joint effects of the factors.

Factorial experiments conducted in completely randomized designs are especially useful for evaluating joint factor effects. Factorial experiments include all possible factor level combinations in the experimental design. Completely randomized designs are appropriate when there are no restrictions on the order of the testing or when all the experimental units to be used in the experiment can be regarded as homogeneous.

The mathematical description of the object under study in the vicinity of the zero point can be obtained by varying each factor at two levels, distinguished from the zero level by the interval of variation. When the experiment includes all possible non-repeated factor-level combinations, such experiment is termed as *the complete block*. The number of such combinations is $N = 2^k$

.

The 2^k factorial experiment (complete block) has showed its usefulness in metal cutting test, when using such test, the regression equation is,

$$\hat{y} = \hat{E}[y] = b_0 + \sum_{i=1}^{3} b_i \tilde{x}_i + \sum_{ij} b_{ij} \tilde{x}_i \tilde{x}_j + b_{123} \tilde{x}_1 \tilde{x}_2 \tilde{x}_3 \qquad (2.5)$$

The complete block enables an experimentalist to obtain the separate estimations for all coefficients *b*. That is the main advantage of such a type of experiment.

Obtaining the mathematical model in form of Eq.. (2.5) includes several stages:

(1) design of experiment: statement of a problem; choice of POO; selection of factors to be involved; choice of the levels of these factors; selection of the sequence of the factor-level combinations; selection of the number of observations to be taken; selection of the order of test to be used; selection of the method of randomization to be used; selection of a mathematical model to describe the experimental results.

(2) experiment itself as a series of tests; data collection in each test

(3) evaluation and analysis: examination of the statistical significance of the model coefficients; examination of homogeneity of the row variances, examination of the adequateness of the obtained mathematical model.

An important step at stage (1) is the selection of the order of test to be used

Table 2.1: Treatment combinations and effects in 2^3 factorial experiment.

Point of the matrix	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$
1	+	-	-	-	+	+	+	-
2	+	+	-	-	-	-	+	+
3	+	-	+	-	-	+	-	+
4	+	+	+	-	+	-	-	-
5	+	-	-	+	+	-	-	+
6	+	+	-	+	-	+	-	-
7	+	-	+	+	-	-	+	-
8	+	+	+	+	+	+	+	+

2.5 Design matrix

Using the code values (+1, -1), the experiment conditions can be written as a table, called *the design matrix*, where the rows correspond to different tests and the columns correspond to different code values of the factors [20-27]

In case of three included factors, a design matrix is as shown in Table 2 1 In this table, columns x_1, x_2, x_3 form the design matrix because they directly set up the tests conditions Further, the columns for the interactions: $x_1 x_2$, $x_1 x_3$, $x_2 x_3$, $x_1 x_2 x_3$ are placed and they are used for the estimation of the factors interactions. An artificial variable x_0 is added to the table and used to estimate the coefficient b_0 Tables contain such a column are called the *extended design matrices*

The following notation of tests is used A number *u (u = 1-8) is attributed to each point in the design matrix*. The tests have double numbering the first number shows the point in the design matrix, the second is the test number at this point The number of parallel tests at the same point is denoted as r_u (r_u >1). For example, y_{uj} is the response, obtained in *j-th* test conducted at *u-th* point

2.6 Properties of the 2^3 factorial experiment, complete block

There are several features of the introduced design matrices making them an optimal tool for getting the mathematical models using the experimental data The first feature is the matrix symmetry relative to the centre of the experiment which can be expressed as follows The sum of elements of each vector-column (except the vector-column x_0) is equal to zero, i e ,

$$\sum_{u=1}^{n} x_{iu} = 0 \,, \quad i = 1, 2, \ldots, 2^k - 1 \tag{2.6}$$

where n is the total number of points in the matrix; u is the number of the current point. The second feature is that the sum of squares of the elements of each vector-column is equal to the number of points in the matrix, i.e.,

$$\sum_{u=1}^{n} x_{iu}^2 = n \,, \quad i = 0, 1, \ldots, 2^k - 1 \tag{2.7}$$

The third feature is called the orthogonality of a design matrix. The orthogonality in such a contest means that the sum of the product of entries of any two vectors-columns in the matrix is equal to zero, i.e.,

$$\sum_{u=1}^{n} x_{iu} x_{ju} = 0, \quad i \neq j \quad i, j = 0, 1, \ldots, 2^k - 1 \tag{2.8}$$

It follows from the orthogonality of the design matrix (Table 2.1), that the matrix normal system is a diagonal system. Another important consequence of this property is the mutual independence of the estimations of the regression coefficients, which significantly simplifies their calculations.

The considered model is linear with respect to the POO but non-linear with respect to the factors. The non-linearity in such a contest means that the factors interactions are included into consideration. The factorial experiment, when the complete block is used, enables an experimentalist to estimate such interactions quantitatively. If in the model $b_{ij} = 0$ and $b_{123} = 0$ then such model becomes linear with respect to both the POO and the factors. The plan 2^3 provides the estimation of eight regression coefficients b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, and b_{123}

2.7 Basic Requirements For Tests Conducting

The design of experiment requires special attention to the accuracy in testing procedure. The statistical estimators of the experimental data used in the design would, inevitably reflect all experimental errors and defects. The single-factor type of experimentation, traditionally used in metal cutting, does not stipulate the estimation of both the experimental error and reliability (adequateness) of the obtained mathematical model. A relatively high variation, occurred in the metal-machining tests, creates the additional difficulties in using DOE, causing the necessity of increasing the number of tests at the same point of the design matrix. Therefore, the first requirement of concern in machining tests is the reduction of the variation of POO.

The second important requirement is the necessity of using in all tests the workpiece material with the same metallurgical and mechanical properties from, better from one batch. It is preferable to use materials from one batch to reduce their properties variations which would affect the value of POO. When it is impossible to do so, the design matrix should be divided into the orthogonal blocks and the work material from one batch should be used within, at least, each block.

The third requirement is the tool calibration when it is possible. The calibration consists of the following stages: (a) choice of tools (cutting inserts, deforming elements, adjustable blades, etc.) from one supply; (b) choice of the cutting regime which approximately corresponds to few minuets of tool life; (c) conducting short cutting tests using the selected tools and regime; (d) examining the amount of tools wear and selecting the tools with approximately identical wear rate; (e) preparing selected tools by regrinding or use another side of cutting inserts in the further tests.

To exclude the influence of the slow-changing conditions (scale factor due to the change in the workpiece diameter, temperature of cutting fluid, tool wear, etc.), the random sequences of test conducting is strongly recommended within each orthogonal block, i.e., the blocks should be randomized.

CHAPTER 3

STATISTICAL DESIGN OF EXPERIMENTS IN METAL CUTTING

Applications and Data Analysis

3.1 Experimental Procedure and Equipment

The experiments were carried out on a specially designed deep-hole drilling machine [6]

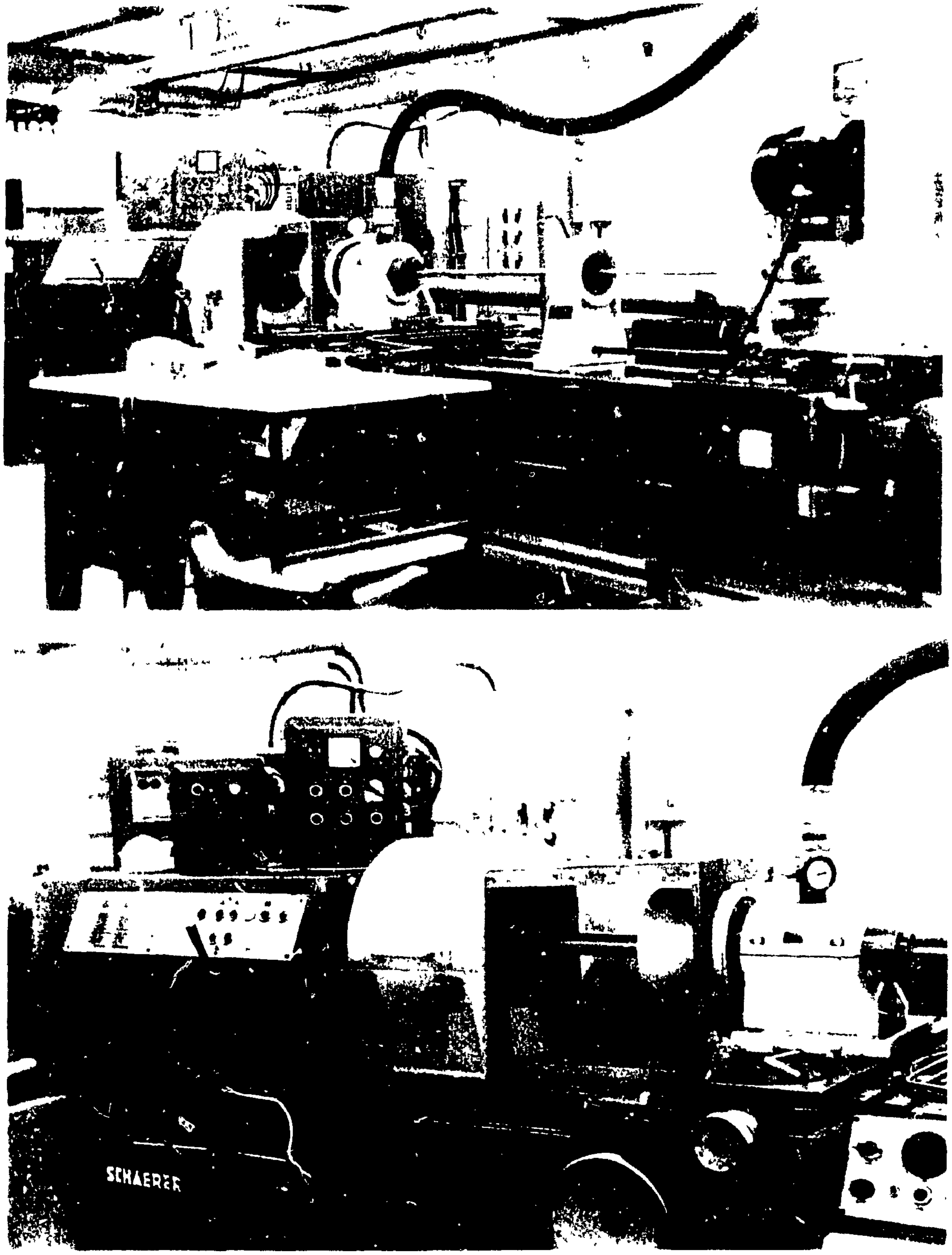
3.1.1 Machine:

Figure 3.1 shows the drilling machine installation used in the experiments. The installation consisted of a drive unit, a pressure head, a boring bar and the drill head, chip traps and filters, precise turbine flow meter and a high pressure cutting fluid flow station. The station was capable of delivering a flow of up to *220 l/min* and generating a pressure of *4.5 MPa*. The stationary workpiece-rotating tool working method was used in the experiments

3.1.2 Tool:

BTA system solid boring heads of *7/8" (22.225 mm)* diameter (American Heller Corp.) were used. Detailed diagram in Figure 3.2 shows drill's design and geometry. The cutting edge is divided into three sections; the outer and the middle cutting edges, separated by a step, are at *18°* and *12°* respectively. The inner cutting edge is reversed so that an edge rather than a point is at the centre of

Figure 3.1 : BTA deep hole boring machine used in the experiments



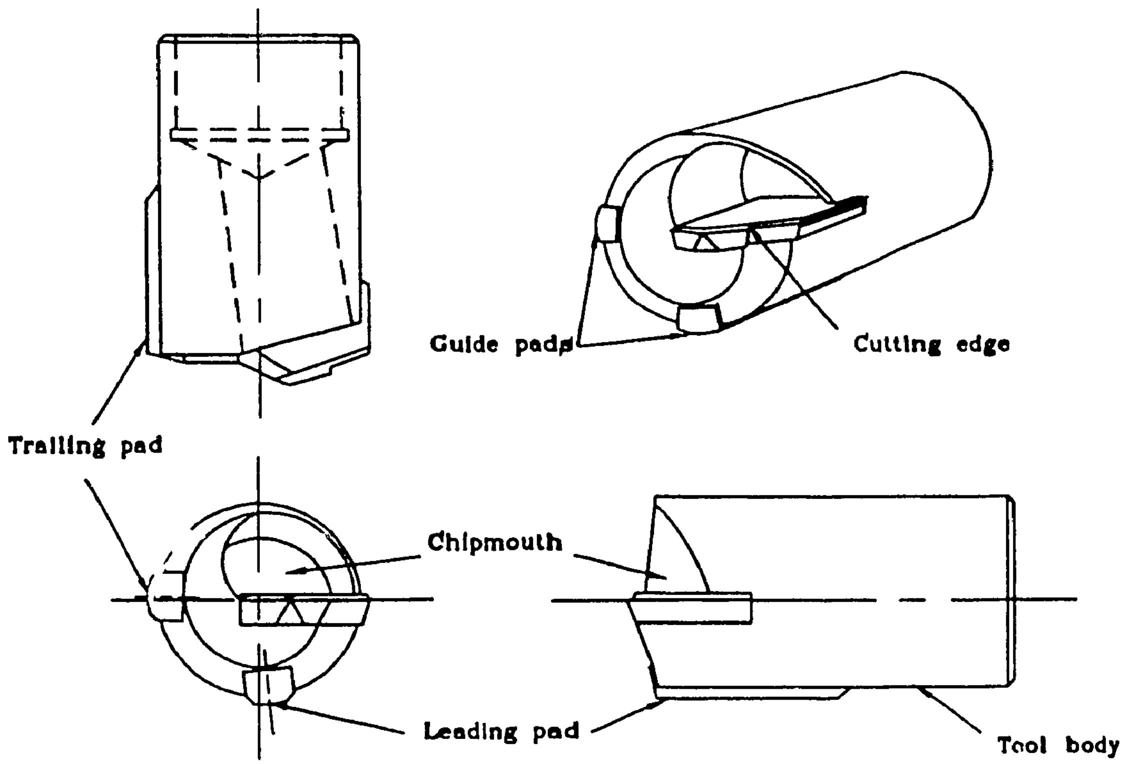


Figure 3.2 Detailed diagram of BTA deep hole boring tool

rotation. The offset is approximately *15 %* of the radius. The rake angle for the inner cutting edge is *30°* negative in comparison to *0°* for outer and middle cutting edges. The geometry parameters of drills were controlled according to standard *B94.50-1975*. Tolerances for all angles were ± *0.5 deg*. The roughness R_a of the face and flank of drills did not exceed *0.25 μm* and was measured according to standard *ANSI B46.1-1978*. Each cutting edge was examined at magnification of *15x* for visual defects as chip of cracks. A special method for microcracks detection on the face and flanks was used [29].

3.1.3 Workpiece:

Workpiece material was hot rolled medium carbon steel *ASTM 1045*. The composition, the element limits and the deoxidation practice were checked to be corresponding to the requirements of the standard *ANSI/ASME B94.55M-1985*. The test bars after been cut to length (*40 mm dia, 1.2 m* length) were normalized to Brinell hardness of *200 HB*. The hardness of the work material was determined over the complete cross-section of the end of each test bar and cutting tests were conducted only on the bars where the hardness lied within the limits ± *10%*. A special parameters as the microstructure, grain size, inclusion count, etc. were checked using the quantitative metallography. Acertificate from the manufacturer is given at the end of this chapter.

3.1.4 Cutting fluid:

"Shell Garia H" cutting fluid was used in the experiments. A reservoir temperature of *27± 3°* was maintained. A precision turbine flow meter was used in the experiments to measure the cutting fluid flow rate to an accuracy ± *1* percent [30].

3.1.5 Cutting forces:

In order to achieve the maximum information about the components of the cutting force and the torque on the different parts of the tool cutting edge, the study was conducted separately for each part, *1*, *2*, *3*, and *4*, of the cutting edge (Fig. 3.2). In experiments, the head was located in a special starting bush which was a part of a dynamometer. The dynamometer design, its static and dynamic calibrations have been presented by authors earlier [31, 32].

3.1.6 Tool life:

The tool life test was performed with the self-piloting drills in accordance with the working manual [33]. The average width of the flank land $VB_{B,\,r} = 0.3\ mm$ was chosen as the tool life criteria and was measured in the tool cutting edge plane which contains the cutting edge and the direction of primary motion. The measurements were made using a toolmaker's microscope with a rotary stage. When regrinding, the drills were ground back at least $2\ mm$ beyond the wear marks and the original geometry was maintained.

3.1.7 Roughness and Roundness:

After drilling, each machined specimen was first cut into sections. After that, the roundness was measured using Tolarund, and roughness was measured using the Talysurf stylus. A special method and a specially equipped surface roughness device were used [34].

3.2 Experimental study of the hole roughness using DOE

Consider the use of DOE in the experimental study of the influence of three parameters (cutting speed, $v(x_1)$, feed, s (x_2), and cutting fluid flow rate, Q (x_3)) on roughness, Δ (y), and roundness, ΔR, of the machined hole in BTA drilling. Thus, the factorial experiment 2^3 complete block was used. As shown in Chapter 2 (Eq. (2.5)), the mathematical model for this case can be written as follows:

$$\hat{y} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3 \quad (3.1)$$

The levels of factors and the intervals of factors variation are shown in Table 3.1.

3.2.1 POO measurements and recording

At each point of factorial space the experiments were conducted genuinely three times $(r = 3)$. The sequence of tests was arranged in accordance with a table of random numbers. Experimental results for roughness and roundness are shown in Tables 3.2 and 3.3, respectively.

3.2.2 Obtaining the mathematical model

The objective of the experiment is to obtain the mathematical model which reflects the phenomenon under study. The detailed procedure for the mathmatical model obtained here is presented only for roughness data.

The orthogonality of the design matrix allows to simplify the calculations of regression coefficients and is one of the distinguished advantages of considered method of experimental design. It is known [20] that for any number of factors, the regression coefficients can be calculated by using the following formula:

$$b_i = \frac{\sum_{u=1}^{n} x_{iu}\overline{y_u}}{n} \quad (3.2)$$

Here, $i = 0, 1, 2, \ldots, k$ is the number of the factor; $\overline{y_u}$ is the average response at the considered point, and is calculated using :

Table 3.1 : Levels of factors and their intervals of variation (roughness and roundness tests).

Levels of factors	Notation	v, m/min (n, min^{-1})	s, mm/rev (s_m, mm/min)	Q, l/min (G/min)
		x_1	x_2	x_3
Basic	*0*	100 (1670.92)	0.07 (116.96)	60 (16)
Interval of variation	Δx_i	15 (250.64)	0.02 (101.93)	20 (5.33)
Upper	*+1*	115 (1921.56)	0.09 (172.94)	80 (21.33)
Lower	*-1*	85 (1420.28)	0.05 (71.01)	40 (10.67)

Table 3.2: Test results (roughness of machined holes, μm).

Points of plane, u	y_1	y_2	y_3	$\bar{y}_u$ Average response	s^2_u Row variance
1	0.57	0.44	1.00	0.67	0.0859
2	0.44	0.38	0.42	0.41	0.0009
3	0.34	0.21	0.15	0.23	0.0095
4	0.22	0.49	0.22	0.31	0.0243
5	0.93	0.49	0.20	0.54	0.1351
6	0.22	0.47	0.21	0.30	0.0217
7	0.17	0.24	0.17	0.19	0.0017
8	0.33	0.21	0.32	0.29	0.0044
	$s^2\{y\} = \sum s^2_u/8 = 0.03543$				

Table 3.3: Test results (roundness of machined holes, μm).

Points of plane, u	y_1	y_2	y_3	$\bar{y}_u$ Average response	s^2_u Row variance
1	4.000	2.900	5.300	4.067	1.508
2	4.000	2.300	2.600	2.967	0.832
3	4.500	4.900	6.000	5.133	0.603
4	3.000	1.200	4.200	2.800	4.560
5	5.500	4.000	5.200	4.900	0.630
6	3.200	3.500	3.000	3.233	0.063
7	3.500	2.200	3.000	2.900	0.430
8	4.500	2.500	2.500	3.167	1.333
	$s^2\{y\} = \sum s^2_u/8 = 1.245$				

$$\overline{y_u} = \frac{\sum_{j=1}^{r} y_{uj}}{r} \tag{3.3}$$

where r is the number of the repeated tests at one point in the plan.

