# SOME ASPECTS OF DRILL PERFORMANCE

DAVID PAUL UPTON

DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF ASTON IN BIRMINGHAM

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SUMMARY

The University of Aston in Birmingham

SOME ASPECTS OF DRILL PERFORMANCE

David Paul Upton

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High speed twist drills are probably the most common of all metal cutting tools and also the least efficient.

In this study, detailed research was undertaken into aspects of drill performance and ways in which drilling could be improved in short hole depths of up to two diameters.

The work included an evaluation of twist drill geometry and grinding parameters. It was established that errors in point grinding lead to increased hole oversize and reduced drill life.

A fundamental analysis was made to establish predictive equations for the drill torque and thrust using modified orthogonal cutting equations and empirical data. A good correlation was obtained between actual and predicted results.

Two new techniques for extending twist drill life by the use of coolant feeding holes and also the application of titanium nitride coatings were evaluated. Both methods were found to have potential for improving drill performance.

A completely new design of carbide tipped drill was designed and developed. The new design was tested and it compared favourably with two commercially available carbide tipped drills.

In further work an entirely different type of drill point geometry was developed for the drill screw. A new design was produced which enabled the drilling time to be minimised for the low thrust forces that were likely to be used with hand held power tools.

ASLIB KEY WORDS:
TWIST DRILLS : DRILLING : CARBIDE : METAL CUTTING.

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## NOMENCLATURE

| | |
|---|---|
| $a$ | Drill body radius |
| $A$ | Normal cross sectional area of undeformed chip (orthogonal cutting) |
| $A_1$ | Drill body cross sectional area |
| $A_s$ | Area in shear (orthogonal cutting) |
| $A_{SEG}$ | Area of segmental part of drill flute |
| $A_D$ | Area of undeformed chip for each drill lip |
| $A_P$ | Area of parabola (drill flute) |
| DPH | Hardness Vickers |
| $d$ | Drill diameter |
| $dc$ | Diameter of chisel edge |
| $e$ | Chisel eccentricity |
| $e_{lim}$ | Limiting chisel eccentricity for only on lip cutting |
| $f$ | Feed rate |
| $f_1, f_2$ | Drill feed rates per lip |
| $F_C$ | Cutting force (orthogonal cutting) |
| $F_{CL}$ | Cutting force on drill lip |
| $F_{CH}$ | Thrust force on drill chisel edge |
| $F_H$ | Normal force component to $F_T'$ |
| $F_S$ | Shear force (orthogonal cutting) |
| $F_{SL}$ | Shear force per lip in drilling |
| $F_T$ | Feed force (orthogonal cutting) |

| | |
|---|---|
| $F_T'$ | Axial feed force per lip in drilling |
| $F_{TL}$ | Feed force at right angles to drill cutting lip |
| $F_x$, $F_y$ | Radial forces measured from drilling dynamometer output |
| $F_Z$ | Thrust force measured from drilling dynamometer output |
| $F_{ZP}$ | Total predicted drill thrust force |
| G | Modulus of rigidity |
| $H_B$ | Hardness Brinnel |
| h | Difference in lip height |
| $\ell$ | Drill lip length |
| $\ell_1$ | Drill flute length in torsion |
| M | Torque measured from drilling dynamometer |
| $M_1$ | Drill lip torque |
| $M_2$ | Drill chisel edge and land torque |
| $M_P$ | Total drill torque (predicted) |
| N | Rotational speed |
| R | Resultant force $\sqrt{F_T^2 + F_C^2}$ |
| rc | Cutting ratio $(f/t_2)$ |
| Rc | Rockwell 'c' hardness |
| T | Applied torque |
| V | Cutting speed |
| x | Half point angle of drill |
| $y_s$ | Centroid of segment (flute) |
| $y_p$ | Centroid of parabola (flute) |
| $\gamma$ | Rake angle (orthogonal cutting) |

| | |
|---|---|
| $\gamma_E$ | Effective rake angle |
| $\phi$ | Shear angle (orthogonal cutting) |
| $\tau$ | Friction angle (orthogonal cutting) |
| $\tau_S$ | Shear stress |
| $\tau_{SE}$ | Effective shear stress drilling |
| $\theta$ | Angle between drill centre line and line drawn through tip of flute. |
| $\theta_1$ | Angle of twist in torsion |

# CHAPTER ONE

# INTRODUCTION

## 1.1 INTRODUCTION

High Speed Steel twist drills are probably the most common of all metal cutting tools that are used throughout the engineering industry in both conventional and CNC Machine tools.

Drilling has traditionally been regarded as a roughing operation prior to the reaming of precision holes. The cutting speeds (30 m/min) with twist drills are relatively slow in order to prevent the High Speed Steel losing its edge hardness by overheating and tempering back. High feed rates are also difficult to achieve with twist drills because of the risks of drill breakage, which may occur under high torque or where swarf becomes trapped in the drill flutes. The performance of drills may also be impaired by the inability of coolant to effectively reach the cutting lips of the drill as the hole is being drilled.

Drill wear and life is dependent upon a number of factors which include the number of holes drilled, the operating conditions (speed and feed), the nature of the material being cut, hole depth, the type and method of application of the coolant, the drill geometry and the accuracy of the drill point grinding.

In this research detailed investigations were undertaken into twist drilling with hole depths of up to two diameters without the use of pilot holes. The overall philosophy of the work was to investigate and quantify developments in drilling which might contribute to improvements in both drill productivity and hole quality.

## 1.2 OBJECTIVES OF THE RESEARCH

Particular emphasis has been placed on ways of improving drill performance by, either, use of new designs or alternatively optimising existing designs to give increased drill life, penetration rates and more precision holes as follows:-

### 1.2.1. H.S.S. Twist Drills

The objectives for conventional H.S.S. twist drills were:-

(i) To investigate the early history of the twist drill in order to establish the fundamentals of the drilling process.