Since each factor (except x_0) is varied at two levels ($+1$ and -1), the calculations are conducted by attributing to the entries of column y_u the signs of the entries of column for corresponding factor, followed by algebraic summation of these entries. A regression coefficient is obtained by dividing the result by the number of plan points. In the examined case:

$$b_1 = \frac{\sum_{u=1}^{8} x_{u1}\overline{y_u}}{8} =$$

$$\frac{1}{8}(-0.67 + 0.41 - 0.23 + 0.31 - 0.54 + 0.30 - 0.19 + 0.29) =$$

$$= -0.04125$$

$$b_2 = \frac{\sum_{u=1}^{8} x_{u2}\overline{y_u}}{8} =$$

$$\frac{1}{8}(-0.67 - 0.41 + 0.23 + 0.31 - 0.54 - 0.30 + 0.19 + 0.29) =$$

$$= -0.1125$$

$$b_3 = \frac{\sum_{u=1}^{8} x_{u3}\overline{y_u}}{8} =$$

$$\frac{1}{8}(-0.67 - 0.41 - 0.23 - 0.31 + 0.54 + 0.30 + 0.19 + 0.29) =$$

$$= -0.0375$$

$$b_{12} = \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8} =$$

$$\frac{1}{8}(0.67 - 0.41 - 0.23 + 0.31 + 0.54 - 0.30 - 0.19 + 0.29) =$$

$$= 0.0850$$

$$b_{13} = \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8} =$$

$$\frac{1}{8}(0.67 - 0.41 + 0.23 - 0.31 - 0.54 + 0.30 - 0.19 + 0.29)$$

$$= 0.0050$$

$$b_{23} \quad \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8} =$$

$$\frac{1}{8}(0.67 + 0.41 - 0.23 - 0.31 - 0.54 - 0.30 + 0.19 + 0.29)$$

$$0.0225$$

$$b_{123} - \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8} =$$

$$\frac{1}{8}(-0.67 + 0.41 + 0.23 - 0.31 + 0.54 - 0.30 - 0.19 + 0.29)$$

$$0.0000$$

Calculation of b_0 is conducted using the same rule:

$$b_0 = \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8} =$$

$$\frac{1}{8}(0.67 + 0.41 + 0.23 + 0.31 + 0.54 + 0.30 + 0.19 + 0.29) =$$

$$= 0.3675$$

$b_0 = 0.3675$; $b_1 = -0.04125$; $b_2 = -0.1125$; $b_3 = -0.0375$; $b_{12} = 0.0850$; $b_{13} = 0.005$; $b_{23} = 0.0225$; $b_{123} = 0.0000$.

Then, the equation in the transformed variables becomes:

$$\hat{y} = 0.3675 - 0.04x_1 - 0.1125x_2 - 0.0375x_3 + 0.0850x_1x_2 - 0.005x_1x_3 + 0.0225x_2x_3 \quad \textbf{(3.4)}$$

3.2.3 Statistical examination of the results

Since DOE emanate from the statistical nature of studying process, the obtained equation has to go through a careful statistical analysis. The objective of the analysis is dual: on one hand it is necessary to extract the maximum information from the collected data , on the other hand, to convince the reliability and accuracy of the obtained results. The following procedure of the experimental data examination is recommended for metal cutting studies.

(1) *Calculation of the Row Variances and Variance of the Response.*

The row variances are calculated using the data from Table 3.2 (3.3) by the following formula:

$$s_i^2 = \frac{\sum_{j=1}^{r} (y_{ij} - \bar{y}_i)^2}{r - 1} \tag{3.5}$$

$$s_1^2 = \frac{(0.57 - 0.67)^2 + (0.44 - 0.67)^2 + (1.00 - 0.67)^2}{3-1} = 0.0859$$

$$s_2^2 = \frac{(0.44 - 0.41)^2 + (0.38 - 0.41)^2 + (0.42 - 0.41)^2}{3-1} = 0.0009$$

$$s_3^2 = \frac{(0.34 - 0.23)^2 + (0.21 - 0.23)^2 + (0.15 - 0.23)^2}{3-1} = 0.00945$$

$$s_4^2 = \frac{(0.22 - 0.31)^2 + (0.49 - 0.31)^2 + (0.22 - 0.31)^2}{3-1} = 0.0243$$

$$s_5^2 = \frac{(0.93 - 0.54)^2 + (0.49 - 0.54)^2 + (0.20 - 0.54)^2}{3-1} = 0.1351$$

$$s_6^2 = \frac{(0.22 - 0.30)^2 + (0.47 - 0.30)^2 + (0.21 - 0.30)^2}{3-1} = 0.0217$$

$$s_7^2 = \frac{(0.17 - 0.19)^2 + (0.24 - 0.19)^2 + (0.32 - 0.19)^2}{3-1} = 0.00165$$

$$s_8^2 = \frac{(0.33 - 0.29)^2 + (0.21 - 0.29)^2 + (0.32 - 0.29)^2}{3 - 1} = 0.0044$$

The results of the calculations are shown in Table 3.2 (3.3).

The variance of the response, $s^2\{y\}$, is the arithmetical average of n different variants of tests (that is the average variance), i.e.,

$$s^2\{y\} = \frac{\sum_{i=1}^{n} s_i^2}{n} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{r}(y_{ij} - \overline{y}_i)^2}{n(r-1)} \qquad (3.6)$$

For the considered case (using the data from Table 3.2) $s^2\{y\} = 0.03543$.

For the case where the numbers of the test repetitions at different points of the design matrix are not identical (due to the throw off of rough errors, lack of workpiece material, etc.), the averaging is conducted using the weighted values of the raw variances taking into account their degrees-of-freedom :

$$s^2\{y\} = \frac{\sum_{u=1}^{n} f_u\, s_u^2}{\sum_{u=1}^{n} f_u} = \frac{\sum_{u=1}^{n} f_u\, s_u^2}{f_F} \qquad (3.7)$$

Here s^2_u is the response variance at the *uth* point, where r_u repeated tests were conducted; $f_u = r_u$ -

l is the degrees-of-freedom of such variance; f_E is the degrees-of-freedom of POO variance $s^2\{y\}$.

It is necessary to mention that the calculations of POO variance can be valid only when the raw variances are homogeneous.

(2) *Examination of variance homogeneity.*

The examination is conducted using the statistical criteria of *Fisher, Cochran, and Barlett.* It should be pointed out that *Fisher, F-criterion,* was usually used for the examination of variance homogeneity and this is a common mistake in the statistical analysis of the experimental data. *F-criterion* cannot be used when the number of the examining variances are greater than two, because this criterion takes into consideration only the maximum and minimum variances but ignor the others. When numbers of test repetitions at each point of design plan are identical, Cochran criterion should be used. This criterion is calculated as a ratio of the maximum variance, $s^2_{i\,max}$, to the sum of all variances. In the considered case :

$$G = \frac{0.1351}{0.2834} = 0.47 \qquad (3.8)$$

Using the table of Cochran numbers, the critical Cochran number is found to be $G_{cr} = 0.61$, for $f_{i\,max} = 2$ and $f_{den} = 24$ (the total number of the tests) degrees of freedom and at 5% level of significance Since the experimentally defined value of G is less than G_{cr}, the variances are considered homogeneous.

(3) Regression analysis.

The mathematical model was defined using the least square method. This method was used as a computational method. Now it is necessary to conduct the statistical estimation of the obtained mathematical model. Normally the regression analysis is based on the following principles:

- the observed results $y_1, y_2, \ldots, y_n$ of response of n points of the factorial space are independent, normally distributed random values;

- the variance of response does not depend on the absolute value of y and the value of factors. In another word, variances at different points of the design matrix are homogeneous. The validity of this principle is shown above;

- the values of factors are not random. In practice it means that the errors of measurements of the independent variables $x_1, x_2, \ldots x_k$ are much less than the errors of factors reproducing.

(4) Examination of significance of the model coefficients.

Examination of the significance of each model coefficient is conducted independently. Thus, the examination by employing the *t-criterion* (Student's criterion) can be used. While using the complete factorial experiment, the confident intervals for all coefficients are equal. First of all, the variance of the regression coefficient, $s^2\{b_i\}$ have to be defined. Under uniform repetition of test, with a number r of repetitions at each point, this variance can be defined as:

$$s^2\{b_i\} = \frac{s^2(y)}{nr} \qquad (3.9)$$

with $f_i = n(r - 1)$ degrees of freedom.

In the considered case :

$$s^2(b_i) = \frac{0.03543}{8 \cdot 3} = 1.46 \cdot 10^3 \qquad s(b_i) = \sqrt{1.46 \cdot 10^3} = 0.038$$

It can be seen from this formula that the variances of all coefficients are equal, because they depend only on the error of experiment itself and on the number of repetitions. Using these data, t_i-*criterion* can be calculated by the following formula:

$$t_i = \frac{|b_i|}{s\{b_i\}} \qquad (3.10)$$

$$t_0 = \frac{0.3675}{0.038} = 9.67 \qquad t_1 = \frac{0.04}{0.038} = 1.05 \qquad t_2 = \frac{0.1125}{0.038} = 2.96$$

$$t_3 = \frac{0.0375}{0.038} = 0.986 \qquad t_{12} = \frac{0.085}{0.038} = 2.24 \qquad t_{13} = \frac{0.005}{0.038} = 0.13$$

$$t_{23} = \frac{0.0225}{0.038} = 0.59$$

The critical value of *t-criteria*, t_{cr}, is defined with $n(r - 1) = 16$ degrees of freedom and at significant level $\alpha = 5\%$. In the considered case $t_{cr} = 1.74$. Now, if $t_i < t_{cr}$ then a coefficient b_i is considered to be insignificant, that is $b_i = 0$. In the considered case, coefficients b_1, b_3, b_{23}, b_{13} are found to be insignificant. A confident interval for each significant coefficient has to be determined. The length of such interval is $2\Delta b_i$, where

$$\Delta b_i = t_{cr} s\{b_i\} = 1.74 \cdot 0.038 = 0.06612 \qquad (3.11)$$

A coefficient b_i is considered to be significant if its absolute value is more than a half of the length of the corresponding confident interval. The orthogonal plan allows to define the confident interval separately for each coefficient of regression, and when any coefficient is found to be insignificant it can be rejected without recalculation of the others. Now, the mathematical model is represented by the equation including only significant coefficients. In our case:

$$\hat{y} = 0.3675 - 0.1125\, x_2 + 0.085\, x_1 x_2 \tag{3.12}$$

To obtain the model in real values of variables, it is necessary to substitute the transformation Eq. (2.4) from chapter 2 into Eq. (3.12), where,

$$x_1 = \frac{x_1 - 100}{15}, \quad x_2 = \frac{x_2 - 0.07}{0.02}$$

By doing this we get:

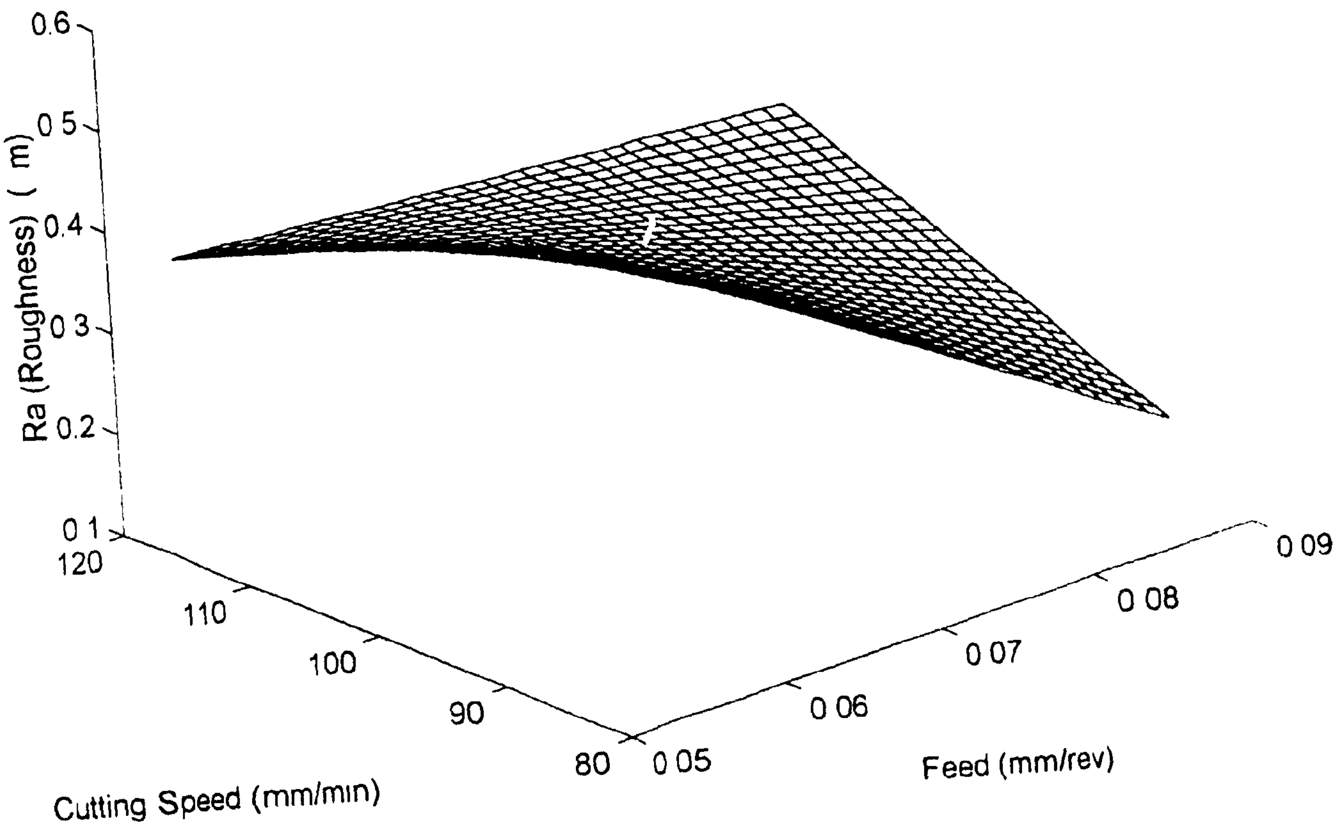
$$\hat{y} = 2.7446 - 0.0198\, v - 33.9583\, s + 0.2833\, vs \tag{3.13}$$

Equation (3.13) reveals that in the presented case, and for the chosen upper and lower factor limits, the surface roughness in deep-hole drilling depends not only on the cutting speed and feed separately but also on their combination. Therefore the influence of these parameters on surface roughness cannot be judged individually as it was considered before [9,12,34,35]. Also it can be seen that the roughness, for the chosen limits, is independent on the cutting fluid flow rate. The response surface describing the parameter of optimization is shown in Figure 3.3. . from this figure we can conclude that the optimal values of speed and feed to give minimum roughness are 85 mm/min and 0.09 mm/rev respectively.

At this stage of the statistical analysis, the common problem is the insignificance of the particular regression coefficient(s) which thought to be significant befor testing. The statistical insignificance of a regression coefficient can be caused by the following reasons:

(1) The chosen zero level x_{i0} is too close to the point of particular extreme of variable x_i

Figure 3.3 Response Surface for Roughness Variation with Speed and Feed



, i.e.

$$b_i = \frac{\partial \hat{y}(\tilde{x}_{i0})}{\partial \tilde{x}_i} = 0 \qquad (3.14)$$

(2) The chosen interval of variation Δx_i is not large enough to detect the influence of x_i on POO;

(3) factor (or factors product) corresponding to the coefficient does not have the functional relation with POO;

(4) conducted experiment has a large error due to the presence of the uncontrollable variables.

When it is believed that the considering factor has a significant influence on POO then:

(1) In the first case, the basic value of the factor should be changed .

(2) In the second case, the interval of variation Δx_i should re-set to be bigger.

(3) In the fourth case, it is necessary to re-do the experiment, trying to reduce errors.

In the considered case the influence of the cutting fluid flow rate is found to be insignificant. It can be explained that the chosen interval of variation of the flow rate was not large enough to affect the hole roughness significantly. But the chosen interval cannot be increased since its upper limit is restricted by the cutting fluid pressure loss in the hydraulic system of the drill. Its lower limit is restricted by the reliable level of the chip removal through the internal drill channels. Therefore, it can be concluded that the flow rate does not affect the hole roughness within the realizable-working-regime range.

(5) ***Adequateness of the model.***

The next step, after calculating the model coefficients, is to check the adequatness of the obtained model. Therefore, the estimation of the deviations between *POO*, predicted by the obtained model, and the experimental value of *POO* at the same matrix points should be determined. This deviation is called the residual variance or variance of adequateness, s^2_{ad}. The estimation of s^2_{ad}, (when the number of the repeated tests at each point in the design plan is the same) can be found as.

$$s^2_{ad} = \frac{r}{n - m} \sum_{u=1}^{n} (\overline{y_u} - \hat{y}_u)^2 \qquad (3.15)$$

Here m is the number of terms (in Eq.(3.12)) in the obtained model including the free term; y_u is the average response at point u; $\hat{y}_u$ is the calculated (Eq. (3.12)) response at the same point. The variance of adequateness is defined with degrees of freedom equal to

$$f_{ad} = n - m = 8 - 3 = 5 \qquad (3.16)$$

The examination of the model adequateness includes the definition of the ratio between the variance of adequateness, s^2_{ad}, and the variance of reproduction, $s^2\{y\}$. The procedure includes using the *F-criterion* of Fisher. This criterion provides the examination, called "null-hypothesis", of the equality of these two variances, and this criterion is formulated as the following ratio

$$F = \frac{s^2_{ad}}{s^2\{y\}} \qquad (3.17)$$

If the calculated value of F / F_{cr}, where F_{cr} is defined using a statistical table for corresponding degrees of freedom

$$f_{ad} = n - m \quad and \quad f_E = n(r - 1) \tag{3.18}$$

and certain level of significance, $\alpha\%$, then the model is recognized to be adequate to the process under study. Otherwise, the model is recognized to be inadequate.

If the variance of adequateness, s^2_{ad}, does not exceed the variance of reproduction, $s^2\{y\}$, then $F < 1$, and the inequality $F < F_{cr}$ is valid for any number of degrees of freedom.

Calculation of the responses:

$$\hat{y}_1 = 0.3675 + 0.1125 + 0.085 = 0.565$$

$$\hat{y}_2 = 0.3675 + 0.1125 - 0.085 = 0.395$$

$$\hat{y}_3 = 0.3675 - 0.1125 - 0.085 = 0.170$$

$$\hat{y}_4 = 0.3675 - 0.1125 + 0.085 = 0.340$$

$$\hat{y}_5 = 0.3675 + 0.1125 + 0.085 = 0.565$$

$$\hat{y}_6 = 0.3675 + 0.1125 - 0.085 = 0.395$$

$$\hat{y}_7 = 0.3675 - 0.1125 - 0.085 = 0.170$$

$$\hat{y}_8 = 0.3675 - 0.1125 + 0.085 = 0.340$$

The result of calculations of $(\bar{y}_i - \hat{y}_i)$ is shown in Table 3.7.

The estimation of s^2_{ad} is

$$s^2_{ad} = \frac{r}{n - m}\sum_{i=1}^{n}(\bar{y}_i - \hat{y}_i)^2 = \frac{3 \cdot 0.0282}{8 - 3} = 0.01692 \qquad (3.19)$$

Since in the considered case s^2_{ad} $s^2\{y\}$ $(0.01692 \cdot 0.03543)$ then the model adequateness is obvious without using *F-criterion* calculations.

The examination of the model adequateness is possible only when $f_{ad} > 0$. If the number of matrix points is equal to the number of the estimated coefficients of the obtained model ($n = m$) then there is no degrees of freedom ($f_{ad} = 0$) to examine the null-hypothesis. The following can be done in this case: As mentioned above, the free term is a mixture estimator. Using the repeated test results at the zero point of the design plan, i.e., at the point with coordinates $(0, 0, 0, \ldots, 0)$, then their average response gives the unbiased estimation

$$\bar{y}_0 \rightarrow \beta_0 \qquad (3.19)$$

Thus, if the difference b_0 - y_0 is found to be statisticaly significant then it points out the inadequateness of the linear model, hence the model should be modified and the factors interactions should be cosidered.

If some regression coefficients were found to be insignificant and it is needed to prove the validity of the linear approximation model within the given factors intervals, then the number of terms of the equation under examination in this case is, as a rule, smaller than the number of matrix points, thus, at least one degree of freedom is left to examine the null-hypothesis.