(ii) To undertake trials with twist drills that were both correctly and asymmetrically ground so that the effects of errors in point grinding could be established.

(iii) To monitor the cutting forces in drilling (torque and thrust) and to establish predictive equations by analysis, empirical data and comparison with orthogonal cutting results from single point trials on a centre lathe. The equations were intended to provide a means of predicting the torque and thrust for different drill diameters.

(iv) To investigate a range of drilling parameters for hole depths of up to two diameters so that comprehensive data could be obtained on the important factors affecting drill performance and hole quality.

(v) To investigate the effects of different methods of coolant application in drilling and compare the performance of coolant fed drills with conventional twist drills.

(vi) To undertake detailed research on the effects of TiN surface coatings on twist drill performance and quantify any potential benefits.

### 1.2.2 Carbide Tipped Drills

The objectives for the work with carbide tipped drills were:-

(i) To design and test an entirely new type of carbide tipped drill geometry using "brazed in" helically twisted tungsten carbide cutting lips.

(ii) To compare the performance of the new Prototype design with H.S.S. drills and two other types of carbide drill that were commercially available.

(iii) To study the important design features of the new Prototype drill in order to establish the torsional strength and chip disposal capacity compared to other types of drill.

### 1.2.3 Self-Tapping Drill Screws

The objectives of the research with drill screws were:-

(i) To evaluate six different types of commercially available drill screws and compare the performance with those of conventional twist drills of the same diameter.

(ii) To establish the important design features of drill screws that may contribute to faster drilling times with low thrust forces.

(iii) To undertake detailed research with one type of drill screw (Type 'F') in order to optimise the design.

# CHAPTER TWO

## THE EARLY HISTORY OF THE TWIST DRILL 1860-1910

When first considering the twist drill, its invention, early history, development and introduction into engineering workshops throughout Great Britain, it is important to appreciate the circumstances that led to its emergence or inhibited its usage.

### 2.1 THE SPEAR POINT DRILL

The predecessor of the twist drill was called the "Flat" or "Spearpoint" drill and prior to the 1860's this was the tool usually used for drilling holes in metal.

The Spearpoint drill was often hand forged by the craftsman to form a flat blade on steel rod and then point ground before being hardened and tempered.

The Spearpoint drill, which was in widespread use until the end of the nineteenth century, suffered from serious disadvantages namely:-

(i) The swarf or chips could not be easily removed from the drilled hole as drilling progressed and it was necessary to stop periodically, withdraw the drill and remove the debris. This resulted in a lot of lost time and increased cost.

(ii) Precision holes could not usually be produced unless the point was ground on a machine to produce equal lip angles (A and B) (Fig.2.1) about the centre line of the drill drawn through P. The drill lands M and N should also be ground to the same radius and easier penetration of the drill obtained by thinning the chisel point. Accurate geometry was virtually impossible to achieve by hand grinding and the tool life and hole size were also difficult to predict. This was because of the very fine feed rates used at that time (.001in/rev). Unless the difference in lip height could be maintained to better than .0005in the drill would tend to cut on only one lip and subsequently wear very quickly.

(iii) The drill geometry was such that high cutting forces would be required by the zero rake angle blade and this would tend to reduce the tool life and impose greater strain on the drilling machine. Attempts to produce a positive rake angle by grinding a semi circular or curve groove on the rake face F (Fig.2.2) of each cutting lip were successful until the drill was reground. It was then a tedious operation to regrind the groove particularly if the drill was tempered back to facilitate easier cutting of the groove.

(iv) Lack of support in the hole diameter along the drill length tended to cause the drill to wander with increasing hole depth.

## 2.2 THE FIRST TWIST DRILLS

It was obvious therefore that the Spearpoint drill was unsatisfactory for precision hole drilling. The need to produce accurate holes quickly, without the need to stop to remove the swarf from the hole, became an important requirement for any new drill.

The demand was first realised in the United States of America and it was brought about by the needs of the ordinance factories. Armaments, particularly small arms were required in great numbers for the American Civil War, 1861-65.

The problem that faced manufacturers was two fold, i.e.

(i) Precision components were not interchangeable unless they could be made to close tolerances.

(ii) New tools and machines were needed to increase production.

It was the mechanics of New England who emerged with the solution to the problem of replacing the Spearpoint Drill with the Twist Drill as we know it today.

The overwhelming superiority of the Twist Drill was immediately recognised but its production at first was infinitely laborious and costly.

One of the first organisations to make the twist drill was the Providence Tool Company of Providence Rhode Island [1]. An engineer, Mr F Howe, of that company was commissioned in 1861 to produce accurate twist drills for making holes in the percussion nipple of a new percussion lock rifle for the Civil War. Twist drills had previously been produced by cutting the flute in a piece of steel rod by a tedious hand filing technique.

The problem was subsequently taken up by Mr J R Brown, of the Brown and Sharpe Company, who developed the solution to milling the flutes in twist drills with the invention of the Universal Milling Machine.

Brown's first Universal Milling Machine (Fig.2.3) and his drawing for it have been preserved by the Brown and Sharpe Company as well as the original patent drawings (U.S. Patents dated 1862 and 1865) [2].

The first (No.1) machine was delivered to the Providence Tool Company in 1862 and the capacity to produce helically fluted drills steadily increased as more machines were sold.

By the end of 1862 the first ten machines had been produced and Joseph Brown followed up his invention by introducing the formed tooth milling cutter which he patented in 1864.

Of the five No.1 Milling machines sold in Great Britain one is preserved in the Science Museum [3]. This machine was donated by the Singer Manufacuturing Company, but it is unlikely that any of the early imported machines were used for twist drill production in Great Britain for the period 1862-1878.

## 2.3 THE FIRST TWIST DRILLS IN GREAT BRITAIN

In Great Britain no references to twist drills were found before 1865, despite an extensive literature search.

In America however, the New England engineers were capitalising on the invention and in 1863 Mr S A Morse was granted his famous Patent for the twist drill [4] which contains detailed drawings of the tool. Mr Morse went on to set up the Morse Twist Drill Company. Drills became known as Morse Twist Drills and his name remains as designation of taper shank size on drills and other tools.

One of the first detailed English references of the Twist Drill appeared in 1865 [5] (Fig.2.4). It was stated that the Manhattan Fire Arms Company, Newark, New Jersey "had perfected a system for the manufacture of twist drills". The drills were "turned from shank to point in a turning lathe and milled out in the grooves (flutes) by a peculiar machine invented by Mr Arnold of the said

Company".

The drills were available in diameters from 3/8" - 1¼" in 1/32" increments and suitable for drilling holes up to nine inches deep. Note that there was no diametral body clearance on these drills and this would have contributed to high surface friction at the drill periphery.

Although Mr Arnold was granted Provisional Patent Protection in 1866 in London [6] for his invention it is not known to what extent his machine was similar to the one by Brown and Sharpe.

By 1867 some twist drills had begun to appear in England but their introduction was at first fiercely resisted [7]. The reasons for this reluctance to use them probably stemmed from a combination of factors which may have included:-

(i) Resistance to change, - engineers preferred to stick to old established traditional methods of drilling.

(ii) Availability, - twist drills were not made in the U.K. at this time.

(iii) Lack of knowledge, - reports circulating at the time suggested that little was known of the twist drill[8].

(iv) Due to the somewhat prototype appearance of early twist drills some may have been tested, failed and been rejected without any further development.

(v) Doubtful quality and heat treatment of the drill tool steel.

(vi) Lack of information about the regrinding or regrinding facilities for twist drills.

In 1874 machine makers were at last beginning to illustrate twist drills in the chucks of their drilling machines [9]. There was also evidence in 1878 that (Fig.2.5) Smith and Coventry of Gresley Iron Works, Salford were offering twist drills for sale. In 1880 however they were to receive some competition when Charles Churchill and Company became the first importers of the "Genuine Morse Twist Drill" [11]. This tool (Fig.2.6) incorporated an axial line (A-B) impressed into the web at drill centre from the chisel edge to the shank. It was called the "Patent Grinding Line" and was introduced to facilitate the easy judgement of lip lengths and point half angles when regrinding the drill by hand. The grinding line was a source of weakness on the drill web however, and a potential stress raiser which tended to result in drill failure by web splitting under high thrust conditions.

The Morse Twist Drill also had a varying helix angle, which ranged from about 45° at the tip to about 30° at the top end of the flute. This may have been beneficial in deep holes in allowing more rapid evacuation of swarf at the top of the flute. However, a constant helix angle is to be preferred so that a constant geometry can be maintained when regrinding. The Morse Drill was nevertheless very successful, mainly because the clearance angle was reduced by 50% over other designs.

By 1883 the Twist Drill was becoming noticed by the English Engineering Institutions and a paper was presented [12] on the "Cutting of Metals". The section, devoted to drilling, covered the "state of the art" at that time.

In the review of drill developments, the merits of both spearpoint and twist drills were considered. It was noted that:-

(i) Attempts by blacksmiths to produce drills from helically twisted square section steel bar generally failed because the twisted stem did not have sufficient precision to lift the chips from the drilled hole. Other developments along similar lines by Sir Joseph Whitworth during the 1850's with twisted bar were also unsuccessful.

(ii) Reports on early twist drills supplied by the Manhattan Fire Arms Company suggested that these drills would not "endure hardship" and they were "apt to drag themselves into the metal, jam fast and then twist themselves into fragments". This was probably due to a combination of high helix angle (about 45°) and a large clearance angle which produced a very weak cutting edge.

(iii) Between 1880-1883 a simple and efficient Twist Drill Grinding Machine was designed and built by Mr W Ford Smith of The Gresley Iron Works. This machine was very successful and many were sold to cover the grinding of Twist Drills up to 3" diameter. The effects of incorrect drill point grinding are demonstrated in Fig.2.7.

(iv) At that time cutting speeds of 20ft/min and feeds of .001 in/rev were quoted for drilling an iron bar with a ½" diameter drill using "soap and water" as a lubricant. The drill life was 120 holes of 1½" depth before regrinding was necessary (ie 15ft of drilled hole depth). It was also reported that in "many establishments all drilling was undertaken entirely by twist drills".

(v) The reluctance of the Engineering Establishment to accept the twist drill was, however, still evident at that time (1883) and spearpoint drills were still in common usage.

At the International Inventions Exhibition, London in 1885 [13] Greenwood and Bateley of Leeds listed amongst their exhibits "Improved and Patented Machinery for making and maintaining twist drills". Hence, as the means to make twist drills became more readily available and the abundance of drills steadily increased through more manufacturers setting up to make drills the flat spearpoint drill became less common.

## 2.4 EARLY TWIST DRILL DEVELOPMENT AND TESTING

The twist drill became a readily accepted tool for the drilling of a wide range of different materials. Changes in the helix angle, clearance angle and point geometry enabled holes to be drilled in different materials although the maximum speeds (20ft/min and .001in/rev) were limited by the metallurgical properties of carbon tool steel.

It was not until the introduction of High Speed Steel to replace carbon tool steel that significant improvements in cutting speeds were achieved. The forerunner of modern high speed steel was discovered by Robert Mushet in 1857. He found, almost by accident, that a carbon tool steel with additions of 7-12% tungsten left to cool in air from the forging temperature was very hard. Due to this feature Mushet Steels were often referred to as self hardening steels.

The modern tungsten high speed steels were first introduced at the Paris Exhibition of 1900 [14] by the Bethlehem Steel Company, Philadelphia, U.S.A. and their development was due to Messrs Taylor and White of that Company.