3.3 Experimental study of the hole roundness using DOE

Using the above recommended procedure for the examination of experimental data (Table 3.3), the following mathematical model for roundness is obtained:

$$\Delta R(\mu m) = -20.044 + 0.238\ v + 396.000\ s + 0.462\ Q - 3.960\ vs - 0.005\ vQ - 6.600\ sQ + 0.066\ vsQ \quad (3.20)$$

This model shows that the roundness depends not only on the regime parameters but also on their combination. Even though the cutting speed, feed, and flow rate have significant influences on roundness, they cannot be judged individually since their interactions exist. The significance of these parameters can be visualised by 2-D or even cubic plot.

3.4 Tool life and cutting forces.

There are certain cases in metal cutting experimentation, where the mathmatical model of

POO is not in a suitable format to be analyzed using the proposed method of DOE. In these cases a transformation of such a mathmatical model to acceptable format should be done. The best example on the necessity of such transformation is the tool life equation.

It is well known that the tool life in metal cutting is expressed in a special equation named after Taylor [37] which has the following form :

$$T = C\, v^{x} s^{y} t^{z} \tag{3.21}$$

Here T is the index of the tool life (simply called tool life) in min; C is a constant includs mainly material properties; v is the cutting speed, *m/min*, s is the feed, *mm/rev*; and t is the depth of cut, *mm*.

Equation (3.21) is the mathematical model of POO. Evidently, it is not possible to obtain the powers of factors using a 2^{3} factorial experiment. In order to apply the proposed method of DOE, some transformation of Eq.(3.21) has to be done. Taking the logarithms of both sides of this equation, a new mathematical model can be obtained :

$$E\{y\} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \tag{3.22}$$

Here $E\{y\}$ is the mathmatical expectation of true tool life in the logarithmic scale; x_1, x_2, x_3 are logarithms of v, s, and t, respectively; β_0, β_1, β_2, β_3 are coefficients to be statistically estimated.

It should be mentioned here that such transformation is not very strict from the statistical point view. Firstly, it is not understood what has happened to the experimental error which is additively included in the original model. Secondly, the estimations found to be biased [20].

Nevertheless, the experience in metal cutting experimental study shows that such transformation may be accepted in most cases [27].

The regression equation for Eq.(3.22) can be written as:

$$\hat{y} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 \tag{3.23}$$

Here y is the estimator for $E[y]$ in Eq.(3.22); b_0, b_1, b_2, b_3 are the estimators for the coefficients β_0, β_1, β_2, β_3, respectively.

Equation (3.23) is an empirical model of the tool life. To define the model coefficients, DOE of 2^3 type may be used. If expression $1/2\ (\ln x_{i\,max} - \ln x_{i\,min})$ is chosen as a new scale unit, then the transformation of the true value of factor $\tilde{x}_i$ to a new value of factor x_i will be basically the same as before (Chapter 2, Eq.(2.4)), thus

$$x_i = \frac{2(\ln\tilde{x}_i - \ln\tilde{x}_{i\,max})}{\ln\tilde{x}_{i\,max} - \ln\tilde{x}_{i\,min}} + 1 \tag{3.24}$$

The results of the coordinate transformations are shown in Table 3.4. In this table t is the width of periphery part of the cutting edge.

The design matrix and the experimental results of the tool life are shown in Table 3.5. Using the proposed approach, the regression equation is:

Table 3.4: Levels of factors and their intervals of variation (tool life and cutting force tests).

Levels of factors	Notation	*v*, m/min		*s*, mm/rev		*t*, mm	
		x_1	lnx_1	x_2	lnx_2	x_3	lnx_3
Basic	*0*	125	4.83	0.125	-2.08	2.5	0.92
Interval of variation	Δx_i	75	4.32	0.075	-2.59	2.0	0.69
Upper (+)	+*1*	200	5.30	0.200	-1.61	4.5	1.5
Lower (-)	-*1*	50	3.91	0.050	-3.00	0.5	-0.69

Table 3.5 :Design matrix and experimental results (tool life test).

Points of plane, u	x_0	x_1	x_2	x_3	Tool life T, min ($ln\ T$)			
					v_1	v_2	v_3	v_4
1	+	-	-	-	95	156	132	128
					4.55	5.04	4.88	4.82
2	+	+	-	-	25	31	23	26.3
					3.22	3.43	3.13	3.26
3	+	-	+	-	135	129	85	116.3
					4.90	4.85	4.44	4.73
4	+	+	+	-	14	16	22	17.3
					2.64	2.77	3.09	2.83
5	+	-	-	+	162	264	185	203.6
					5.08	5.57	5.21	5.29
6	+	+	-	+	45	78	40	54.3
					3.80	4.35	3.69	3.95
7	+	-	+	+	143	215	170	176
					4.96	5.36	5.13	5.15
8	+	+	+	+	10	8	12	10
					2.30	2.08	2.48	2.30
9	+	0	0	0	124	68	45	79
					4.81	4.22	3.80	4.27
b_i	4.04	-0.96	-0.29	0.13				

$$\hat{y} = 4.04 - 0.96x_1 - 0.29x_2 + 0.13x_3 \qquad (3.25)$$

The statistical data evaluation should be conducted in a certain order First of all it must be checked so that the chosen regression equation of the first order, is statistically sufficient to describe the phenomenon under study. To do this, the null-hypothesis should be verified, that is the sum of all regression coefficients $\sum\beta_{ii}$ of the second order terms x_i^2 is equal to zero For the case under consideration: $b_0 = 4.04$; the average response at the zero-level (point No 9 of the matrix) is y_0 4.27; the variance of the response, $s^2\{y\}$ 0.25. Then $b_0 - y_0$ $4.27 - 4.04$ 0.23 s^2 $\{y\}$ Therefore, the quadratic effects are small and statistically negligible

By substituting Eq (3 24) into Eq. (3.25), the regression equation in the true variables, is obtained:

$$\hat{y} = 9.55 - 1.37 \ln x_1 - 0.41 \ln x_2 + 0.19 \ln x_3 \qquad (3.26)$$

or in the common exponential form

$$\hat{T} = \frac{e^{9.55}\, t^{0.19}}{v^{1.37}\, s^{0.41}} \qquad (3.27)$$

Using the same approach, the equations for the cutting force components acting on each part (t, t_1, and t_2, Fig 3.4-) of the drill cutting edge are shown in Table 3 6

Table 3.6: Experimental result for cutting force components

Cutting edge number (Fig. 4)	Statistical relationship for the cutting force components		
	P_z, N	P_y, N	P_x, N
1	$1497\, t^{0.98}\, S^{0.81}$	$450\, t^{1}\, S^{[illegible]}$	$594\, t^{0.94}\, S^{0.61}$
2	$1560\, t^{0.99}\, S^{0.78}$	$585\, t^{1.07}\, S^{0.96}$	$636\, t^{0.93}\, S^{0.66}$
3	$1620\, t^{0.94}\, S^{0.77}$	$770\, t^{0.92}\, S^{0.90}$	$728\, t^{0.93}\, S^{0.63}$

Table 3.7: Calculations of $(\bar{y}_i - \hat{y}_i)$.

Points of plane, u	$\bar{y}_i$	$\hat{y}_i$	$(\bar{y}_i - \hat{y}_i)$
1	0.67	0.565	0.0110
2	0.41	0.395	0.0002
3	0.23	0.170	0.0036
4	0.31	0.340	0.0009
5	0.54	0.565	0.0006
6	0.30	0.395	0.0090
7	0.19	0.170	0.0004
8	0.29	0.34	0.0025

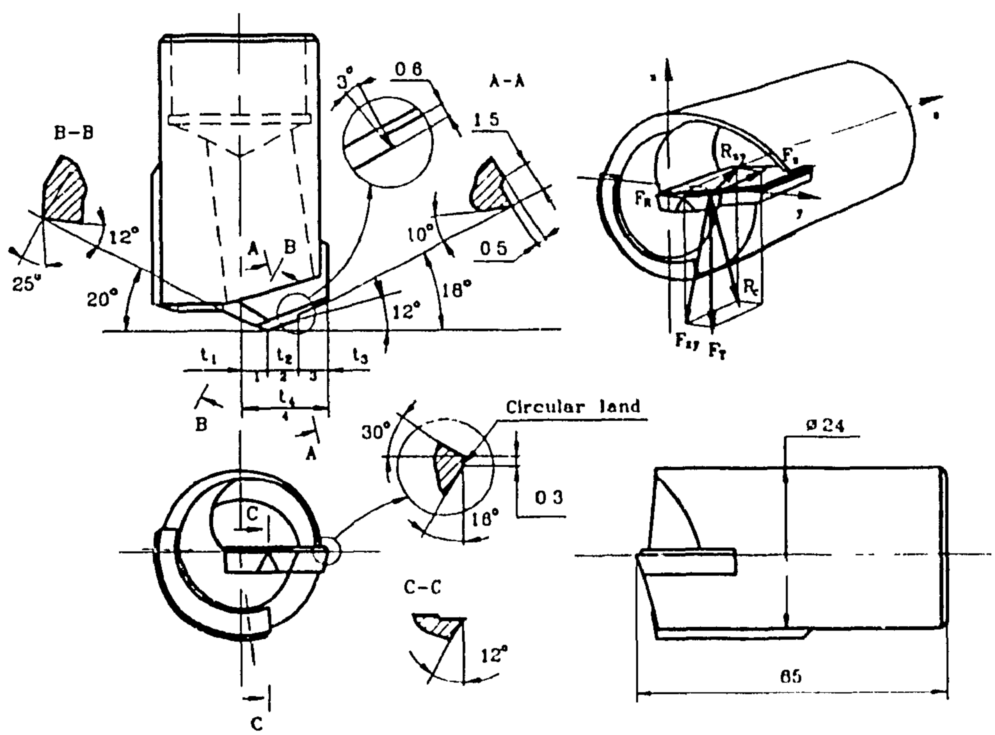


Figure 3.4 Design and geometry of BTA drill used in the experiment
(showing the cutting force components)

MILL TEST REPORT

SOLD TO

RTEL METAL & PLASTIQUE, INC
5 BOUL DES ENTERPRISES
RRE BONNE
EBEC, CANADA J6W5C7

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SHIP TO

VARTEL METAL & PLASTIQUE, INC
365 BOUL DES ENTERPRISES
TERRE BONNE
QUEBEC, CANADA J6W5C7

00000

GRADE	SIZE	PROD	HEAT NO	C	Mn	Si	S	P	V	Cu	Ni	Cr	Mo	Pb	CUST PART #
45	2 1/4	TGP	444433	.46	.75	.22	.018	.009	[illegible]						
45	1 1/8	TGP	134534	.46	.82	.30	.040	.020	.003						
45	1 15/16	TGP	135664	.47	.70	.24	.030	.010	.002						
45	1 11/16	TGP	226275	.44	.80	.23	.040	.020	.002						
15	1 3/4	[illegible]	225789	.43	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
5	2 3/4	TGP	408993	.44	.73	.24	.013	.007							
5	3	TGP	412632	.46	.76	.24	[illegible]	[illegible]	[illegible]						
5	1 3/4	TGP	540371	.49	.71	.28	.040	.010	.001						
15	[illegible]	TGP	540835	.44	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
5	1 1/4	TGP	541550	.46	.74	.22	.030	.010	.002						
5	[illegible]	TGP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
5	1 1/2	TGP	542911	.45	.72	.20	.020	.010	.001						
5	[illegible]	TGP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						

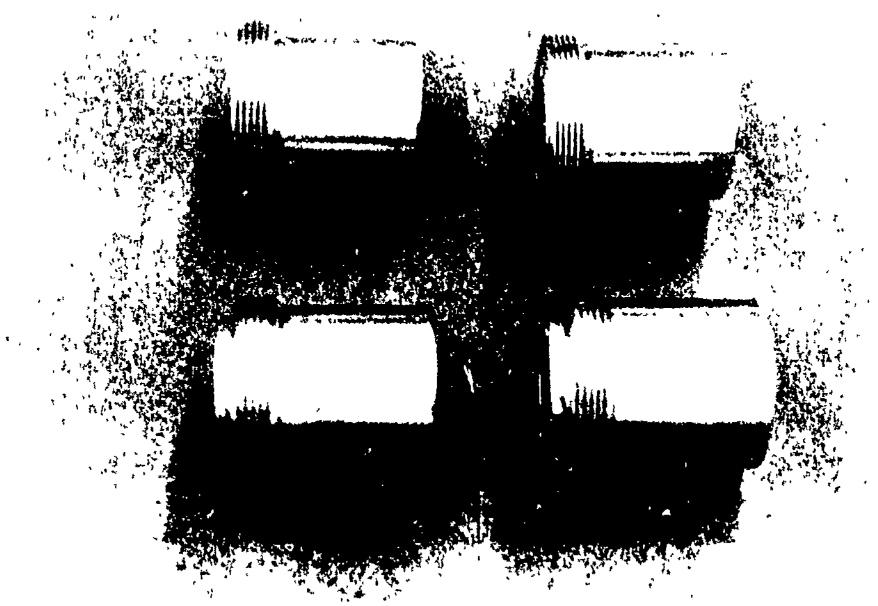
CHAPTER 4

Experimental Study of Bell Mouth Formation

4.1 Experimental setup

The machine used to conduct experiments is the same one described in Chapter 3. BTA drills 7/8 (22.225 mm) diameter (described in chapter 3) were tested on the regime chosen from Table 4.1. Workpiece material was hot rolled medium carbon steel *ASTM 1045*. The composition, the element limits and the deoxidation practice were checked to be corresponding to the requirements of the standard *ANSI/ASME B94.55M-1985*. The test bars after been cut to length (*40 mm dia, 1.0 m* length) were normalized to Brinell hardness of *200 HB*. The hardness of the work material was determined over the complete cross-section of the end of each test bar and cutting tests were conducted only on the bars where the hardness lied within the limits ± *10%*. A special parameters as the microstructure, grain size, inclusion count, etc. were checked using the quantitative metallography, acertificate of the material properties from the manufacturer is provided at the end of this chapter. From Table 4.1, it can be seen that the effect of three factors on bell mouth formation were studied (experiment 1). The first factor is the clearance between the tool and the starting bush which is the difference between the radius of the starting bush and the radius of the tool (clearance = *c*). starting bushes with different diameters (result in different clearances) are shown

Figure 4.1 : Starting bushes with different diameters and lengths



in Figure 4.1. The second factor is the distance between the face of the starting bush and the face of the workpeice (distance = f), starting bushes with different lengths (result in different face distances) are shown in Figure 4.1. The third factor is feed (s). Drill's rotating speed (v) is maintained on 85 m/min (1420.28, min^{-1}), coolant supply (Q) is also taken as a constant and maintained on 80 l/min (21.33, G/min).

Table4.1: Levels of factors and their intervals of variation (Bell Mouth tests)

Levels of Factors	Notation	c, mm x_1	f, mm x_2	s, mm/rev (s_m, mm/min) x_3
Basic	*0*	0.015925	3.000	0.07 (116.96)
Interval of Variation	x_i	0.009575	2.000	0.02 (101.93)
Upper Limit	+*1*	0.0255	5.000	0.09 (172.94)
Lower Limit	-*1*	0.00635	1.000	0.05 (71.01)

4.2 Experiment 1

On each point of the design plan, experiment were repeated three times. The sequence of experiments should be randomized. Randomization ensures that replicate runs are at the same experimental conditions and the variation between runs and bias are eliminated or considered at all conditions. The results of bell mouth (y)(the maximum difference between bell mouth diameter and the required diameter) are presented in the form of a matrix as shown in Table 4.2. The measuring device used in bell mouth measurements is shown in Figure 4.2.

Table 4.2: Test Results for Bell Mouth Formation Units in mm

points of plane, u	y_1	y_2	y_3	y_u average rsponse	s^2_u row variances
1	0.4572	0.5588	0.5588	0.5248	0.003441
2	0.5588	0.4572	0.5080	0.5080	0.002581
3	0.5334	0.5334	0.4572	0.5080	0.001935
4	0.5334	0.5080	0.4826	0.5080	0.000645
5	0.7874	0.7874	0.7620	0.7788	0.000215
6	0.6604	0.7620	0.6350	0.6858	0.004516
7	0.6350	0.7874	0.5842	0.6690	0.011183
8	0.8128	0.7112	0.6858	0.7366	0.004516

4.2.1 Data Analysis

Obtaining the mathematical model : Regression coefficient can be obtained using the procedure of the proposed method presented in Chapter 3

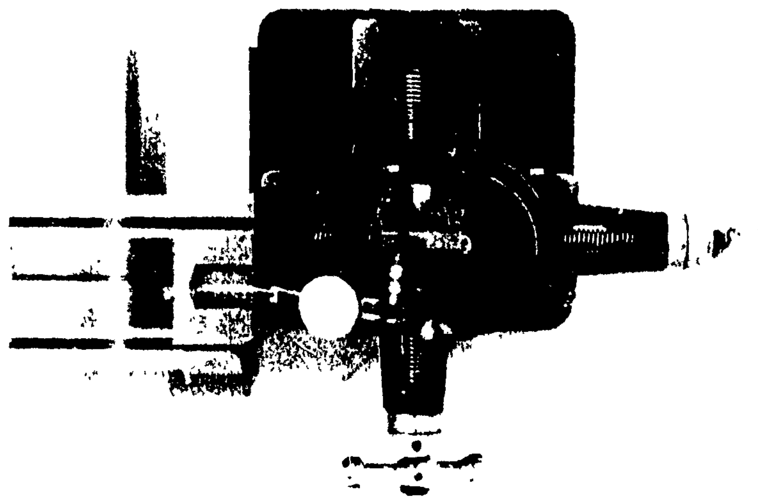


Figure 4.2 : Measuring device used in bell mouth measurement

$$b_1 = \frac{\sum_{u=1}^{8} x_{1u}\overline{y_u}}{8} =$$

$$\frac{1}{8}(-0.5248 + 0.508 - 0.508 + 0.508 - 0.7788 + 0.6858 - 0.669 + 0.7366) =$$

$$= -0.00529162$$

$$b_2 = \frac{\sum_{u=1}^{8} x_{2u}\overline{y_u}}{8} =$$

$$\frac{1}{8}(-0.5248 - 0.508 + 0.508 + 0.508 - 0.7788 - 0.6858 + 0.669 + 0.7366) =$$

$$= -0.00952487$$

$$b_3 = \frac{\sum_{u=1}^{8} x_{3u}\overline{y_u}}{8} =$$

$$\frac{1}{8}(-0.5248 - 0.508 - 0.508 - 0.508 + 0.7788 + 0.6858 + 0.669 + 0.7366) =$$

$$= 0.102658$$

$$b_{12} = \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8} =$$

$$\frac{1}{8}(0.5248 - 0.508 - 0.508 + 0.508 + 0.7788 - 0.6858 - 0.669 + 0.7366) =$$

$$= 0.0222249$$

$$b_{13} = \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8} =$$

$$\frac{1}{8}(0.5248 - 0.508 + 0.508 - 0.508 - 0.7788 + 0.6858 - 0.669 + 0.7366) =$$

$$= -0.00105838$$

$$b_{23} = \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8}$$

$$\frac{1}{8}(0.5248 + 0.508 - 0.508 - 0.508 - 0.7788 - 0.6858 + 0.669 + 0.7366)$$

$$= -0.00529163$$

$$b_{123} = \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8} =$$

$$\frac{1}{8}(-0.5248 + 0.508 + 0.508 - 0.508 + 0.7788 - 0.6858 - 0.669 + 0.7366)$$

$$= 0.0179916$$

Calculation of b_0 is conducted using the same rule:

$$b_0 = \frac{\sum_{u=1}^{8} x_{iu}\overline{y_u}}{8} =$$

$$\frac{1}{8}(0.5248 + 0.508 + 0.508 + 0.508 + 0.7788 + 0.6858 + 0.669 + 0.7366)$$

$$= 0.614875$$

b_0 = 0.614875; b_1 = -0.00529162; b_2 = -0.00952487; b_3 = 0.0102658; b_{12} = 0.0222249; b_{13} =

$-0.00105838;\ b_{23} = -0.00529163;\ b_{123} = 0.0179916.$

Then, the equation in the transformed variables becomes:

$$\hat{y} = 0.614875 - 0.00529162x_1 - 0.00952487x_2 + 0.102658x_3 + 0.0222249x_1x_2 - 0.00105838x_1x_3 - 0.00529163x_2x_3 + 0.0179916x_1x_2x_3 \quad (4.1)$$

4.2.2 Statistical examination of the results

(1) *Calculation of the Row Variances and Variance of the Response.*

The row variances are calculated using the data from Table 4.2 by the following formula:

$$s_i^2 = \frac{\sum_{j=1}^{r} (y_{ij} - \overline{y_i})^2}{r - 1} \quad (4.2)$$

$$s_1^2 = \frac{(0.4572 - 0.5248)^2 + (0.5588 - 0.5248)^2 + (0.5588 - 0.5248)^2}{3-1} = 0.00344085$$

$$s_2^2 = \frac{(0.5588 - 0.5080)^2 + (0.4572 - 0.5080)^2 + (0.5080 - 0.5080)^2}{3-1} = 0.00258064$$

$$s_3^2 = \frac{(0.5334 - 0.508)^2 + (0.5334 - 0.508)^2 + (0.4572 - 0.508)^2}{3-1} = 0.00193548$$

$$s_4^2 = \frac{(0.5334 - 0.508)^2 + (0.508 - 0.508)^2 + (0.4826 - 0.508)^2}{3-1} = 0.00064516$$

$$s_5^2 = \frac{(0.7874 - 0.7788)^2 + (0.7874 - 0.7788)^2 + (0.7620 - 0.7788)^2}{3-1} = 0.000215053$$

$$s_6^2 = \frac{(0.6604 - 0.6858)^2 + (0.7620 - 0.6858)^2 + (0.6350 - 0.6858)^2}{3-1} = 0.00451612$$

$$s_7^2 = \frac{(0.6350 - 0.6690)^2 + (0.7874 - 0.6690)^2 + (0.5842 - 0.6690)^2}{3-1} = 0.0111828$$

$$s_8^2 = \frac{(0.8128 - 0.7366)^2 + (0.7112 - 0.7366)^2 + (0.6858 - 0.7366)^2}{3-1} = 0.00451612$$

The results of the calculations are shown in Table 4.2.

The variance of the response, $s^2\{y\}$, is the arithmetical average of n different variants of tests (that is the average variance), i.e.,

$$s^2\{y\} = \frac{\sum_{i=1}^{n} s_i^2}{n} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{r}(y_{ij} - \overline{y}_i)^2}{n(r-1)} \qquad (4.3)$$

For the considered case (using the data from Table 4.2) $s^2\{y\}$ =0.00362903

(2) ***Examination of variance homogeneity.***

$$G = \frac{0.0111828}{0.0290322} = 0.385185 \qquad (4.4)$$

Using the table of Cochran numbers, the critical Cochran number is found to be $G_{cr} = 0.61$, for $f_{max} = 2$ and $f_{den} = 24$ (the total number of the tests) degrees of freedom and at 5% level of significance. Since the experimentally defined value of G is less than G_{cr}, the variances are considered homogeneous.

(3) Examination of significance of the model coefficients.

$$s^2\{b_i\} = \frac{s^2(y)}{nr} \qquad (4.5)$$

with $f_t = n(r - 1)$ degrees of freedom.

In the considered case :

$$s^2(b_i) = \frac{0.00362903}{8 \cdot 3} = 1.5121 \cdot 10^{-4} \qquad s(b_i) = \sqrt{1.5121 \cdot 10^{-4}} = 0.0122 \qquad (4.6)$$

Using these data, t_i-*criterion* can be calculated by the following formula:

$$t_i = \frac{|b_i|}{s\{b_i\}} \qquad (4.7)$$

$$t_0 = \frac{0.614875}{0.012297} = 50.0045 \qquad t_1 = \frac{0.00529162}{0.012297} = 0.4303274 \qquad t_2 = \frac{0.00952487}{0.012297} = 0.77458$$

$$t_3 = \frac{0.102658}{0.012297} = 8.34843 \qquad t_{12} = \frac{0.0222249}{0.012297} = 1.80738 \qquad t_{13} = \frac{0.00105838}{0.012297} = 0.086069$$

$$t_{23} = \frac{0.00529163}{0.012297} = 0.430329 \qquad t_{123} = \frac{0.0179916}{0.012297} = 1.46312$$

The critical value of t-criteria, t_{cr} is defined with $n(r - 1) = 16$ degrees of freedom and at significant level $\alpha = 5\%$. In the considered case $t_{cr} = 1.74$. Now, the mathematical model is represented by the equation including only significant coefficients. In our case:

$$\hat{y} = 0.614875 + 0.102658\ x_3 + 0.0222249\ x_1 x_2 \qquad (4.8)$$

To obtain the model in real values of variables, it is necessary to substitute the transformation Eq. (3.4) from Chapter 2 into Eq. (13). By doing this we get:

$$\hat{y} = 0.311035 - 3.48171c - 0.0184821f + 5.1329s + 1.16057cf \qquad (4.9)$$

Equation (4.9) reveals that in the presented case, and for the chosen upper and lower factor limits, the bell mouth formation in deep-hole drilling depends on feed, clearance, face distance, and the interaction between clearance and face distance.

(4) ***Adequateness of the model.***

$$s_{ad}^2 = \frac{r}{n - m}\sum_{u=1}^{n} (\overline{y_u} - \hat{y}_u)^2 \qquad (4.10)$$

$$F = \frac{s_{ad}^2}{s^2\{y\}} \qquad (4.11)$$

If the calculated value of F / F_{cr}, where F_{cr} is defined using a statistical table for corresponding degrees of freedom

$$f_{ad} = n - m \quad and \quad f_t = n(r - 1) \tag{4.12}$$

$$s_{ad}^2 = \frac{r}{n - m}\sum_{i=1}^{n}(\overline{y_i} - \hat{y}_i)^2 = \frac{3 \cdot 0.003773}{8 - 3} = 0.0022638 \tag{4.13}$$

at certain level of significance, α%, then the model is recognized to be adequate to the process under study. Otherwise, the model is recognized to be inadequate.

If the variance of adequateness, s^2_{ad}, does not exceed the variance of reproduction, $s^2\{y\}$, then $F < 1$, and the inequality $F < F_{cr}$ is valid for any number of degrees of freedom.

Calculation of the responses:

$\hat{y}_1 = 0.614875 - 0.102658 + 0.0222249 = 0.534459$

$\hat{y}_2 = 0.614875 - 0.102658 - 0.0222249 = 0.490009$

$\hat{y}_3 = 0.614875 - 0.102658 - 0.0222249 = 0.490009$

$\hat{y}_4 = 0.614875 - 0.102658 + 0.0222249 = 0.534459$

$\hat{y}_5 = 0.614875 + 0.102658 + 0.0222249 = 0.739775$

$\hat{y}_6 = 0.614875 + 0.102658 - 0.0222249 = 0.695325$

$\hat{y}_7 = 0.614875 + 0.102658 - 0.0222249 = 0.695325$

$$\hat{y}_8 = 0.614875 + 0.102658 + 0.0222249 = 0.739775$$

The result of calculations of $(\bar{y}_u - \hat{y}_u)$ is shown in Table 4.3 .

The estimation of s^2_{ad} is: *0.0022638*

Since in the considered case s^2_{ad} $s^2\{y\}$ *(0.0022638 0.00362903* then the model adequateness is obvious without using *F-criterion* calculations.

Table 4.3: Calculation of the estimated response

points of plane, u	$\bar{y}_u$ average response	$\hat{y}_u$ estimated response	$(\bar{y}_u - \hat{y}_u)^2$
1	0.524933	0.534459	0.000091
2	0.508000	0.490009	0.000324
3	0.508000	0.490009	0.000324
4	0.508000	0.534459	0.000700
5	0.778933	0.739775	0.001533
6	0.685800	0.695325	0.000091
7	0.668867	0.695325	0.000700
8	0.736600	0.739775	0.000010

4.3 Experiment 2

This experiment is to make sure that our decision to exclude cutting speed as a factor affecting bell mouth formation, is a reasonable one. We are going to investigate the effect of two factors on bell mouth formation. Feed (s) is taken as the first factor, cutting speed (v) is the second one. Factors levels are shown in Table 3.1. For two factors with two levels, 2^2 factorial design of experiment has to be done. The design matrix is shown in Table 4.4

Table 4.4 : 2^2 factorial design matrix

point of the matrix	x_0	$x_1(s)$	$x_2(v)$	x_{12}
1	+	-	-	+
2	+	+	-	-
3	+	-	+	-
4	+	+	+	+

The experiment was randomized, and three repetitions at each point of the design matrix were taken. The result of the experiment is shown in Table 4.5.

Table 4.5 : Experiment results for the bell mouth formation

point of the matrix	y_1	y_2	y_3	y_u average response	S_u^2 row variance
1	0.4318	0.508	0.4572	0.465667	0.00150537
2	0.8382	0.762	0.7874	0.795867	0.00150537
3	0.508	0.4572	0.508	0.491067	0.000860214
4	0.7366	0.6858	0.7366	0.719667	0.000860212

4.3.1 Data analysis and obtaining the mathematical model

Using a computer program written on C^{++} language, the data analysis procedure presented in Chapter 3 can be done easily. The results of analysis are:

$b_0=0.618067$

$b_1=0.1397$

$b_2=-0.0127$

$b_{12}=-0.0254$

$G=0.318182$, since this value is less than G_{cr}, the variances are considered homogeneous.

$s_y^2=0.00118279$

Using the t-criterion, the significant factors are b_0, b_1 and b_{12} Now the model is represented by the equation including only significant coefficients :

$$y = 0.618067 + 0.1397\ x_1 + 0.0254\ x_{12}$$

The mathematical model in real values of the variables is :

$$y = -0.46355 + 15.45175\ s + 0.0059267\ v - 0.084666\ sv$$

The final step is to check the adequateness of the model :

$$s_{ad}^2 = 0.00193548$$

$$F = \frac{s^2_{ad}}{s^2(y)} = \frac{0.00193548}{0.00118279} = 1.636368$$

If the calculated value of $F<F_{cr}$, then the model is recognized to be adequate to the process under study. F_{cr} = *5.32* using F-tables at the corresponding degrees of freedom and at 95% level of significance. The model is adequate.

From Figure 4.3 we can see that the minimum bell mouth can be achieved at the lower level of the cutting speed *(85 mm/min)*, and at the lower level of feed *(0.05 mm/rev)*. It can be seen from the obtained mathematical model and Figure 4.3 that cutting speed can be considered insignificant and can be fixed at *(85 mm/min)* its lower level which is the considered value in experiment 1. Feed rate has a significant influence on bell mouth formation, this influence is also shown in the results of experiment 1. The interaction between feed and speed has also an appreciable effect on bell mouth formation which can be seen by the obtained mathematical model.

4.4 Some observations on bell mouth formation

Measurements of the length of the bell mouth were done, these measurements were carried on the drilled workpieces in experiment 1. All measurements are between *2.5* and *2.85 mm*. Therefore, we conclude that the length of the bell mouth has a maximum value of *2.85 mm* for a tool diameter of *7/8" (22.225 mm)*. Figure 4.4 shows the variation of bell mouth diameter a long its length (from the entrance until the end of the bell mouth), this figure gives an idea about the shape of the bell mouth. Two Figures 4.5, 4.6 are also provided which show that bell mouth has variable shape depending on the test conditions. Three different points in the design matrix were chosen, the

Figure 4 3 Response Surface for Bell Mouth Variation with Speed and Feed

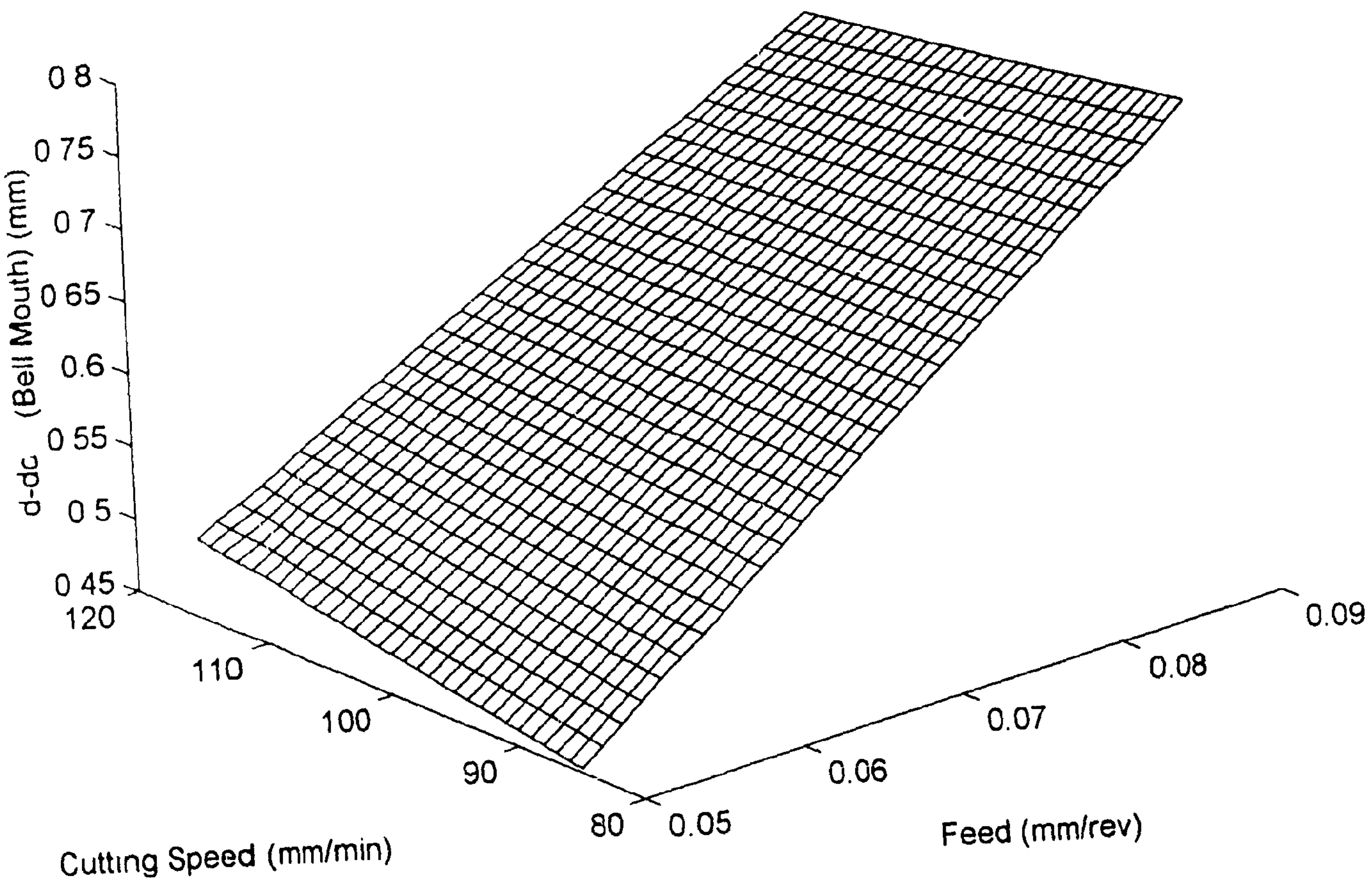


Table 4.6 The bell mouth diameter variation along its length

Point 1 in the design matrix				
a (mm)	Y11 (mm)	Y12 (mm)	Y13 (mm)	Y1(ave) (mm)
0	0.4572	0.5588	0.5588	0.5248
0.508	0.2794	0.2921	0.2866	0.2860
1.016	0.2032	0.2413	0.1937	0.2127
1.524	0.1397	0.1397	0.1016	0.1270
2.032	0.0889	0.0508	0.0381	0.05927
2.54	0.0254	0.0127	0.0127	0.01693
2.794	0	0	0	0
Point 6 in the design matrix				
a (mm)	Y61 (mm)	Y62 (mm)	Y63 (mm)	Y6(ave) (mm)
0	0.6604	0.7620	0.6350	0.6858
0.508	0.508	0.4826	0.4445	0.4781
1.016	0.4318	0.2940	0.2797	0.3352
1.524	0.3556	0.1778	0.2995	0.2776
2.032	0.2032	0.1270	0.1970	0.1757
2.54	0.0254	0.01016	0.0508	0.02879
2.664	0	0	0.00889	0.0030
Point 5 in the design matrix				
a (mm)	Y51 (mm)	Y52 (mm)	Y53 (mm)	Y5(ave) (mm)
0	0.7874	0.7874	0.7620	0.7788
0.508	0.6477	0.5842	0.5334	0.5184
1.016	0.3175	0.4826	0.3429	0.3810
1.524	0.1650	0.2794	0.2032	0.2159
2.032	0.0889	0.1016	0.0889	0.09313
2.54	0	0.0254	0.0127	0.0127

experiment was repeated three times at each point, the average of these repetitions was considered in Figures 4.4, 4.5, 4.6. These measurements are shown in Table 4.6, the first column is the distance from the entrance (a), columns from the second to the fifth are the three repetition of the bell mouth measurements and their average.

One of the important observations is that the roughness within the bell mouth is higher than any where else a long the hole length. Table 4.7 shows a comparison between the roughness within the bell mouth and *20 mm* after the end of the bell mouth. Three repetitions were taken at each point in the design matrix, and three measurements of roughness were taken at three different locations within the bell mouth, then the average of these measurements is considered in the second column of Table 4.7. The factors considered are described in Table 3.1, and the design matrix is shown in Table 4.4. This table shows that roughness increases 2-5 times when the measurement is taken within the bell mouth region.