Cutting speeds with H.S.S. were increased by a factor of five to about 100ft/min for drilling mild steel. Feed rates were similarly improved, higher feed rates being attainable with the higher torsional stiffness in larger diameter drills, the limitation being the amount of clearance angle available before the drill would fail through rubbing.

It was also about this time that the first scientific analysis of twist drill performance began to appear when the thrust and torque were probably first measured by a dynamometer in 1905 by Messrs Bird and Fairfield [15]. Another paper [16] in 1909 begins to show the interest in drilling different materials with the forces measured for both cast iron and steel.

Drill performance became increasingly important as new and improved machine tools were introduced and new materials were required to be drilled.

Fundamental limitations in the design of the drill, the need for a central web and the swarf constriction space in the flutes, led to the need to develop improvements. These improvements included special new drill point configurations for enhanced performance and hole quality. New flute shapes were also developed to enable better swarf evacuation from deep holes.

Coolant fed twist drills were also introduced to assist in swarf removal and the reduction of heat generation at the cutting lips. Other improvements included the surface coatings applied to the drill. Bright finishes on "as ground" drills resulted in rapid tool wear through excessive heat build up at the cutting lips. Steam tempering was introduced to provide a tenacious oxide film on the drill to reduce the chip friction, Nitriding techniques were also used.

More recently Titanium Nitride (TiN) coatings have been applied to drills to enhance their performance. Improved grades of cobalt H.S.S. were also adopted.

The demand for higher productivity has resulted in the use of tungsten carbide tipped drills. Solid Carbide drills have also been recently perfected.

The high speed steel twist drill has thus emerged after one hundred and twenty five years with great potential for increased performance. Some of these improvements are quantified within this Research.

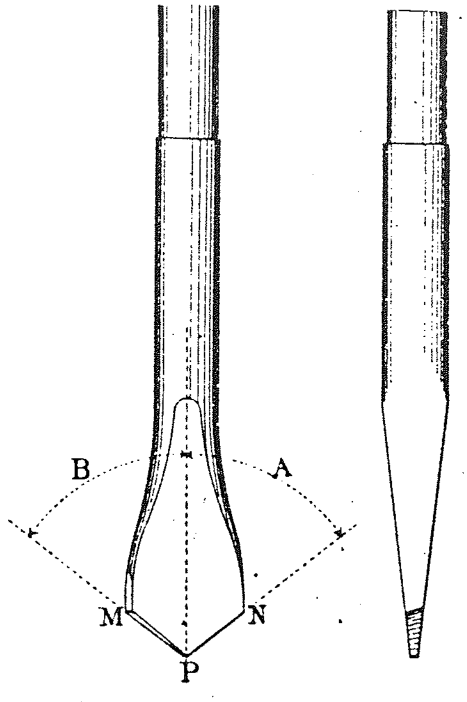



FIG 2.1 THE SPEARPOINT DRILL -ILLUSTRATING THE IMPORTANCE OF CORRECT POINT SYMMETRY

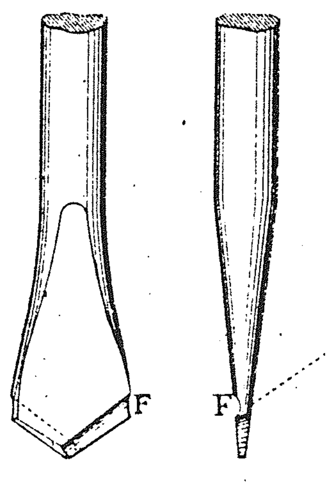



FIG 2.2 THE SPEARPOINT DRILL -WITH GROOVE "F" TO PROVIDE POSITIVE RAKE CUTTING

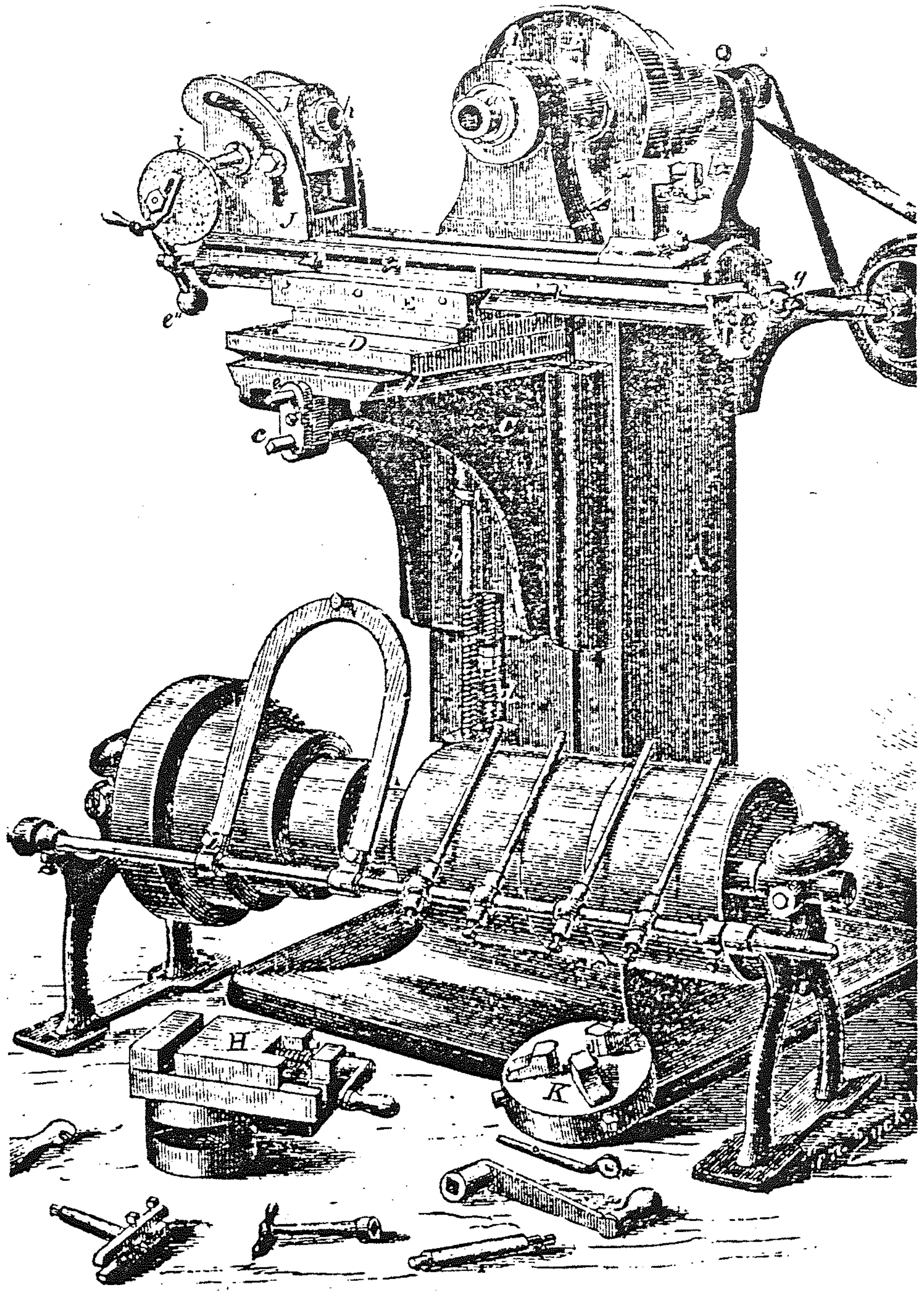


FIG 2.3 THE FIRST UNIVERSAL MILLING MACHINE (BROWN AND SHARPE -1861)

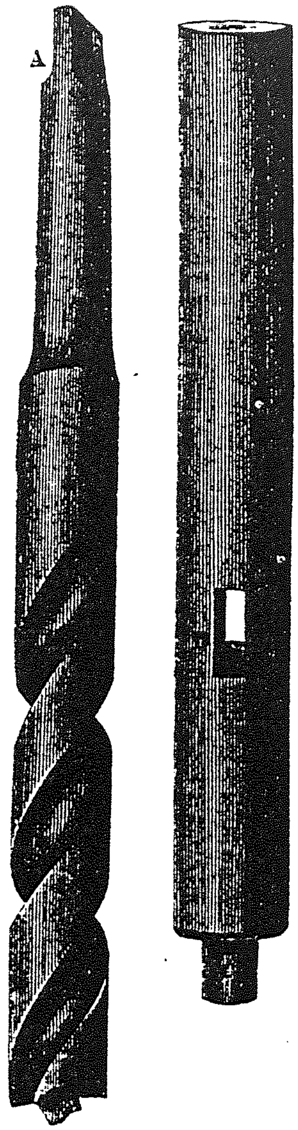



FIG 2.4 THE STANDARD TWIST DRILL AND SOCKET ADAPTOR -1865
(MANHATTAN FIREARMS COMPANY, NEWARK,NEW JERSEY,USA)