Table 4.7 : A comparison between roughness within bell mouth and roughness of the machined after the bell mouth region.

point of the matrix	x_1 (v)	x_2 (s)	R_a (within the bell mouth) μm	R_a (after the bell mouth) μm
1	-	-	1.15	0.61
2	+	-	0.97	0.36
3	-	+	1.11	0.22
4	+	+	0.93	0.31

Figure 4 4 The variation of Bell Mouth Diameter Along its Length

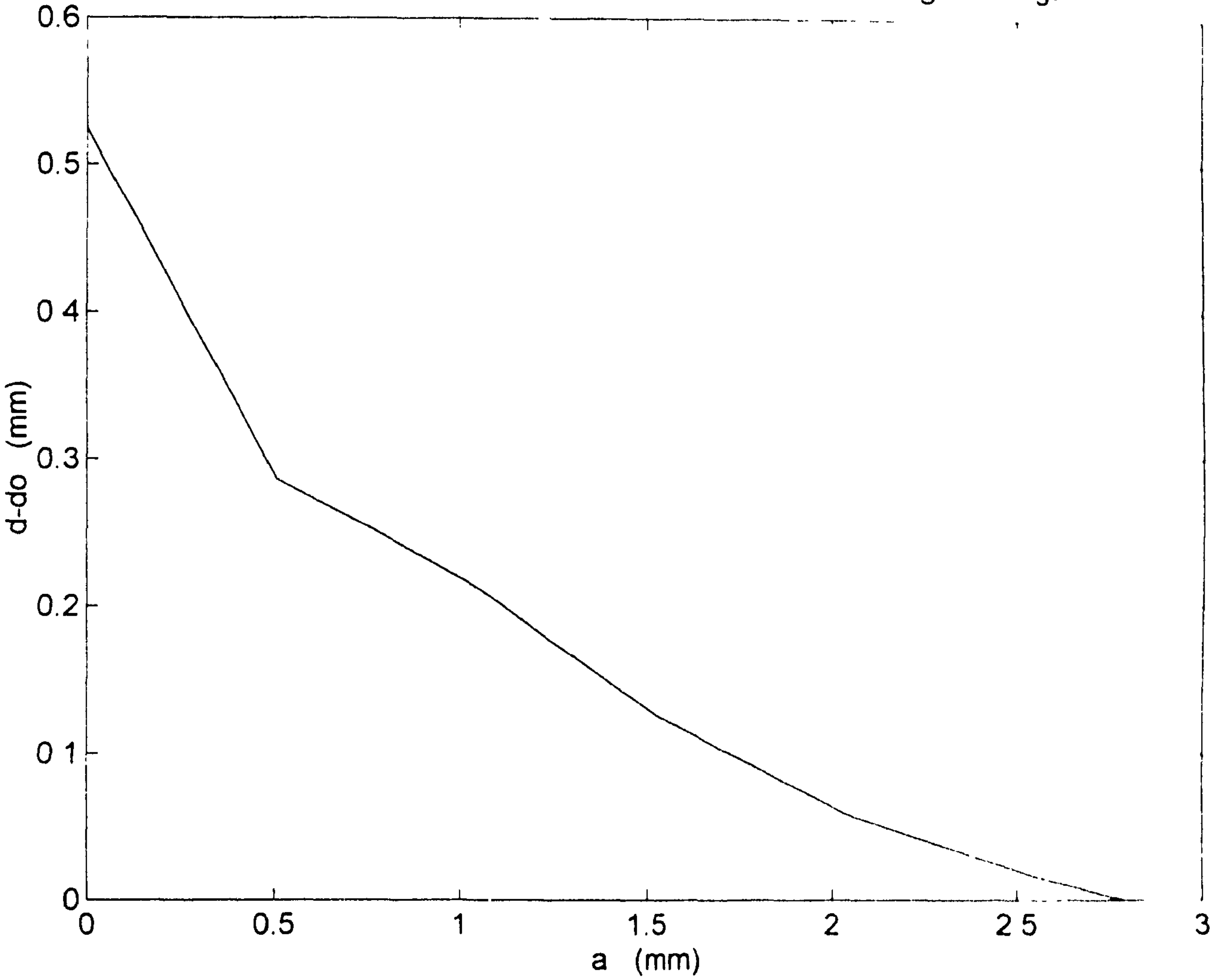


Figure 4.5 The variation of Bell Mouth Diameter Along its Length

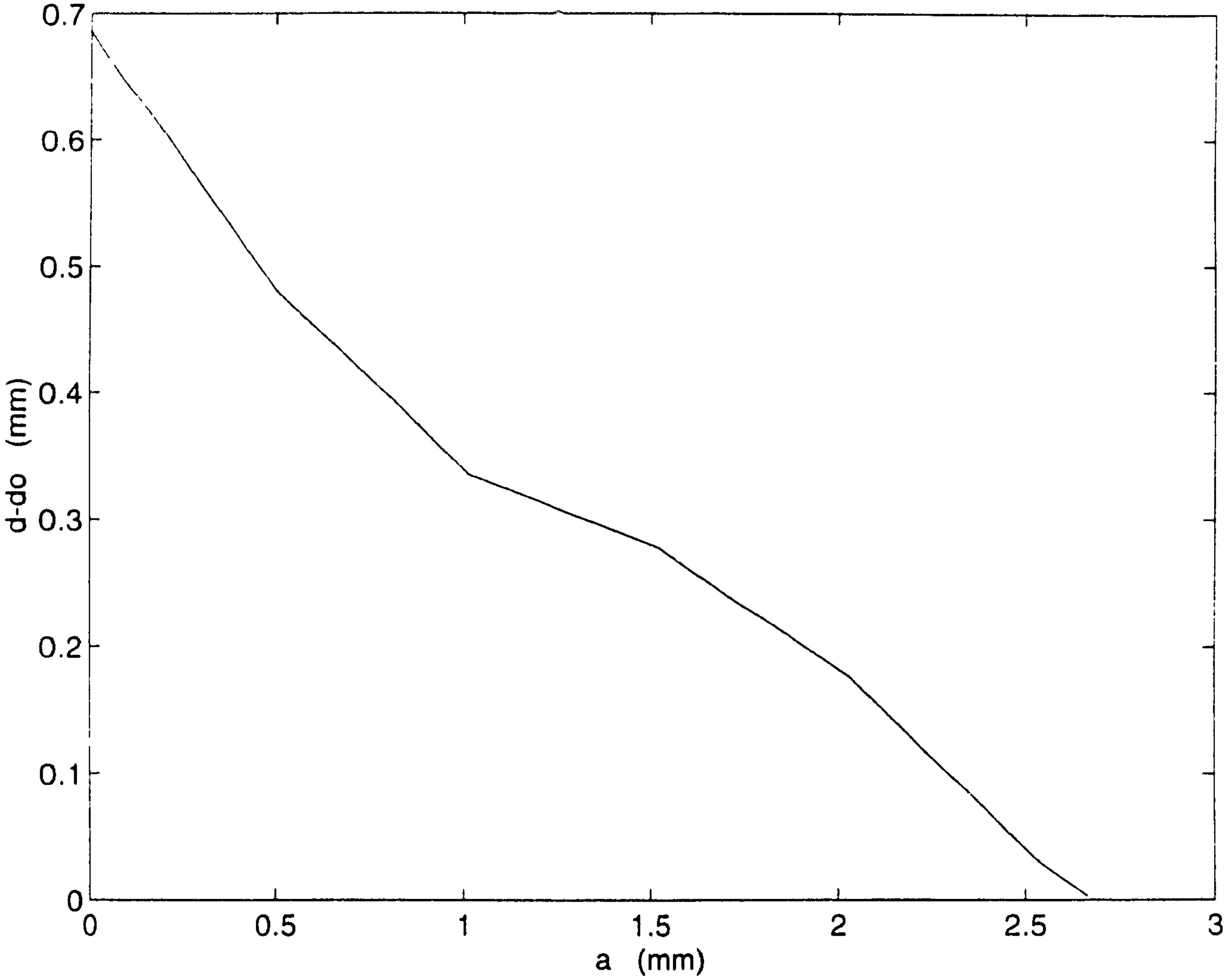
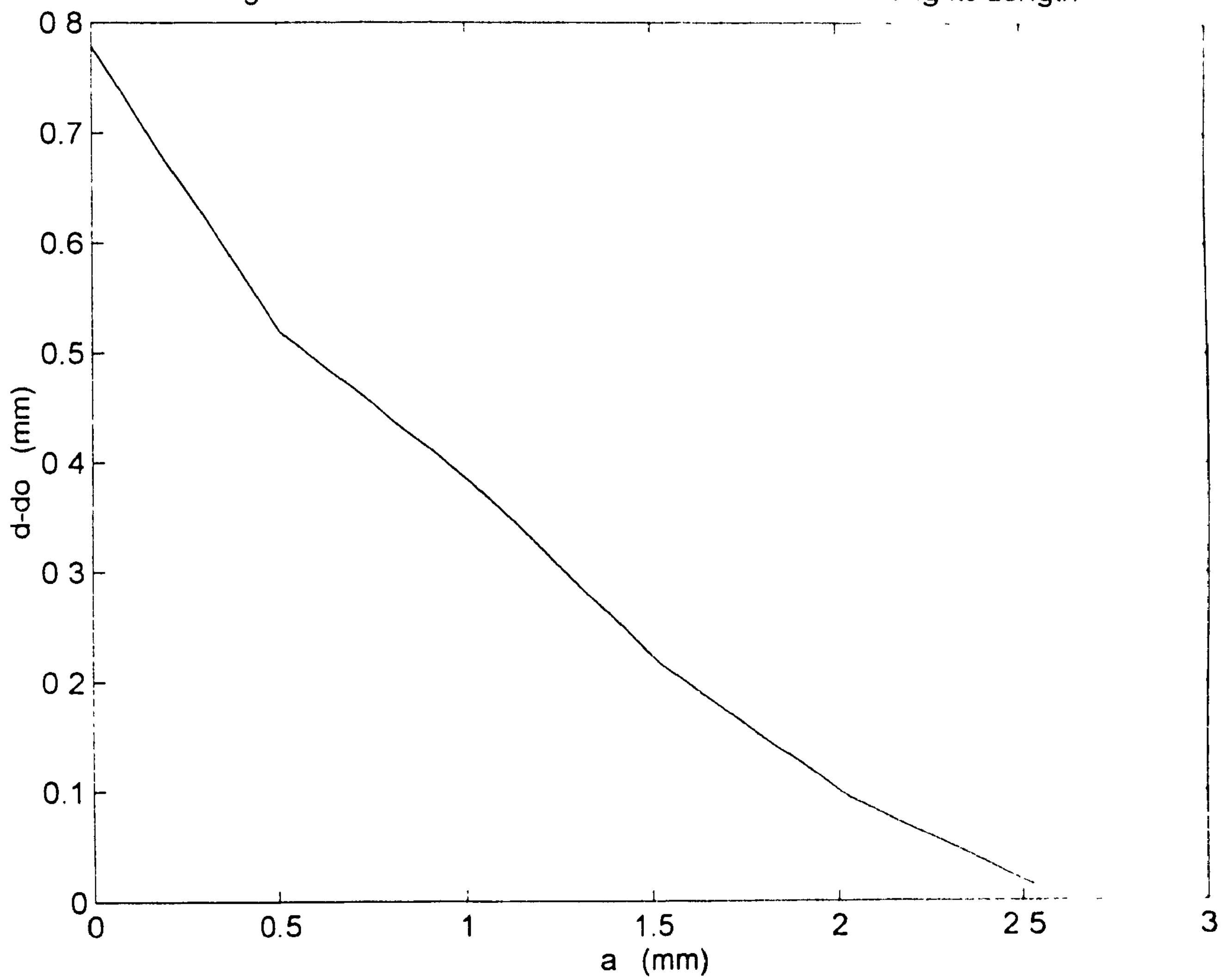


Figure 4 6 The variation of Bell Mouth Diameter Along its Length



CHAPTER 6

CONCLUSIONS

In metal cutting, because of the lack of methodological study, the DOE has not been widely used. Any new field of DOE application requires a special, and careful approach. The experience gained in the statistical studies in one field cannot be automatically applied on another, even on a close one. A 2^k factorial experiment, complete block was chosen as the basic type of the design of experiments in metal cutting. Several distinguished features of this kind of DOE, such as the design matrix symmetry and its orthogonality, provide the independent estimations of the chosen mathematical model coefficients and enable an experimentalist to quantitatively estimate the possible non-linearities such as the factors interactions.

An important stage in DOE is the selection of POO. POO should be effective, easily measured, and single-valued function of the chosen parameters. Only essential factors should be included into consideration in DOE. Such factors can be quantitative or qualitative, but both should be controllable, and their combinations used in DOE should be compatible.

The mathematical model in DOE represents a response surface. Within DOE such a surface is assumed to be continuous, two times differentiable, and have only one extreme. At the early stage of DOE, a response surface is assumed to be linear (hyperplane, hypercube, etc.), that enables an experimentalist to define the direction of variation of the POO. At later stages of DOE when the stationary region of POO is achieved, a response surface of second, or even third order is more suitable.

The range of a factor variation in DOE is a matter of an experimentalists experience. On one hand, this range should be wide enough to detect the influence of this factor on POO, on the other hand, this range should be compatible with the ranges of other included factors

The use of DOE in metal cutting experiments requires a special attention to the accuracy in testing procedure. Such attention includes minimization of the influence of uncontrollable process parameters by using the workpiece material from the same batch, calibration of tools, and randomization of tests within the experiment.

Chapter 4 establishes the relationship between the basic input and output parameters in BTA deep-hole drilling using DOE. It has proven that a 2^k factorial experiment, complete block type of DOE can be used for studying the experimental relationships in metal cutting The obtained mathematical model is a regression equation, thus, it should be statistically analyzed Such an analysis includes the examinations of variance homogeneity, the significance of the model coefficients and the model adequateness. A method to examine the variance homogeneity using Cochran criterion instead of F-criterion has been proposed.

The DOE with the transformation of POO provides the way of using a 2^k factorial experiment for the study of the tool life and the cutting forces. Even though such transformation is not very strict from the statistical point of view and estimations found to be biased, the experience of the metal cutting experimental study shows that such transformation may be accepted in most cases

In order to apply methodology of DOE in metal cutting, a comprehensive analysis of BTA deep-hole machining was carried out. This is the first time that the cutting fluid flow rate is taken into consideration when studying the machined holes quality. The machined holes roughness was found to be dependent on the cutting speed, feed, and their combination. The roundness of the machined holes depends not only on the regime's parameters but also on the cutting fluid flow rate. Even though the cutting speed, feed and cutting fluid flow rate have significant influence on roundness, but they cannot be judged individually since their interactions exist. The tool life, as was expected, depends mainly on the cutting speed, while the cutting force components depend mainly on the feed. The optimal settings to achieve minimum roughness and minimum out of roundness are at the lower level of speed *(85 mm/min)*, the upper level of feed *(0 09 mm/rev)*, and the upper level of cutting fluid *(80 l/min)*.

The bell mouthing is the process of the formation of the entrance part of the hole being drilled. The most noticeable phenomenon in deep hole machining with self-piloting tools(at least it was pointed earlier by some researchers), is the bell mouth, that is the machined hole entrance has a tapered shape, the diameter of this part is usually out of tolerance, the surface finish, depending on particular conditions of machining, has different appearance, but always much worse than the surface finish of the other part of the machined hole. The working conditions of a self-piloting tool at the period of bell-mouthing are very different from those that thought by a tool designer. Often, the auxiliary cutting edge gains the transverse feed (normal to the direction of the longitudinal working feed). Experience shows that the result of these working conditions are the elevated rate of tool wear, the tool and workpiece vibration that can lead even to the tool breakage, and the present of small, even tiny chips cut by the auxiliary cutting edge.

The bell mouthing is the least studied phenomenon in the self-piloting machining. This can be explained by its complexity, changing appearance from one working method to another, from one given set of technological parameters to other, etc. Consequently, there is no clear understanding of the influence of the different working methods on the machined hole accuracy. There are so many contradictions in the available data that the impression is formed that the proper choice of the process parameters is a matter of luck rather than the knowledge-based decision. As a result, the parameters of the machined hole accuracy mentioned in technical catalogs and other sources are rather the best randomly and separately achieved results than the common practice. Definitely, such a state formed the negative impression about this process and its great ability to produce precise holes.

The tool and the machine tool parameters play an important role in the formation of a precise hole. There are several parameters affecting the bell mouth formation: the clearance between the starting bush and the tool, the distance between the workpiece and starting bush faces, the misalignment of the starting bush and workpiece longitudinal axes, the working method to be used, and feed. Three of the above mentioned factors were considered when the bell mouth formation in deep hole machining were studied using the proposed method of statistical design of experiment. Stationary workpiece-rotating tool is the working method that used in conducting the experiments. From the obtained mathematical model (Eq. 4.9), it can be seen that the minimum bell mouth is achieved at the lower level of feed *(0.05 mm/rev)*. Also, to obtain minimum bell mouth there are two optimal settings of clearance (c) and distance (*f*), the first is the lower level of *c (0.00635 mm)* and the upper level of *f (5.00 mm)*, the second is the upper level of *c (0.0255 mm)* and the lower level of *f (1.00 mm)*.

From figure 5.3 it can be seen that the minimum bell mouth can be achieved at the lower level of the cutting speed *(85 mm/min)*, and at the lower level of feed *(0.05 mm/rev)*. It can be seen from the obtained mathematical model and Figure 5.3 that cutting speed can be considered insignificant and can be fixed at *(85 mm/min)*. Feed rate has a significant influence on bell mouth formation, and this influence is also shown in the results of experiment 1. The interaction between feed and speed has also an appreciable effect on bell mouth formation which can be seen from the obtained mathematical model.

Measurements of the length of the bell mouth were done, these measurements were carried on the drilled workpieces in experiment 1. In all measurements the length of the bell mouth did not exceed *2.85* mm. Therefore, the length of the bell mouth has a maximum value of *2.85 mm* for a tool diameter of *7/8" (22.225 mm)*. Figure 5.4 shows the variation of bell mouth diameter along its length (from the entrance to the end of the bell mouth), also this figure gives an idea about the shape of the bell mouth. Two figures 5.5, 5.6 are also provided which show that bell mouth has variable shape depending on the test conditions.

One of the important observations is that the roughness within the bell mouth is higher than any where else a long the hole length. Table 5.6 shows a comparison between the roughness within the bell mouth and the roughness of the machined surface *(20 mm* after the end of the bell mouth region). This table shows that the roughness within the bell mouth region is much worse than the roughness of other parts of the drilled hole.

A significant amount of indepth study has been conducted into the effect of machining conditions and factors on hole accuracy in deep hole machining. A developed methodology in statistical design of experiment has been applied on deep hole machining. Even though this has resulted in significant knowledge regarding the statistical design of experiment in machining processes and the accuracy of the machined hole, further research is necessary to produce a complete and comprehensive knowledge on the applicability of this developed method and the effect of the considered factors on the hole accuracy. In order to bring forward significant changes in deep hole machining, all experimentations should be statistically designed and the effect of the factors affect the response should be studied at the same time.

REFERENCES

[1] Griffiths B. J, "An Investigation into the Role of the Burnishing Pads in the Deep Drilling Process," Ph.D. Thesis, 1982, Brunel University, UK.

[2] Swinehart H. J., "Gundrilling, Trepanning, and Deep Hole Machining," ASTME, Dearborn, 1967.

[3] Griffiths B. J, "Introduction to Deep Hole and Boring, International Conference on Deep Hole Drilling and Boring," Brunel University, 22-23 May, 1975.

[4] Steeds W., "A History of Machine Tools 1700-1910," Oxford press, 1969.

[5] Subramanya P. S., "Expert Control of Deep Hole Machining System," Ph.D. Thesis, 1994, Concordia University, Canada.

[6] Astakhov V.P., Subramanya P.S., and Osman M.O.M., "An Investigation of the Cutting Fluid Flow in Self-Piloting Drills," Int. Journal Mach. Tools Manufact., Vol. 35, No. 4,1995, pp. 547-563.

[7] Greuner B., "The Technology of BTA Process," International Conference on Deep Hole Drilling and Boring, Brunel University, 22-23 May, 1975.

[8] Thomas Geoffrey G., "Engineering Metrology," 1974, Butterworths, London.

[9] Ramakrishna P.K., and Shunmugam M.S., "Accuracy and Surface Finish in BTA Drilling," International J. Prod. Res., 1987, Vol. 25, No. 1, 31-44.

[10] Scarr J.T., "Metrology and Precision Engineering," 1967, McGraw Hill, London.

[11] Mitutoyo, "Surftest 501 series 178 Surface Texture Parameters manual No. 4386."

[12] El-Khabeery M.M., and Ramadan M.R., "Some Observations of Surface Integrity of Deep Drilling Holes," Wear, 142, 1991, 331-349.

[13] Sukuma K., Taguchi K., and Katsuki A., "The Burnishing Action of Guide Pads and their Influence on Hole Accuracies," 1980, Bulletin of JSME.

[14] George Box, and Soren Bisgaard, "The Scientific Context of Quality Improvement," 1987, Report No. 25, Centre for Quality and Productivity Improvement, University of Wisconsin, Madison.

[15] Mittag H.J., and Rinne H., "Statistical Methods of Quality Assurance," 1993, Chapman and Hall.

[16] Rayan T.P., "Statistical Methods for Quality Improvement," 1989, Wiley.

[17] Astakhov V.P., Galitsky V.V., and Osman M.O.M., "An Investigation of the Static Stability in Self-Piloting Drilling," Int. Journal of Production Research, 1995 (in press).

[18] Wu S.M., "Statistical Methods for Manufacturing engineers," 1983, The Winter Annual Meeting of the American Society of Mechanical Engineers, Boston, Massachusetts.

[19] Goforth R.eE., and Kulkarni N.A., "In-process Tool Life Evaluation by Cutting Force Ratio Analysis -part 1," 1983, The Winter Annual Meeting of the American Society of Mechanical Engineers, Boston, Massachusetts.

[20] Montgomery D.C. "Design and Analysis of Experiments," 1976, New York: John Wiley and Son, Inc.

[21] Davies O. L. (Ed.) "Design and Analysis of Industrial Experiments," 1971, New York: John Wiley and Son, Inc.

[22] Diamond W.J. "Practical Experimental Design," 1981, Belmont, CA: Wandsworth, Inc.

[23] Cochran W,G. and Cox D.R. "Experimental Design," 1957, New York: John Wiley and Son, Inc.

[24] Jonson N.L., and Leone F.C. "Statistics and Experimental Design in Engineering and the Physical Sciences," 1977, New York: John Wiley and Son, Inc.

[25] Mason R.L., Gunst R.F., and Hess J.L. "Statistical Design and Analysis of Experiments with Application to Engineering and Science," 1989, New York: John Wiley and Son, Inc.

[26] Trent, E.M., 1991, "Metal Cutting" Butterworth-Heinemann Ltd.

[27] Astakhov V.P., and Shalafman N.L. "Mathematical Modelling of Machine Tools and Machine Tool Complexes," (in Russian), 1992, Odessa:OPU.

[28] Astakhov V. "Mathematical modelling of metal cutting process," (in Russian), *Metallorezushie stanky*, **25**, 1994, p.35.