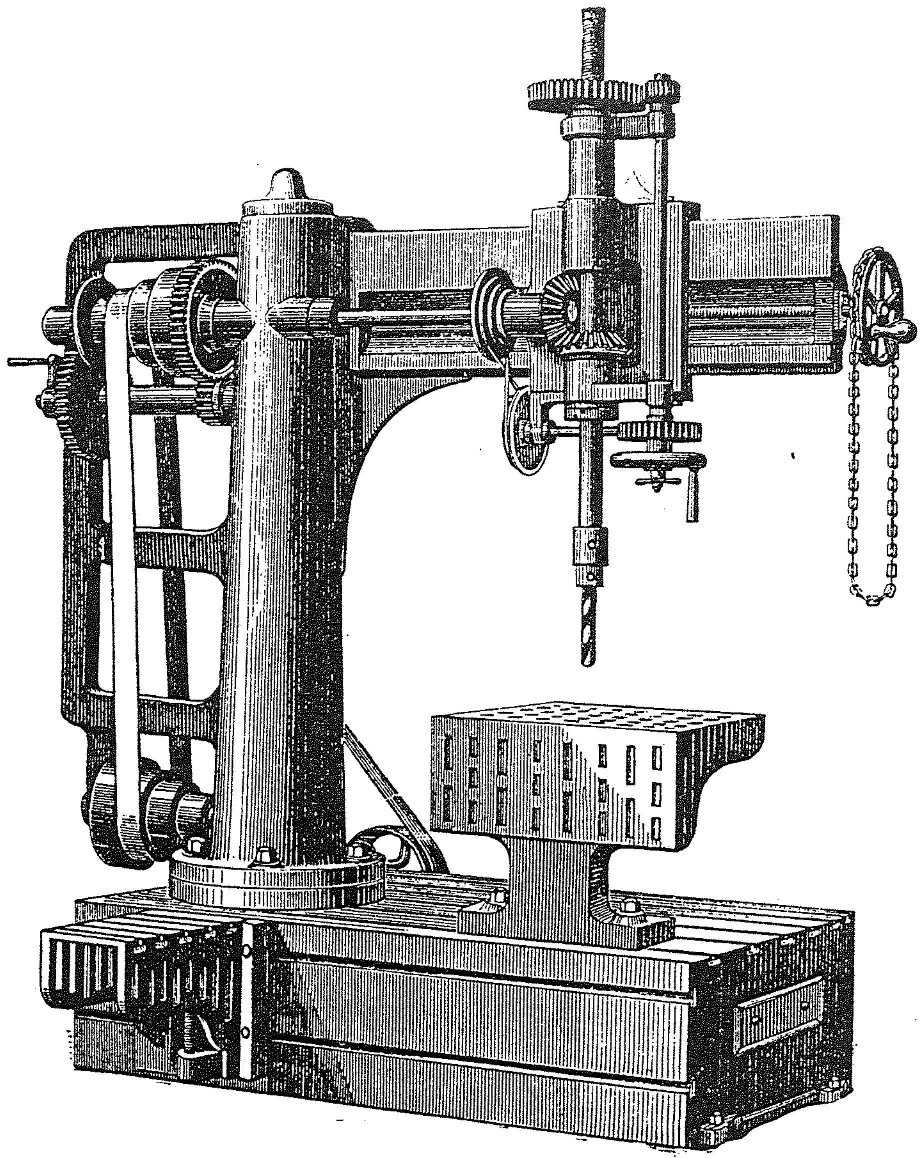
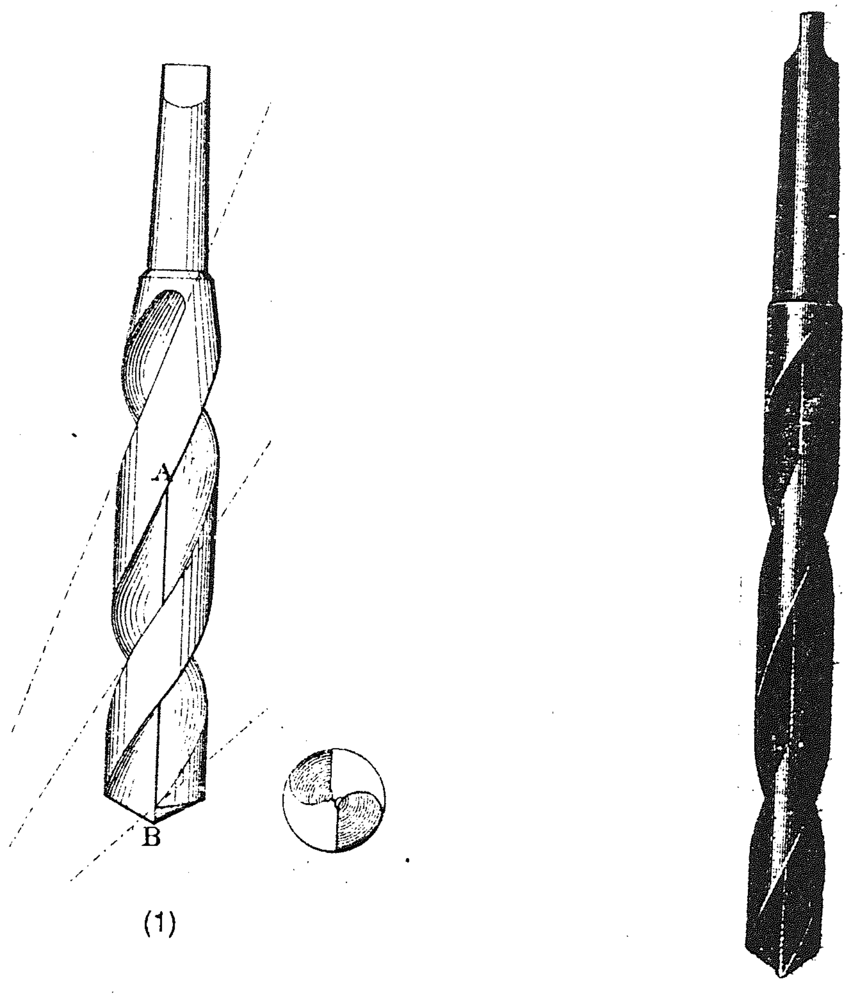


FIG 2.5 EARLY RADIAL ARM DRILLING MACHINE WITH TWIST DRILL-1874
(MESSERS LOWRY & CO, SALFORD, MANCHESTER)




(1)

(2)