[29] Astakhov V.P., Evtifeev S.L. et al. "Method of detecting the hidden surface defects on carbide inserts." *USSR patent No 1667491*, 1991, GKNT USSR.

[30] Astakhov V.P., Frazao J., and Osman M.O.M. "On the experimental optimization of tool geometry for uniform pressure distribution in single edge gundrilling," *Trans. ASME Journal of Engr. for Industry*, Nov. 1994, Vol. 116, pp. 449-456.

[31] S. Chandrashekhar, M.O.M. Osman and T.S. Shakar "An Experimental Investigation for the Stochastic Modelling of the Resultant Force System in BTA Deep Hole Machining," *Int. J. Prod. Res*, Vol. 23, 1985, pp 697-711.

[32] Astakhov V.P. "Modelling of Cutting Force in Deep Hole Drilling" (in Russian). *Metallorezushie stanky*, Vol. 24, 1993, p.48-57.

[33] Astakhov V.P., and Osman M.O.M. "Tool Life Testing with self-piloting drills," (Working manual), Concordia University, 1993.

[34] Osman M.O.M., and Sankar T.S. "The Measurement of Surface Texture by Means of Random Function Excurcion Technique," Proc. 21at Int. Instrumentation Symp., May 19-21, 1975, Philadelphia, Pen.

[35] Bloch F., et al. "Gundrilling, Trepanning, and Deep-Hole Machining," ASTME, 1967, Dearborn, MI.

[36] Sacuma K., Taguchi K., and Kinjo S. "Study on Deep-Hole-Drilling with Solid-Boring Tools - The Effect of Tool Materials on the Cutting Performance -," Bulletin of the JSME, Vol. 21, No 153, 1978, pp. 532-539.

[37] An American National Standard "Tool Life Testing With Single-Point Turning Tools," *ANSI/ASME*

APPENDIX A

TAGUCHI METHOD

APPENDIX A

TAGUCHI METHODS

In this appendix we introduce the reader to Taguchi's quality engineering ideas, which for the most part have been enthusiastically received. This discussion is divided into two parts. The first one is his statistical procedures, which are somewhat controversial (Rayan 1989). The second is an application of Taguchi method on roughness of deep hole machining, and make a comparison between his method and the developed method presented in Chapter 3. Taguchi method and related procedures were discussed in Rayan 1989 chapter 14

A.1 Orthogonal arrays as Fractional Factorial

The relationship between the orthogonal arrays presented in Taguchi and Wu(1979) and fractional factorial designs will be discussed. Considering their 8-point orthogonal array shown in table A.1, we notice that the BC column is the negative of the product of the B and C columns. Therefore, we would actually be estimating -BC rather than BC (which is of no real consequence) similarly, we would be actually estimating -BD.

What is not clear from Table A.1 , however, is the alias structure. We know that non of the six effects that are to be estimated could be aliased among themselves since the columns are obviously pairwise orthogonal. It would be helpful, however, to know the alias structure, and the structure is not readily apparent from the array.

Table A.1 The L_8 Orthogonal Array for two levels

Treatment Combination	B	C	(-)BC	D	(-)BD	A	e
(1)	-1	-1	-1	-1	-1	-1	-1
ad	-1	-1	-1	1	1	1	1
ac	-1	1	1	-1	-1	1	1
cd	-1	1	1	1	1	-1	-1
b	1	-1	1	-1	1	-1	1
abd	1	-1	1	1	-1	1	-1
abc	1	1	-1	-1	1	1	-1
bcd	1	1	-1	1	-1	-1	1

Table A.2 2^{4-1} Design with I=ABCD

Treatment Combination	A	B	C	D	BC	BD	e
(1)	-1	-1	-1	-1	1	1	1
ad	1	-1	-1	1	1	-1	-1
bd	-1	1	-1	1	-1	1	-1
ab	1	1	-1	-1	-1	-1	1
cd	-1	-1	1	1	-1	-1	1
ac	1	-1	1	-1	-1	1	-1
bc	-1	1	1	-1	1	-1	-1
abcd	1	1	1	1	1	1	1

This is a potential weakness of the orthogonal array approach, as the equivalent fractional factorial design (if one exists) needs to be identified for the alias structure to be clear. It can be determined that this is actually a 2^{4-1} design with -ACD as the defining contrast (Rayan 1989). Therefore,, the alias structure can now be determined, which is as follows:

A = -CD	B = -ABCD	C = -AD	D = -AC
AB = -BCD	-BC = ABD	-BD = ABC	I = -ACD

We can see that the BC and BD interactions that are to be estimated are confound with three-factor interactions. Thus, if the BC and BD interactions were deemed as likely to be significant before the experiment is carried out, there is no problem in estimating them provided that the three-factor interactions are not significant. What could be quite risky, however, is the fact that three of the four main effects are aliased with two-factor interactions. The experimenter had better have a strong belief that those three interactions are not likely to be important. In other words, in using this design he would be assuming that two of the two-factor interactions are likely to be important (i.e., statistically significant), but not the others. That would be a rather bold assumption in the absence of data from a previous experiment.

This design can be improved, there is no need to confound main effects with two-factor interactions. We can always construct a 2^{4-1} (Table A.2) design in such a way that main effects are confound with three-factor interactions. We simply use ABCD as the defining contrast so that the alias structure is as follows:

A = BCD	B = ACD	C = ABD	D = ABC
BC = AD	BD = AC	AB = CD	I = ABCD

Of course, we now have the two-factor interactions that are anticipated as being important aliased with other two-factor interactions. This is better than having main effects aliased with two-factor interactions. If the estimates of the BC and BD effects were determined to be significant, additional design points could be used to disentangle BC from AD and BD from AC. [See appendix 12B of Box Hunter, and Hunter (1979) for general information concerning the selection of such additional points.]

A.2 Determining Optimal Conditions

For whichever type of design is used, it is desirable to use the resultant data to determine the best combination of levels of the process factors ("best" in terms of optimizing some function). This determination is not easily made, however.

Taguchi and Wu (1979) have used graphs of marginal averages in attempting to arrive at the optimal levels of the process factors. Marginal averages are obtained by computing the average of the response variable at each level of each process factor, while ignoring the other process factors. Unfortunately, this method will not identify optimum conditions, in general, but might identify conditions that are close to the optimum.

To illustrate, we shall assume that we have data from unreplicated design as in Table A.3(Rayan 1989, p.370). The marginal averages for A and B are given in Figure A.1. Following Taguchi and Wu, if we were to use marginal averages in determining the levels of A and B so as

Table A.3 Data from an unreplicated 3^2 design

		A		
		1	2	3
B	1	8	8	10
	2	6	8	11
	3	5	9	10

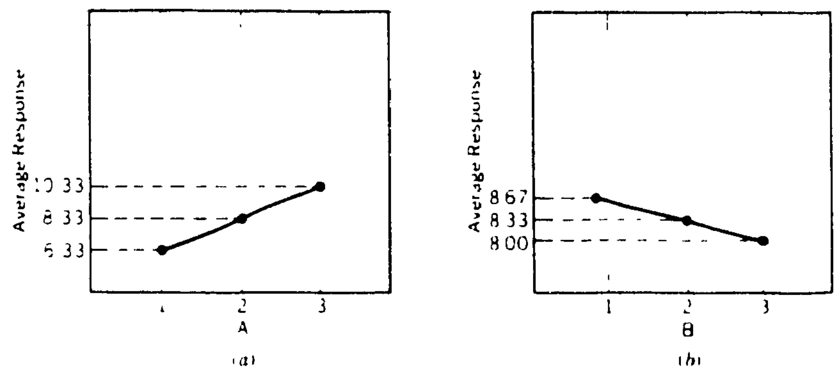


Figure A.1 Marginal averages for Table A 3

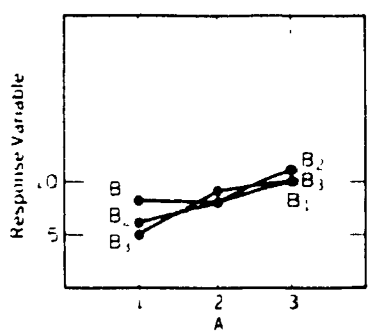


Figure A.2 Interaction profile for Table A.3

to maximize the response variable, we would use the third level of A and the first level of B, as can be seen from Figure A.1. It is apparent from Table A.3, however, that the maximum occurs with the second level of B, not the first. Notice that we do not miss the maximum by very much (for this example).

Of course, we can see in Table A.3 that all possible combinations of factors levels are used, and orthogonal arrays do not use all possible combinations. It should be clear, however, that since the marginal averages approach will frequently not work when we do have all combinations of factors levels, then obviously it will not work, in general, when we do not have all possible combinations. For this example the interaction profile is given in Figure A 2. We can see that the interaction is not extreme, and this is why the marginal averages approach closely approximates the maximum. Another example is given on Rayan 1989 p.372 shows that the marginal averages approach would lead to the selection of the fifth best combination. The reason is that the interaction between the considered factors is more pronounced.

To summarize, we have seen that the orthogonal arrays illustrated by Taguchi and Wu are often inferior to the better known and understood fractional factorial, and to maximize or minimize, it is logical to attempt to do so using known mathematical optimization procedure, rather than trying to rely upon graphs of marginal averages.

Taguchi's main contribution appears to be in focusing our attention on new objectives in achieving quality improvement. The statistical tools for accomplishing these objectives will likely continue to be developed.

A.3 Application of Taguchi Method on Roughness in Deep Hole Machining

The following experiment was designed using the Taguchi method to evaluate the effect of three factors: speed, feed rate, and cutting fluid on surface roughness in deep hole machining process. Two levels are selected for each factor and are listed in Table A.4

Table A.4: Factors and their levels

Factor	Level 1 (-)	Level 2 (+)	Unit
Speed (v)	85	115	m / min
Feed Rate (s)	0.05	0.09	mm / rev
Cutting Fluid (Q)	40	80	l / min

An orthogonal array L_4 as shown in Table A.5 is chosen for the design of experiments. It contains four different factor-combinations.

Table A.5: An experimental results using L_4 orthogonal array

Point	A = v	B = s	C = Q	y_1	y_2	y_3	y_{avg}
1	-	-	-	0.57	0.44	1.0	0.67
2	-	+	+	0.17	0.24	0.17	0.19
3	+	-	+	0.22	0.47	0.21	0.3
4	+	+	-	0.22	0.49	0.22	0.31

Statistical analysis of the data:

The results for surface roughness are shown in Table A.5. The experiment was repeated three times at each point. First compute the average effect of factor A at lower level, by adding the results of trials of factor A at its lower level and then divide by the number of trials. Looking at Table A.5 we find that the lower level of A occurs in points 1 and 2.

Let : A_L be factor A at lower level and

A_U be factor A at upper level, and so on for other factors.

$$A_L(ave) = \frac{0.67 + 0.19}{2} = 0.43$$

$$A_U(ave) = 0.305$$

$$B_L(ave) = 0.485$$

$$B_U(ave) = 0.25$$

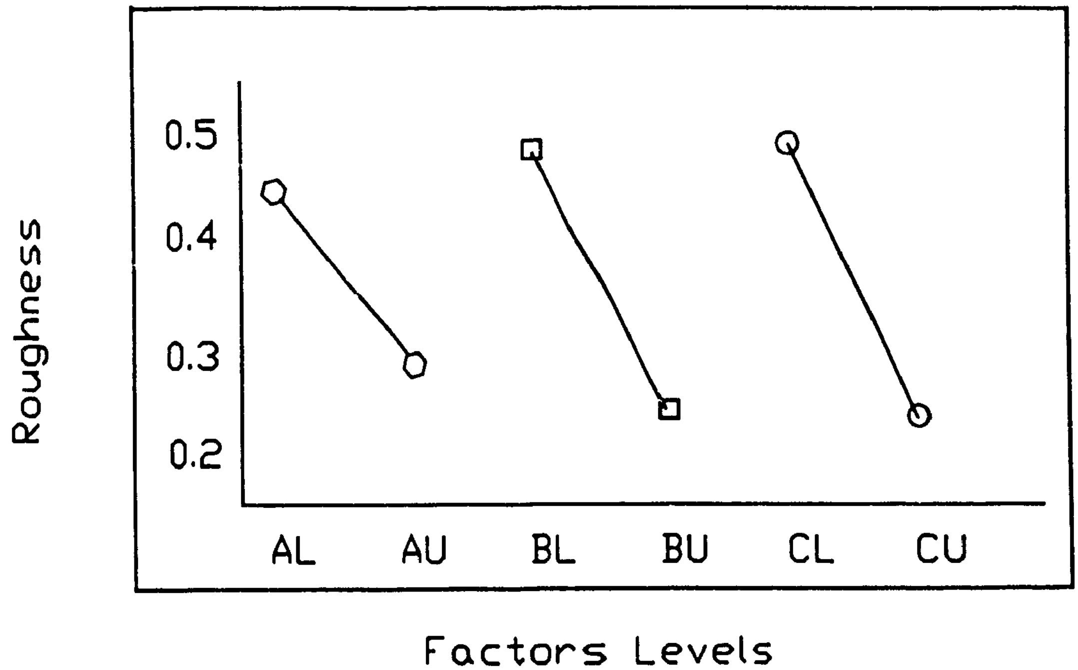
$$C_L(ave) = 0.49$$

$$C_U(ave) = 0.245$$

Using the above averages to generate Figure A.3 to show the effect of each factor on surface roughness. This figure shows that minimum roughness can be achieved at the upper level of speed (115 mm/min), the upper level of feed (0.09 mm/rev), and the upper level of cutting fluid (80 l/min).

- **Total number of experiments (n)** = r 4 = 3 4 = 12
- **T (Sum of all trials)** = 0.57 + 0.44 + 1.0 + 0.17 + 0.24 + 0.17 + 0.22 + 0.47 + 0.21 + 0.22 + 0.49 + 0.22 = 4.42
- **Correction factor (F)** = $T^2 / n = (4.42)^2 / 12 = 1.628$

Figure A.3 Main effects of factors on roughness



• **Sum of squares of all trials (S_T)** = $(0.57)^2 + (0.44)^2 + (1)^2 + (0.17)^2 + (0.24)^2 + (0.17)^2 +$
$(0.22)^2 + (0.47)^2 + (0.21)^2 + (0.22)^2 + (0.49)^2 + (0.22)^2 - F = 0.6562$

• The effect of factor A at lower level = sum of trials at lower level of A.

$A_I = 0.57 + 0.44 + 1.0 + 0.17 + 0.24 + 0.17 = 2.59$

Similarly,

$A_{II} = 1.83$

$B_I = 2.91$

$B_{II} = 1.51$

$C_I = 2.94$

$C_{II} = 1.48$

• **Sum of squares** (For 2 level-factor)

$$S_A = \frac{(A_I - A_{II})^2}{n_{A_I} + n_{A_{II}}} = \frac{(2.59 - 1.83)^2}{6+6} = 0.0481$$

$S_B = 0.16333$

$S_C = 0.1776$

$S_e = S_T - (S_A + S_B + S_C) = 0.6562 - (0.0481 + 0.16333 + 0.1776) = 0.2672$

f_T (total DOF) $= n - 1 = 12 - 1 = 11$

f_A = number of levels - $1 = 2 - 1 = 1$

$f_e = f_T - (f_A + f_B + f_C) = 11 - 3 = 8$

Variances:

$$V_A = S_A / f_A = 0.0481$$

$$V_B = 0.16333$$

$$V_C = 0.1776$$

$$V_e = S_e / f_e = \frac{0.2672}{8} = 0.0334$$

Contributions:

$$C_A = \frac{S_A}{S_T} \times 100 = \frac{0.0481}{0.6562} \times 100 = 7.34\%$$

$$C_B = 24.89\%$$

$$C_C = 27.07\%$$

$$C_e = 40.7\%$$

F - Criterion:

$$F_A = V_A / V_e = 0.0481 / 0.0334 = 1.44$$

$$F_B = 4.889$$

$$F_C = 5.3$$

Degree of freedom of factor: $f_i = 1,\ i = A, B, C$

Degree of freedom of error: $f_e = 8$

Using F-tables (F for Fisher's) at $f_1 = 1$, $f_e = 8$ and 95% of significance, we find $F_{critical} = 5.32$. At 90% of significance, $F_{critical}$ will be 3.46.

A.4 Conclusions

Figure A.3 shows that minimum roughness can be achieved at the upper level of speed (115 mm/min), the upper level of feed (0.09 mm/rev), and the upper level of cutting fluid (80 l/min). Comparing F_A, F_B, and F_C with $F_{critical}$, we conclude that the speed effect is insignificant on surface roughness when using 95% of significance. When using 90% of significance, speed and feed effects are insignificant, and cutting fluid is the factor that has the significant effect. But, experiments show that the feed is the most important factor affecting the surface roughness and the cutting fluid has a small effect on it. Comparing these results with the results obtained using the proposed method in chapter 3, we can see that Taguchi method selects the upper level of speed as an optimal setting, and the proposed method selects the lower level of this factor as an optimal one. The experiment done using the optimal settings resulted from each method shows that the minimum roughness is obtained at the optimal setting of the proposed method which means that the lower level of speed is the optimal.

The discussion at the beginning of this appendix has showed that the fractional factorial is superior to the orthogonal array. The optimization using graphs of marginal averages always identifies conditions that are close to the target but not optimal conditions.

APPENDIX B

ROUNDNESS MEASUREMENTS

ROUGHNESS MEASUREMENTS

APPENDIX B

GEOMETRICAL INACCURACIES

B.1 ROUNDNESS

Roundness measurement falls into two basic systems which depend upon the choice of the datum surface from which the measurement is taken. The conventional method which uses points on the surface of the part for reference is called the "intrinsic datum" system and is illustrated in Fig. B 1 The "extrinsic datum" system illustrated in Fig. B 2 depend upon an external reference of known precision from which the measurement is taken

B.1.1 Roundness measurement with intrinsic datum

The necessary equipment for this measurement method is fairly inexpensive, is adequate for many applications, and is considered standard instrumentation in most manufacturing plants It is rugged, simple to use, and provides relatively quick measurement

(a) Diameter methods

Fig (B.1 a) reveals the two-point or diameter measuring operation. Variation in the measurement may be the indication of an out-of-round condition due to an even number of lobes. However, there are two major possibilities for a false analysis: (1) the surface area may not conform to what is apparent from the specific measurement taken, and (2) there can be present out-of-roundness not revealed by a diameter measurement

(b) V-Block methods

The simplest and most direct method of detecting the presence of out-of-roundness in a component is to mount it in a vee block under a dial gauge or similar measuring instrument, as shown in Fig.(B.1.b). The presence of errors in roundness will be indicated by a movement of the dial gauge when the component is rotated in the vee block The most serious disadvantage of this arrangement lies in the difficulty of establishing the actual shape of the component from the variations in the reading of the dial gauge. These variations will depend ,first, on the included angle of the vee block and, second, on the number of lobes present on the component The method provides a good type of check in establishing whether or not the component is round

(c) Center-supported method

Fig.(B.1.c) showing the center-supported setup for out-of-roundness measurement, is very popular and is preferred by many technicians and engineers It is generally more stable and will reveal all conditions of roundness variation.Howevere, it too presents hazards to reliable measurement. Any misalignment of the centers holding the part will reveal itself as an error in cylindricity.And, there is always the question, as to how well this system picks up the true center axis of the part.