FIG 2.6 THE MORSE TWIST DRILL WITH PATENT GRINDING LINE A-B

(1) - SHOWING VARIATION IN HELIX ANGLE

(2) - AS IMPORTED BY CHARLES CHURCHILL & CO -1880

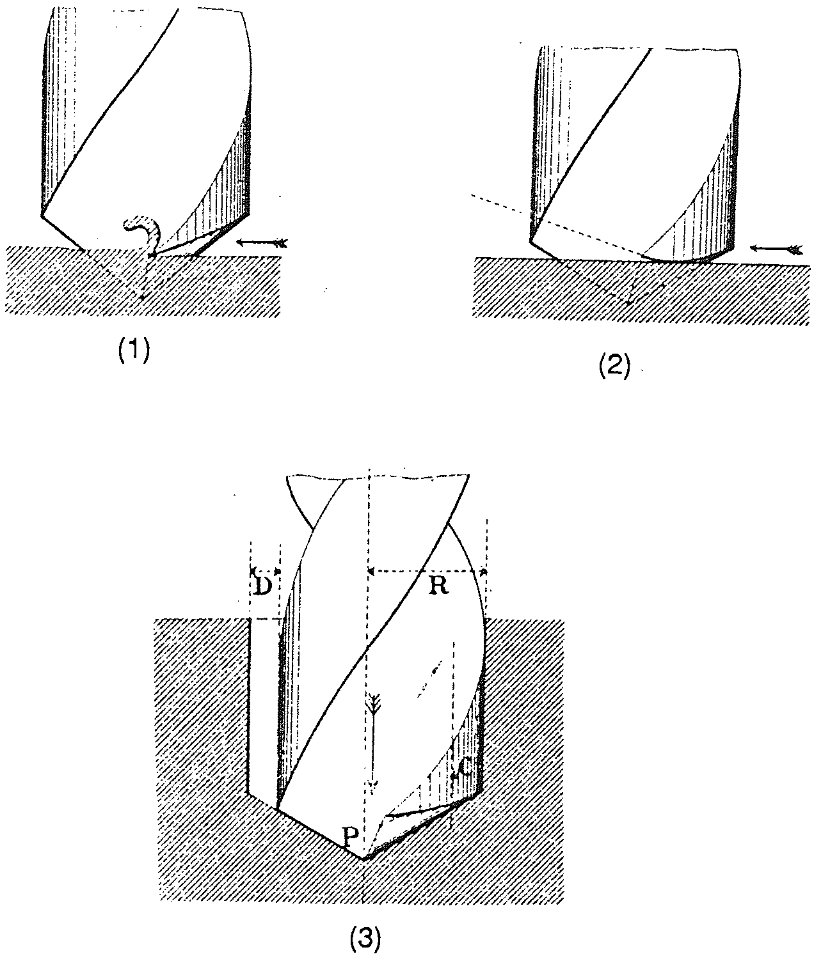



FIG 2.7 TWIST DRILL- POINT GRINDING PROBLEMS-1883

(1) - CLEARANCE ANGLE TOO LARGE

(2) - INSUFFICIENT CLEARANCE ANGLE

(3) - DRILL POINT GROUND OFF CENTRE

# CHAPTER THREE

# DESIGN OF EXPERIMENTATION AND INSTRUMENTATION

## 3.1 METHODS OF HOLE PRODUCTION BY DRILLING

Hole making is the most common of all machining operations and twist drills are the most commonly used metal cutting tools [17]. In order to produce holes with twist drills or 2 flute carbide tipped drills, two basic motions are required, i.e., rotation and rectilinear motion of the tool. There are four kinematic possibilities to achieve this in drilling:-

(i) Vertical Drilling - In which the tool performs both rotation and rectilinear motion.

(ii) Horizontal Drilling (Type 1) - In which the tool is stationary and moves rectilinearly whilst the workpiece rotates.

(iii) Horizontal Drilling (Type 2) - In which a rotating tool is used whilst the workpiece moves rectilinearly.

(iv) Stationary Tool Dilling - This involves both rotation and feed of the workpiece with a stationary drill.

In this research drilling configurations (i) to (iii) above were used and the machine and tooling configurations used are described below.

## 3.2 MACHINE TOOLS

The use of special purpose machine tools enabled a wide range of different drilling tests to be undertaken. The variables that were set on the machine included the operating speed, feed rate and drilling depth.

### 3.2.1 Vertical Drilling

#### 3.2.1.1. Olivetti N.C. Milling Machine

The Olivetti N.C. Milling Machine (Fig.3.1) (see Appendix I) was used extensively for trials with 12.70 mm dia. twist drills. The paper tape program facility enabled multi hole drilling trials to be undertaken automatically and quickly. The drill was held in a collet chuck. Both speed and feed and tool life tests were undertaken. The spindle speeds were selected from the gearbox and feed rates were programmed on to the N.C. tape. The workpiece was fixed to the machine bed.

#### 3.2.1.2. Drill Press

A bench-top Drill Press, with a hand feed arrangement with a lever arm extension was used for vertical drilling trials with twist drills and drill screws. The drilling speed was adjusted on the selector as required. Pre-selected feed rates were not used because constant thrust forces were required rather than constant feed rates. Thrust forces were applied by hanging weights on to the lever arm. Both twist drills and drill screws were held in a 3-Jaw Jacobs Chuck. The workpiece was fixed in a vice on the machine table.

#### 3.2.1.3. Radial Arm Drilling Machine

Verical drilling tests on the Asquith Radial Arm Drilling Machine were performed with both H.S.S. and Carbide Tipped drills. The speed and feeds were selected from the range available on the spindle gearbox. The drills were held by a series of Morse Taper Adaptors. The workpiece was fixed to the Machine Table.

### 3.2.2. Horizontal Drilling

#### 3.2.2.1. Torshalla CNC Lathe

The Torshalla CNC Lathe (Fig.3.2) (Appendix II) was used for horizontal drilling trials of the Types 1 and 2 previously specified.

For the basic horizontal drilling of the Type 1 with a staionary tool, the workpiece was held in the lathe chuck. The drill was secured into a special adaptor that was fitted to the Lathe Turret. A programe was written which enabled a drilled hole to be made and the appropriate speed and feed rate to be chosen.

An alternative arrangement for horizontal drilling (Type 2) was adopted for some carbide tipped drills in which the drilling trials were performed with a rotating drill gripped in the lathe chuck. The drill was secured in a special adaptor and the workpiece was fixed into a special holder on the Lathe Turret. A program was written that enabled the workpiece to be positioned onto the centre line of the chuck and advanced to produce the drilled hole.

## 3.3 DRILLING TOOLS

The research was concentrated on H.S.S. twist drills, carbide tipped drills and carbon steel drill screws, the individual features and geometries of which are described separately.

## 3.4 DRILL POINT GRINDING

Lorenz [18] demonstrated that drill points ground by machine enabled superior quality holes to be produced compared to holes made with drills sharpened by hand held methods. Precision Drill Point Grinding techniques were therefore essential [19],[20],[21],[22].

The grinding of H.S.S. twist drills and drill screws was undertaken on Micron Model 108 drill point grinding machine. Detailed grinding modifications included changes to point angle, clearance angle and chisel edge angle. (Fig.3.3)

On the carbide tipped drills some drill point grinding was undertaken on a Universal Grinding Machine as well as by hand methods.

## 3.5 MEASUREMENT AND INSTRUMENTATION

In all aspects of the research, measurement of the drill geometry, drill wear, hole quality and drill performance provided the basis for accurate data on the entire hole producing operation.

### 3.5.1. Drill Measurement

The measurement of drill geometry was the first fundamental requirement in the experimental design. Correct drill geometry and symmetry were necessary to ensure repeatability in the test results.

All basic drill point measurements, including lip heights and angles, were undertaken on the Universal Measuring Machine (Fig.3.4). A Shadow Graph and a Jig Boring Machine with eyepiece attachment were also used.