B.1.2 Roundness measurement with extrinsic datum

The other system for measuring the roundness of surfaces of rotation obviates using any part of the workpiece as a datum and, therefore, it is called the extrinsic system The referencing is accomplished from some external qualified member such as an ultra-precise spindle with almost perfect roundness of rotation. Several instruments of this type are available Fig B 2 Some support the part on a stationary fixture and rotate the spindle an exploring point around the part Other instruments support the part on a rotating spindle and explore the surface with a stationary electronic height gage contact point. All of the instruments include a polar chart recorder and some provide an additional strip chart

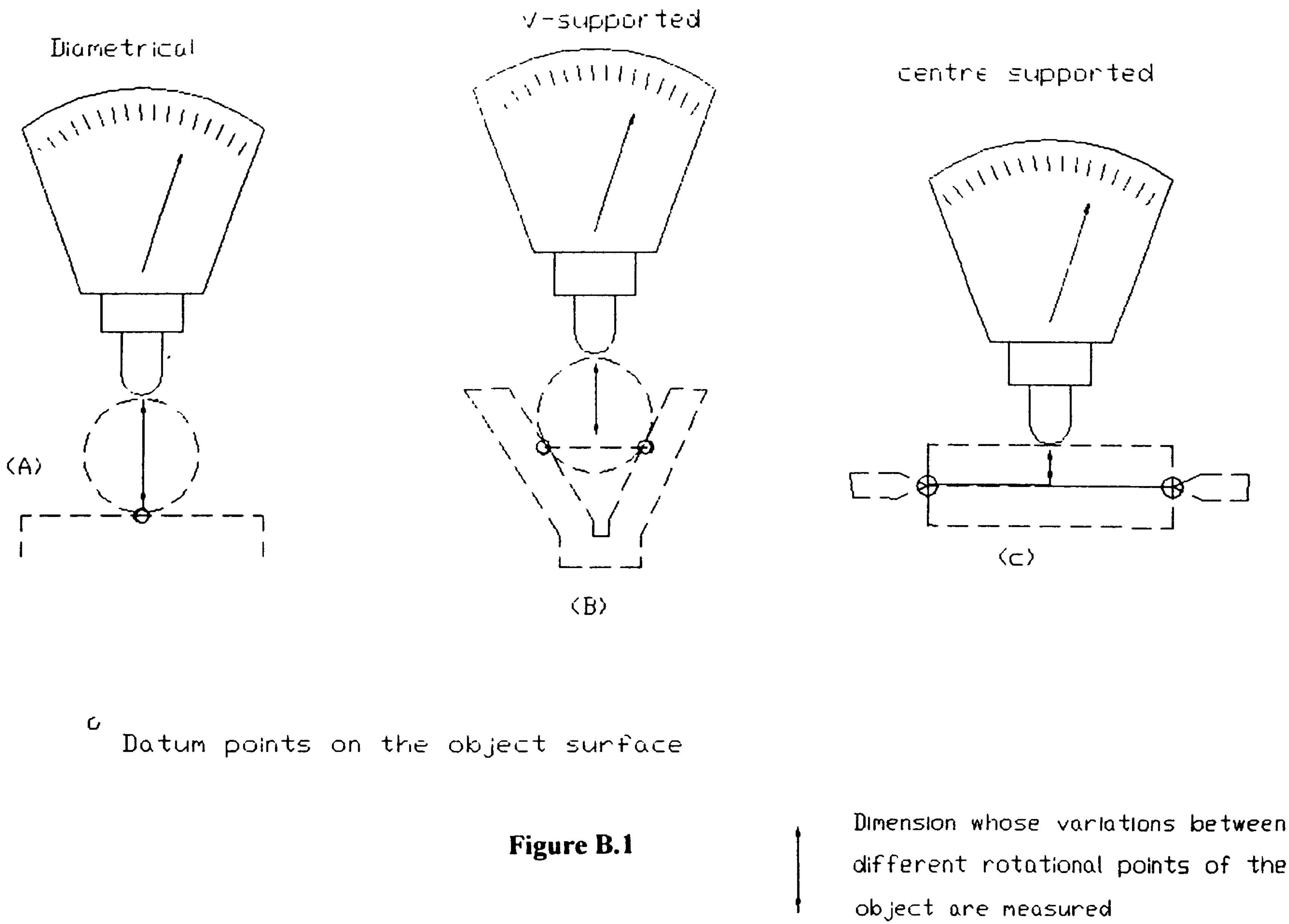

Diametrical
V-supported
centre supported
(A)
(B)
(c)
Datum points on the object surface
Dimension whose variations between different rotational points of the object are measured

Figure B.1

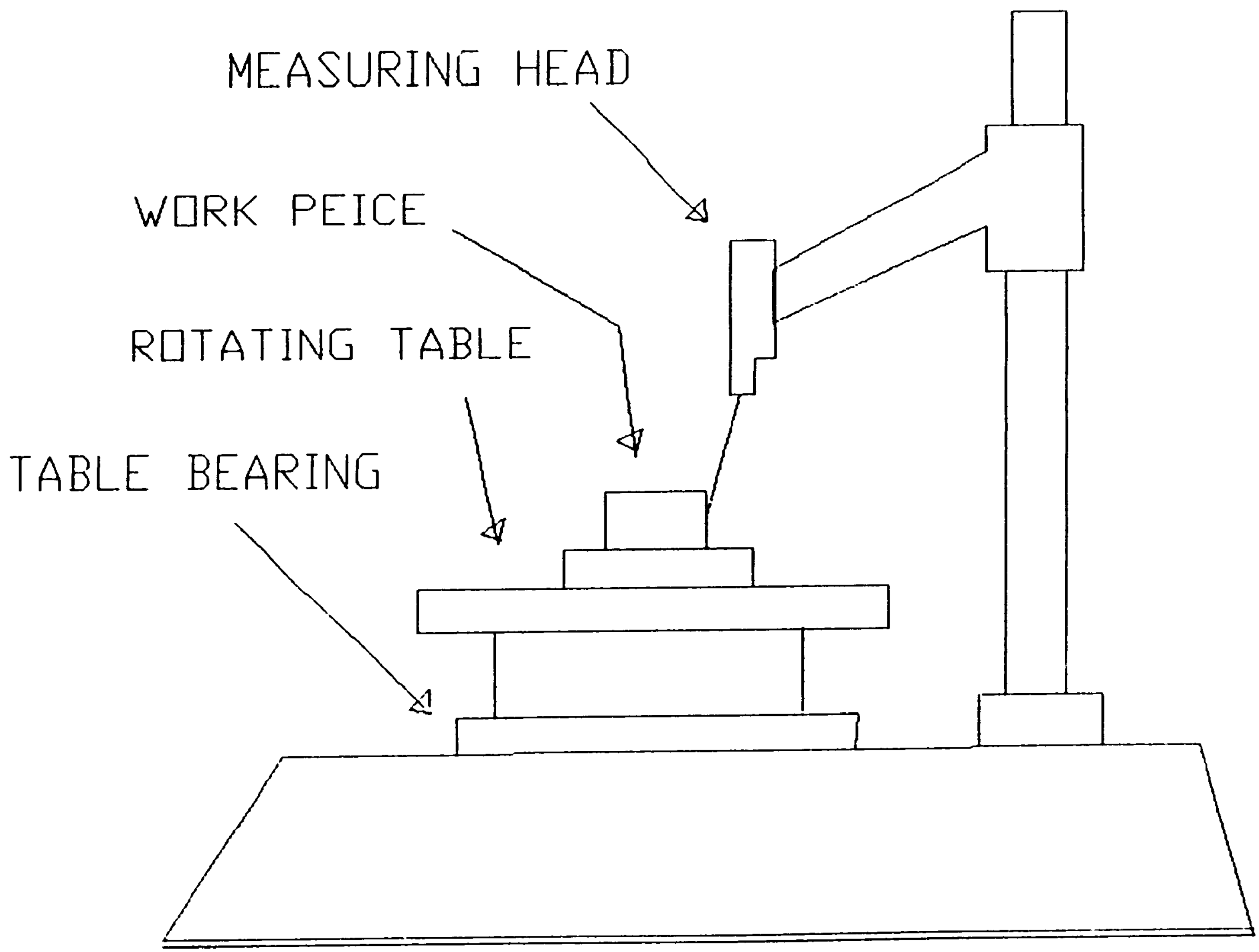


Figure B.2.a INSTRUMENT WITH ROTATING WORKPEICE TABLE: SENSING HEAD STATIONARY

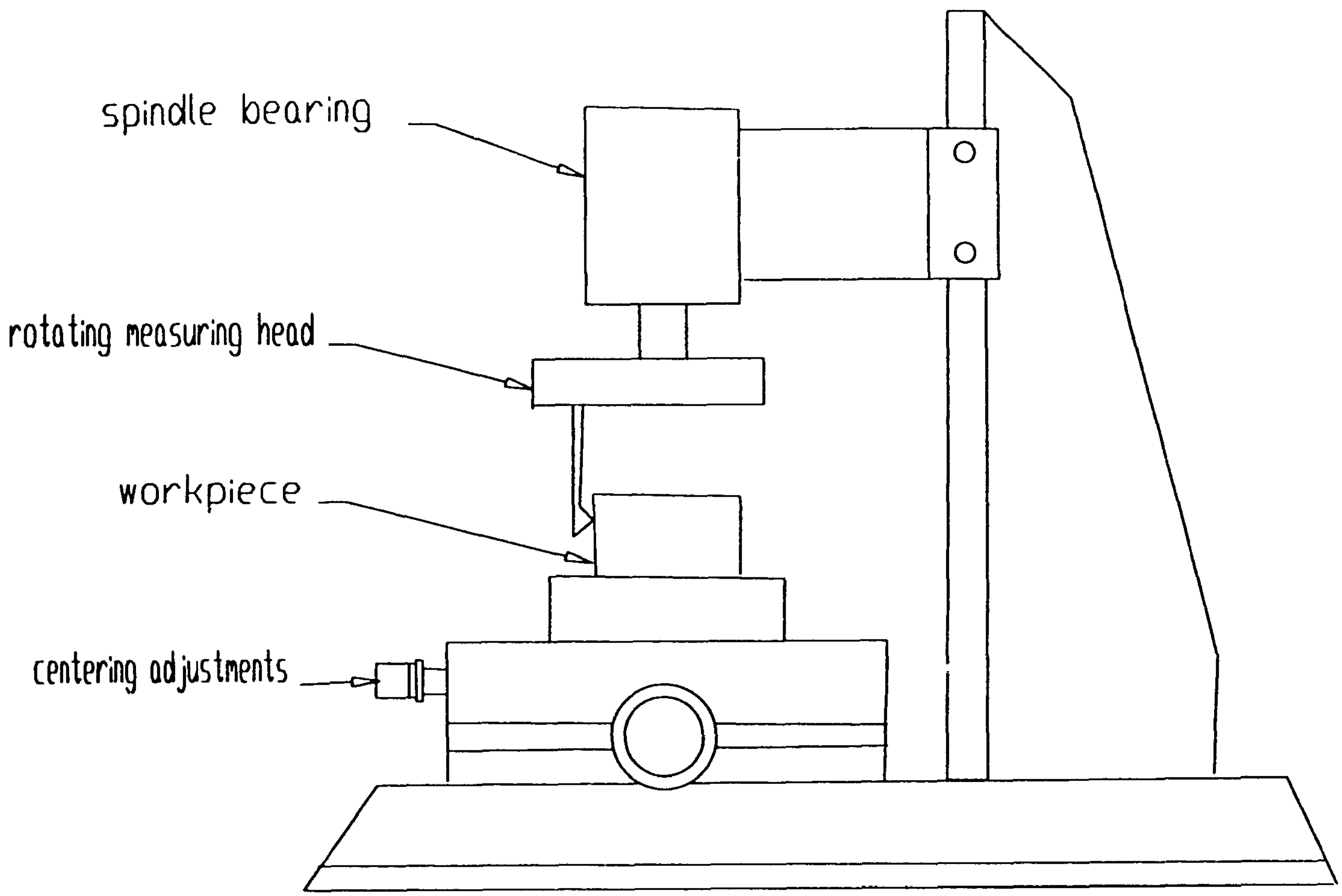


Figure B.2.b instrument with rotating spindle workpiece remains stationary

A number of roundness measuring machines are now available commercially of which the Talyrond manufactured by Rank Taylor Hobson is perhaps the most popular example This instrument is shown in Fig.B 3.

The basis of the machine is the spindle which rotates about a fixed axis within extremely close limits (2-3 .μin). The spindle is used to rotate a stylus around in contact with the workpiece which is adjusted to be concentric with the spindle Radial movements of the stylus are magnified electrically and a polar diagram is produced indicating the errors in roundness relative to a true circle at a suitable magnification.

Definition of roundness errors. A British standard,BS 3730 1964 Methods for the Assessment from Roundness, recommends two alternative methods for defining errors of roundness. The first of these based upon the radial separation of two concentric circles which just enclose the polar diagram profile The error of roundness is specified as the radial separation of the two concentric circles expressed in μin. This method has the virtue of being simple to apply when using a transparent template, on which concentric rings are drawn at a suitable spacing (say 0.1 in) and which can be adjusted over the polar diagram to give the best fit The radial separation can then be readily estimated from the encompassing concentric rings, taking due account of the magnification in the system

The main defect of the radial separation approach lies in the fact that it does not offer a rigorous definition of roundness and differing values of the radial separation may be obtained for the same polar diagram This may be illustrated by considering Fig B 4 taken from British standard 3730. This shows three identical polar diagrams in each of which the radial separation

Figure B.3 : Roundness measuring machine (Rank Taylor Hobson)

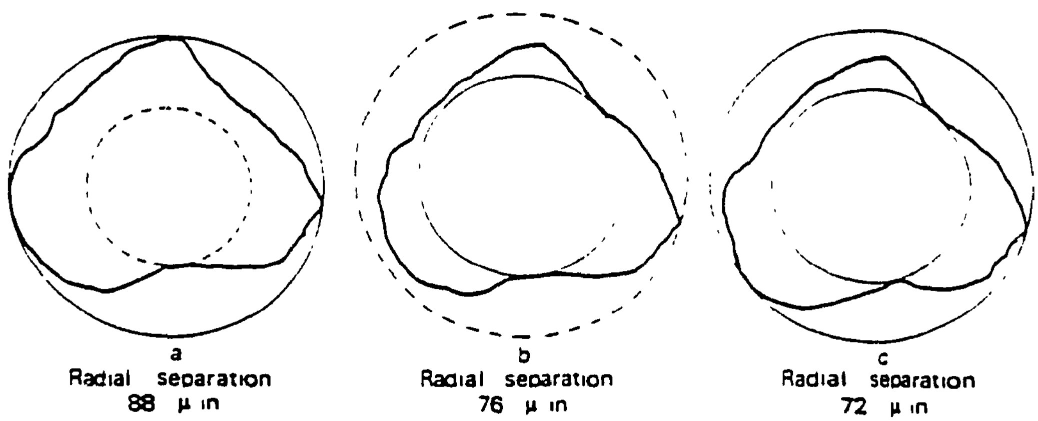


Figure B.4 Effect of choice of different centers in the assessment of roundness errors.

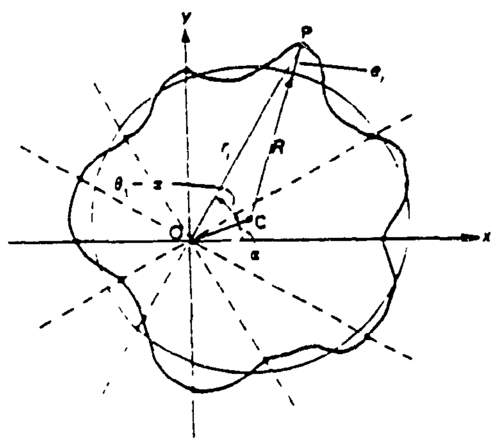


Figure B.5 Diagram for determination of the least squares center has been interpreted differently. In Fig.(B.4.a), the polar diagram is considered to be the shape of a shaft and, functionally, it is desirable to draw the concentric circles on the basis of the smallest hole into which the shaft would fit. The smallest circumscribing circle is therefore drawn first and concentric with it the largest inscribing circle. It can be seen that this approach gives a radial separation of 88 μin In Fig.(B 4.b),the component has been changed into a hole and,functionally, we are interested in the largest shaft that will fit into it. The largest inscribing circle is therefore drawn first and concentric with it the smallest circumscribing circle. This gives a radial separation of 76μin. It is obviously possible to choose a centre from which to strike the concentric circles which will give the radial separation a minimum value; this is shown in Fig.(B.4.c) giving a value of 72 μin. The standard recommends that where the radial separation approach is used it should be determined in terms of the minimum value, and specified on a drawing by the letters MZC standing for Minimum Zone Centre. Thus, 16 MZC would indicate that departures from ideal roundness of up to 16 (0 000016 in) are present when assessment is made by measurement on a polar graph across the minimum radial zone which just contains the peripheral undulations of the measured profile.

The alternative and recommended definition of roundness error is based on the least squares principle. Where we wish to establish a circle in relation to a series of measured values, i e , the polar diagram In this case it is required to calculate the centre of the least squares circle and also its radius and to use this as a datum from which to specify the errors of roundness

It has been established in British Standard 3730, that the centre of the least squares mean circle and its radius may be determined for any polar diagram from simple, easily calculated formula

B.1.3 Proof of the Formula for the Determination of the Least Squares Centre and Circle.

Consider a polar graph in rectangular co- 'inates x_i and y_i, originating at O, as shown in Fig.B.5. Take a number n of radii r_i, at equal angular spacings about O, which meet the trace at points given by $(r_i \theta_i)$, where

$$i = 1, 2, 3, \ldots\ldots, \quad \text{and} \quad \theta_i = \frac{2\pi i}{n}.$$

Let the least squares circle have centre C, whose rectangular coordinates are (a,b), and whose radius is R. Let the distance from the origin O to the centre C be c, and let the angle which OC makes with the x-axis be α. Then,

$$c^2 = a^2 + b^2 \quad \text{and} \quad \tan\alpha = \frac{b}{a}$$

From the triangle OPC,

$$r_i = c\cos(\theta_i - \alpha) + \sqrt{\{(R + e_i)^2 - c^2\sin^2(\theta_i - \alpha)\}}$$

Where e_i is the deviation from the least squares circle along the radius r_i Now in a well-centred trace c is very much less than R, and

$$r_i = c\cos(\theta_i - \alpha) + R + e_i \quad \text{approximately}$$

By the principle of least squares $\sum e_i^2$ is a minimum, i.e , $\sum[r_i - R - c\cos(\theta_i - \alpha)]^2$ is a minimum, and so

$$\frac{\partial \sum e_i^2}{\partial R} = 0 \qquad \frac{\partial \sum e_i^2}{\partial c} = 0 \qquad \frac{\partial \sum e_i^2}{\partial \alpha} = 0$$

$$\frac{\partial \sum e_i^2}{\partial R} = -2\sum[r_i - R - c\cos(\theta_i - \alpha)] =$$

Giving

$$\sum r_i - nR - c\sum\cos(\theta_i - \alpha) = 0 \ldots\ldots\ldots\ldots(1$$

$$\frac{\partial \sum e_i^2}{\partial c} = -2\sum[\cos(\theta_i - \alpha)(r_i - R - c\cos(\theta_i - \alpha))] = 0$$

Giving

$$\sum r_i\cos(\theta_i - \alpha) - R\sum\cos(\theta_i - \alpha) - c\sum\cos^2(\theta_i - \alpha) = 0 \ldots\ldots(2)$$

$$\frac{\partial \sum e_i^2}{\partial \alpha} = -2\sum[c\sin(\theta_i - \alpha)(r_i - R - c\cos(\theta_i - \alpha))] = 0$$

Giving

$$\sum r_i\sin(\theta_i - \alpha) - R\sum\sin(\theta_i - \alpha) - c\sum\cos(\theta_i - \alpha)\sin(\theta_i - \alpha) = 0 \;..\; (3)$$

Expressing

$$\frac{\sum f(\theta)}{n} \quad \text{as} \quad \frac{1}{2\pi}\int^{2\pi} f(\theta)d\theta$$

Gives

$$\Sigma \cos(\theta_i - \alpha) = 0$$

$$\Sigma \cos^2(\theta_i - \alpha) = \tfrac{n}{2}$$

and

$$\Sigma \cos(\theta_i - \alpha)\sin(\theta_i - \alpha) = 0$$

also

$$\Sigma r_i \cos(\theta_i - \alpha) = \cos\alpha \, \Sigma x_i + \sin\alpha \, \Sigma y_i$$

$$= \cos\alpha n \bar{x} + \sin\alpha n \bar{y}$$

since

$\bar{x} = \frac{\Sigma x_i}{n}$ and $\bar{y} = \frac{\Sigma y_i}{n}$

similarly

$$\Sigma r_i \sin(\theta_i - \alpha) = \cos\alpha \, \Sigma y_i - \sin\alpha \, \Sigma x_i$$

$$= \cos\alpha n \bar{y} - \sin\alpha n \bar{x}$$

Applying these results to equations (1), (2), and,(3) gives.

$$\Sigma r_i - nR - 0 = 0 \qquad \text{from (1)}$$

i.e.

$$R = \frac{\Sigma r_i}{n}$$

$$\cos\alpha n\,\bar{x} + \sin\alpha n\,\bar{y} - 0 - \tfrac{cn}{2} = 0 \qquad \text{from (2)}$$

i.e.

$$c = 2(\bar{x}\cos\alpha + \bar{y}\sin\alpha \qquad \ldots (4)$$

and

$$\cos\alpha n\,\bar{y} - \sin\alpha n\,\bar{x} - 0 = 0 \qquad \text{from (3)}$$

i e

$$\tan\alpha = \frac{\bar{y}}{\bar{x}}$$

Hence

$$\sin\alpha = \frac{y}{\sqrt{(x^2 + y^2)}} \quad \text{and} \quad \cos\alpha = \frac{\bar{x}}{\sqrt{(\bar{x}^2 + \bar{y}^2)}}$$

which substituted in (4) gives

$$c = \frac{2(x^2 + y^2)}{\sqrt{(x^2 + y^2)}}$$

$$c = 2\sqrt{(\bar{x}^2 + \bar{y}^2)} \qquad (5)$$

Now

$$c = \sqrt{(a^2 + b^2)} \quad \text{and} \quad b = a\tan\alpha$$

$$= \frac{a\bar{y}}{\bar{x}}$$

Therefore

$$\sqrt{\left(a^2 + \frac{a^2 y^2}{x^2}\right)} = 2\sqrt{(\bar{x}^2 + \bar{y}^2)} \qquad \text{from (5)}$$

$$a\sqrt{\frac{(\bar{x}^2+\bar{y}^2)}{\bar{x}^2}} = 2\sqrt{(\bar{x}^2+\bar{y}^2)}$$

Giving

$$a = 2\bar{x}$$

$$b = \frac{a\bar{y}}{\bar{x}} = 2\bar{y}$$

i e.

$$a = \frac{2\sum x_i}{n}$$

and

$$b = \frac{2\sum y_i}{n}$$

B.1.4 Example:

Twelve equally-spaced radial ordinates are drawn relative to the centre of the chart and numbered 1 to 12 as shown in Fig.B 6 The rectangular coordinates of the point of intersection between each ordinates and the polar diagram are measured with respect to the x and y axes, taking into account the sign.

These may be tabulated, as shown in Table B 1, and the values of $\sum x$ and $\sum y$ used to establish the centre of the least squares circle with respect to the centre of the chart The radial distance between each point of intersection and the least squares centre may now be measured and used to calculate the radius of the least squares circle

The roundness error is determined on the basis of the maximum peak to least squares circle plus maximum valley to least squares circle Which in the example shown in Fig B 6 equals $4\mu m$, to accord with the recommendation in British Standard 3730, this would be specified as $4\mu m$ LSC, based on the least squares centre

$$a = \frac{2\sum X}{12} = \frac{2\times 1.5}{12} = +0.25 \quad \text{mm}$$

$$b = \frac{2\sum Y}{12} = \frac{2\times(-2.3)}{12} = -0.3833 \quad \text{mm}$$

$$R = \frac{\sum r}{n} = \frac{479.7}{12} = 39.975 \quad \text{mm}$$

Table B.1 Calculation of least squares centre and radius

POSITION	X (mm)	Y (mm)	r (mm)
1	0	40	40.3
2	20.5	35.8	41.5
3	35.6	20.5	41.2
4	39.5	0	39
5	34	-19.5	38.7
6	20	-34	38.7
7	0	-40	39.6
8	-20.6	-35.7	41
9	-36.3	-21	42.2
10	-39	0	39.5
11	-33.2	19	39
12	-19	32.6	39
SUM	1.5	-2.3	479.7

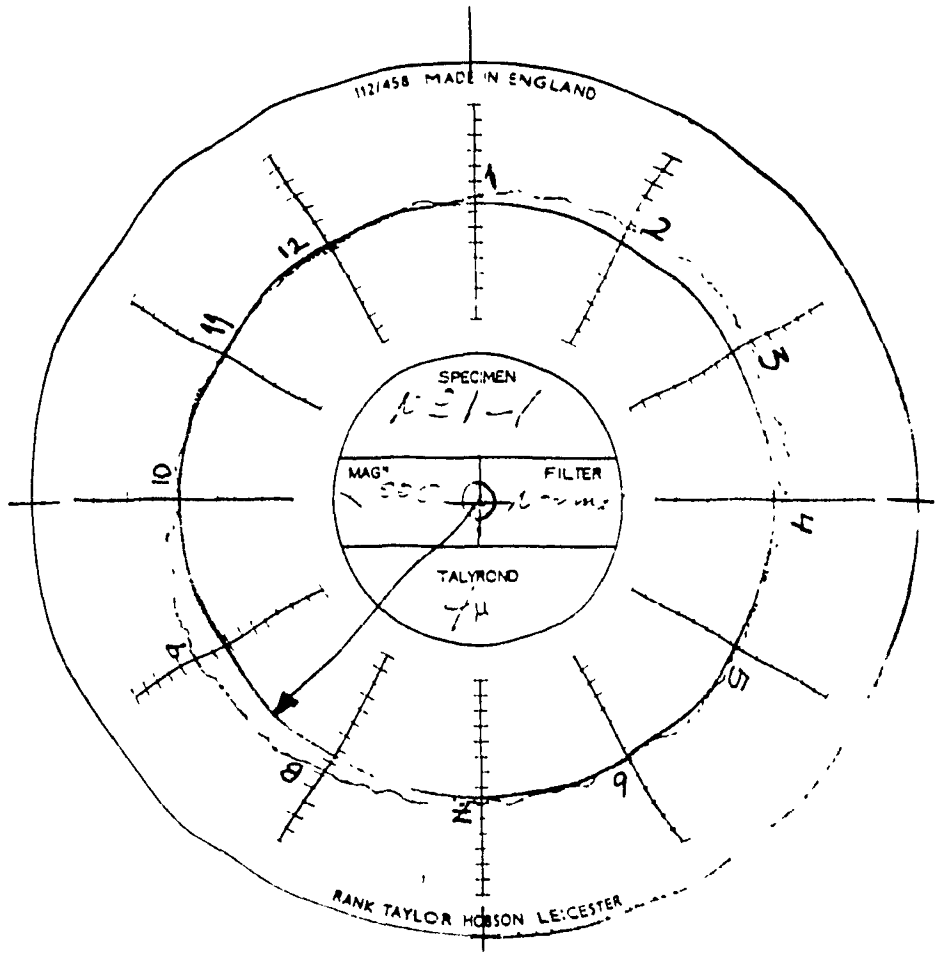


Figure B.6 Roundness test diagram

B.2 ROUGHNESS

It is possible to give the surface texture a numerical value in one of several different ways. Currently there are over 50 parameters defined by various standards organization, such as DIN, ISO and JIS, to quantify the surface texture. The following are the most commonly used values.

(a) Arithmetic Mean Deviation of the profile (Ra) : Consider the roughness profile and place a straight line through it as shown in Fig.B.7 such that for some evaluation length l_m the sum of the area above this line is equal to the sum of the area below the line. This line is called the centre line.

If one consider the centre line as X-axis then let the roughness curve be defined by some function f(x). The Arithmetic Mean Deviation is the mean of the absolute value of f(x) over the evaluation length l_m as shown in Fig.B.8 It is sometimes called the Centre Line Average CLA. It is given by the equation:

$$Ra = \frac{1}{l_m} \int_0^{l_m} |f(x)| dx$$

The evaluation length l_m for calculating Ra is typically five times the cutoff value (the wavelength below which the frequency is considered to be low)

(b) Average Peak-to-Valley Height (Rz (DIN)): Consider again the roughness profile. Taking a sampling length l_m of five times the cutoff value, divide the roughness profile into five sections of equal sampling length l_e equal to the cutoff value as shown in Fig B.9. Let Zi be defined as the difference between the highest peak and the lowest valley in the i^{th} sampling

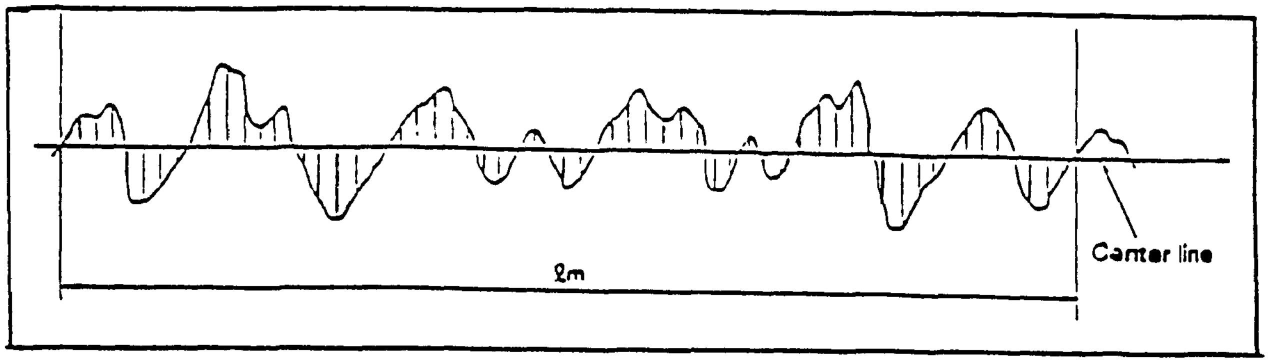


Figure B.7 Centre line of roughness profile.

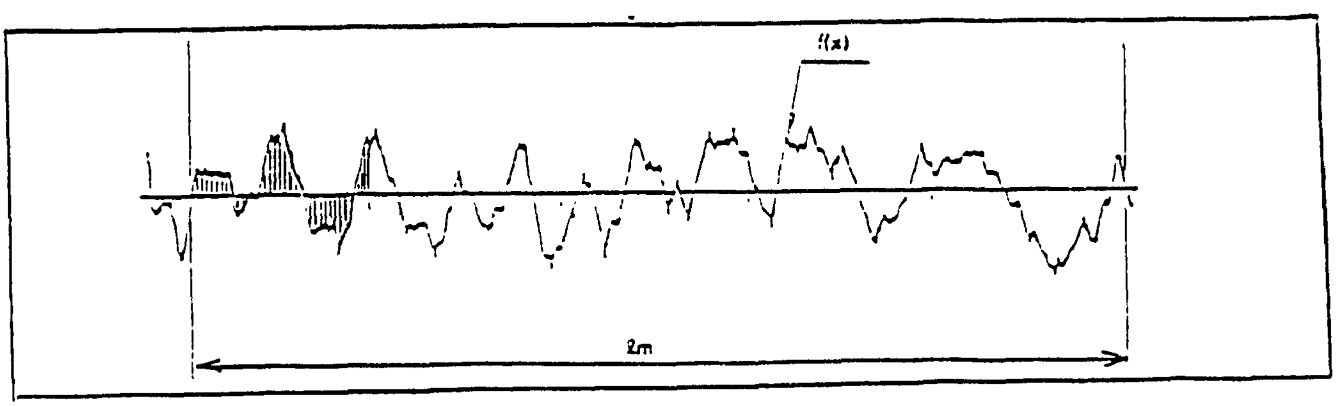


Figure B.8 Arithmetic Mean Deviation of the roughness curve(Ra).

length. The Average Peak-to-Valley Height Rz (DIN) is defined as the average value of Zi for the five sampling lengths.

$$Rz(DIN) = \frac{1}{5}\sum_{1}^{5} Zi$$

If there is not sufficient length on the surface for an evaluation length five times the cutoff value, then an evaluation length of three times the cutoff value may be used, but the sampling length must always be equal to the cutoff value.

(c) Maximum Peak-to-Valley Height Ry (DIN) : Ry is defined as the maximum value of Zi used when calculating the average Peak-to-Valley Height.

$$Ry(DIN) = Zi_{\max}$$

Consideration must be given to the effect of the length of profile selected when determining the numerical value. For surface textures of simple periodic form, the selected sample length is immaterial providing that it includes a sufficient number of pitches. In practice, however, it may be found that the surface texture is made up of two or more basic wavelengths superimposed upon one another and for surfaces such as these, the sample length will have a fundamental bearing on the numerical value obtained.

Let us take as an example the surface profile indicated in Fig. B.10, where in addition to the primary texture produced by the cutting action of the machining process, there is a secondary texture, perhaps induced by the presence of some vibration in the machine tool It is now apparent that the peak-to-valley height, and correspondingly the other numerical values, will vary with the

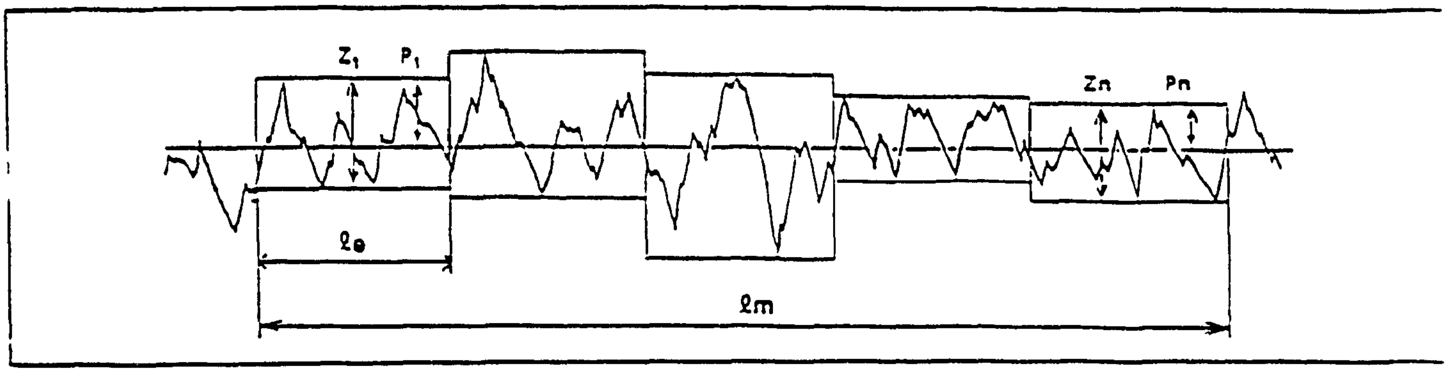


Figure B.9 Average Peak-to-Valley Height Rz(DIN)

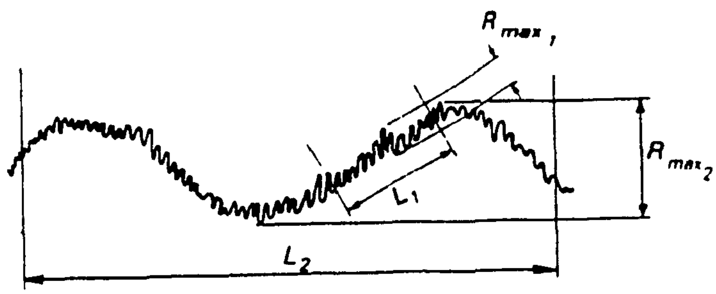


Figure B.10 Effect of different sample lengths length of the profile selected For example, a sample length L_1 will be associated with a peak-to-valley value $R_{max\ 1}$, while if the sample length is increased to L_2, the peak-to-valley value will be increased to $R_{max\ 2}$.

Therefore, it is clear that in order to obtain consistent results, the distance over which the measurement is to be made, the sample length, must be specified The length selected should be sufficient to include those features of the texture which it is necessary to control from a functional viewpoint but not so great as to include other features of wider spacing

B.2.1 Measurement of Roughness

1. Standard Roughness Specimens The practice of comparing the roughness of a surface with that of a standard piece is now being adopted extensively in workshops during production. The reference surface may be that of a selected component, the finish of which is known to be satisfactory for its purpose, or it may be one of the surfaces of a graded set of surface finish reference blocks, or cylinders, which are now obtainable commercially These are available in sets finished by different machining processes and it is recommended that the surface under consideration should be compared against roughness specimens which have been finished by the same process.

The comparison between the finish of workpieces and the blocks is usually made by sight or by finger-nail test. In the case of the finer finishes, a more critical comparison can be made with a Busch microscope which is fitted with two objectives, and so arranged that the two surfaces to be compared are illuminated and can be seen side-by-side at the same magnification. It should, however, be realized that the assessment of surface finish on this basis is a subjective one and that differences are likely to arise between one person's judgment and another

2. Stylus instruments. The instruments which have received the widest approval are those based on the amplification of the movement of a finely pointed probe or stylus as it is moved across the surface. The essential features of such an instrument are

(a) A measuring head carrying a stylus with provision of magnifying its vertical and horizontal movements

(b) Means for traversing the measuring head across the work Both manual and mechanical means have been used

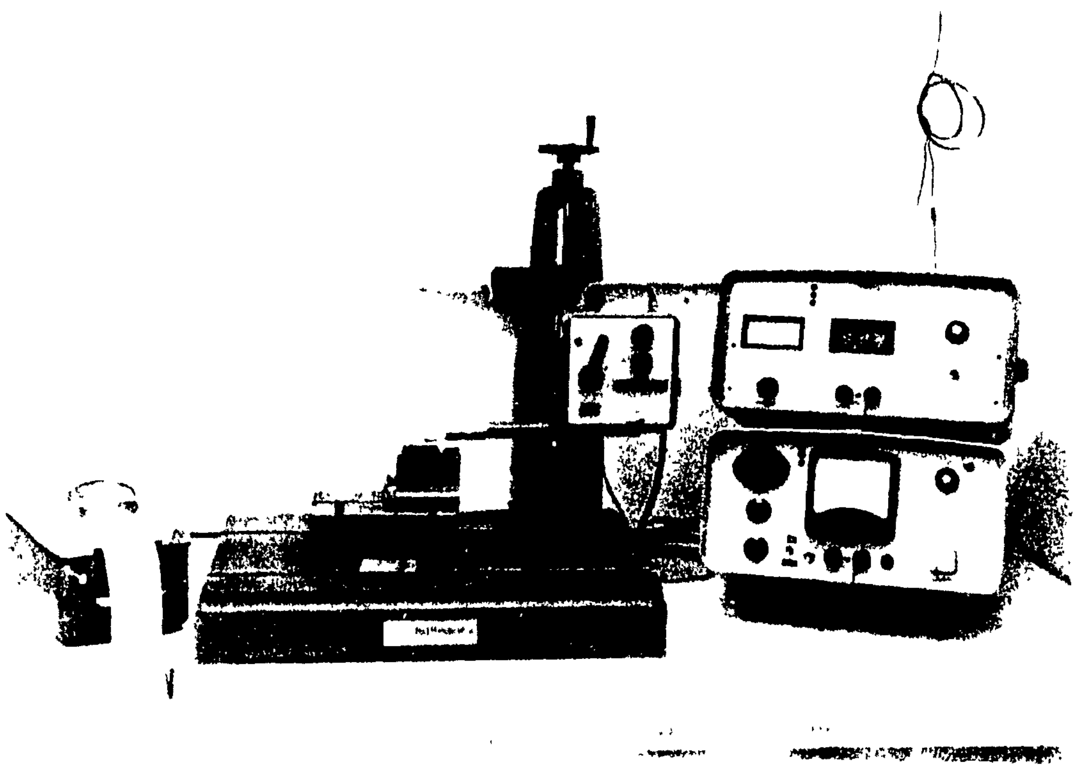
(c) Means for providing a graphical representation and numerical value of the surface.

The stylus which is used to explore the surface of the component should ideally have a mathematically sharp point. This is obviously impossible to achieve in practice and the finite radius on the tip of the stylus will involve some loss in accuracy of movement in relation to the shape of the surface profile which the stylus is exploring

The magnification of the stylus movement by electrical means to provide a graphical record, and the integration of the electrical output to provide a centre line average meter reading, is by far the most common technique used in the surface-finish measuring instruments

Figure B.11 shows the profiling-type Talysurf instrument. Talysurf is a versatile instrument for the evaluation of the surface texture It is robust enough for use in the workshop while its accuracy and high magnification make it suitable also for standards room use

Figure B.11 : Profiling type Talsurf for showing both profile and average finish



B.3 REFERENCES

[1] Scarr J.T., 1967, "Metrology and Precision Engineering", McGraw, Hill, London.

[2] Thomas, Geoffrey G., 1974, "Engineering Metrology", Butterworths, London.

[3] American Society of Tool and Manufacturing Engineering, 1967 ,"Hand Book of Industrial Metrology", Prentice Hall INC., New Jersey.

[4] Mitutoyo, "Surftest 501 series 178 Surface Texture Parameters manual No 4386"

[5] Mitutoyo, MST-211 Surface User's Manual,manual No 4360, series 178"

[6] Ramakrishna, and Shunmugam, 1987, "Accuracy and surface finish in BTA drilling", INT J. PROD. RES., vol 25, No.1,31-44