The nominal drill diameters were 12.70, 15.875 and 19.05 mm and for the drill screw tests, the nominal drill diameter was 5.1 mm, for Type 'F' drill screw.

### 3.5.2. Drill Wear Measurement

In order to compare the extent of drill wear after repeated hole drilling some tool wear tests were undertaken. The tool wear was assessed by measuring the amount of corner wear on the land of the drill. The measurements were made on the Universal Measuring Machine, with the aid of a Sylvac linear transducer and digital display unit.

### 3.5.3. Hole Quality Measurement

Although twist drilling was not traditionally regarded as a precision hole producing operation [23], the use of new surface coatings on drills and new carbide tipped drill geometries may result in improved hole quality. The demand for precision holes arises in applications where reamed hole tolerances are specified. For tapping applications better control of hole diameter may lead to improved screw thread joint strength.

Good quality holes produced directly by drilling without reaming, counterboring or the use of centre drills at the start of the hole [24] may offer tremendous scope for savings in both machining time and tooling costs.

In order to assess the drilled hole quality several inspection techniques were adopted in the experimental design to ensure that the geometrical tolerances of the hole were measured as follows.

### 3.5.3.1. Hole Diameter

Measurements to determine the hole diameter of the through holes were made by taking bore gauge readings at drill entry and exit from the workpiece.

A Sylvac bore gauge probe, connected to a digital readout was used in later work (Fig.3.5). The advantage of this system was that a computer interface with the digital display unit enabled hole diameter measurements to be switched directly to a Macintosh Computer (Fig.3.6) and subsequently plotted on to a printer as a chart. (Fig.3.7)

### 3.5.3.2. Hole Roundness

Hole roundness comparison tests were undertaken on selected holes at drill entry and exit. A TalyRond Roundness Measuring Machine was used.

Sample traces were produced that enabled the roundness of holes produced by different drills and with different operating conditions to be compared.

### 3.5.3.3. Hole Surface Finish

The surface finish obtained in a drilled hole can provide a good indication of the metal cutting conditions. Any built up edge (BUE) or wear on the cutting lips or lands can result in a deterioration in the hole surface finish. The use of pressure fed coolant and new surface coatings on drills may lead to reduced friction and improved chip ejection in the flutes of the drill and subsequently an improved finish. Hole surface finish measurements were therefore essential in determining the drill performance.

All surface finish measurements were made on a Taly Surf Machine, the average finish (μmRa) was obtained over a number of readings and selected finish traces were also made.

### 3.5.4 Drill Performance Measurements

Important drill performance criteria, torque, thrust force and radial out of balance force were obtained using a Drilling Dynamometer. The Dynamometer was used in both the horizontal and vertical drilling modes. For horizontal drilling it was attached to the lathe turret and acted as an additional holder to carry either the workpiece or the drill. In vertical drilling the Dynamometer was attached to the bed of the machine and the workpiece fixed on to it.

Details of the Kistler Dynamometer and the associated Amplifiers and U.V. Recorder are given in Appendix (III).

The drill performance data, for any given drill or set of operating conditions was displayed on a U.V. Recorder Trace.

The magnitude and changes in torque, thrust and out of balance force was observed for the entire hole depth. The accuracy of performance measurements obtained from the U.V. Trace was generally in the order of ±2%. In some cases when the difference in the comparative test data were very small other performance criteria was presented as supporting evidence.

3.5.4.1 Torque Measurement

The changes in drilling torque at a given speed were accompanied by proportional changes in power consumed at the spindle motor.

The torque in drilling was dependent upon the operating conditions (speed feed), drill diameter, drill geometry and the hardness of the material being drilled.

The torque was measured from the U.V. trace and the values obtained were usually averages taken from a mean line drawn through the trace.

Where fluctuations in the trace occurred this provided a guide to the metal cutting conditions. If swarf clogging in the flutes, or built up edge on the drill lips or chisel edge occurred this was likely to lead to increases in torque.

3.5.4.2. Thrust Measurement

Measurements of the drill thrust force were made in order to assess the effectiveness of different drill point geometries.

The thrust force was very sensitive to changes in point geometry, particularly point angle, chisel edge angle, chisel length and clearance angle.

For any given drill and set of operating conditions the thrust force, like the torque, provided an indication of the cutting efficiency of the drill.

The thrust force was measured from the U.V. trace and the values stated were usually averages taken from a mean line drawn through the trace.

3.5.4.3. Out of Balance (Radial Force Measurement)

The radial force measurement provided an indication of the drill run out or deflection.

Measurements of the radial force were also used for assessing the effectiveness of different drill point designs.

If asymmetric point configurations were used or when errors occurred in point grinding, the radial force was measured. The maximum radial force often occurred at drill entry to the workpiece and this was measured off the U.V. trace.

## 3.6 TEST MATERIAL

All the drilling tests were confined to drilling shallow through holes with hole depths of twice the diameter using EN1A or EN8 steel. Regular hardness tests were made to ensure that the material in either bar or plate form was consistent.

## 3.7 COOLANT

All drilling tests with H.S.S. and carbide tipped drills were performed with Edgar Vaughan HoCut Type 3210A soluble cutting fluid diluted one part fluid to ten parts water. This was an extreme pressure additive type coolant designed to provide enhanced lubrication properties under arduous cutting conditions.

For conventional drills, the coolant was applied from an external nozzle which directed a jet of coolant on to the drill/workpiece interface. This method provided "flood" cooling for both the CNC Lathe and NC Milling Machine. The existing suds coolant pumps were used in each case and the maximum pressures developed were about 4 bars,

For the tests with coolant fed drills an additional pump was installed on to the CNC Lathe and the coolant was fed directly through the shank of the drill via a coolant inducer manifold on the Lathe turret. The new pump was a Grundfoss Multistage Type CP2-200K, which enabled pressures of up to 16 bar to be developed.

The tests with drill screws were performed without lubrication to simulate the actual working conditions encountered with normal usage.

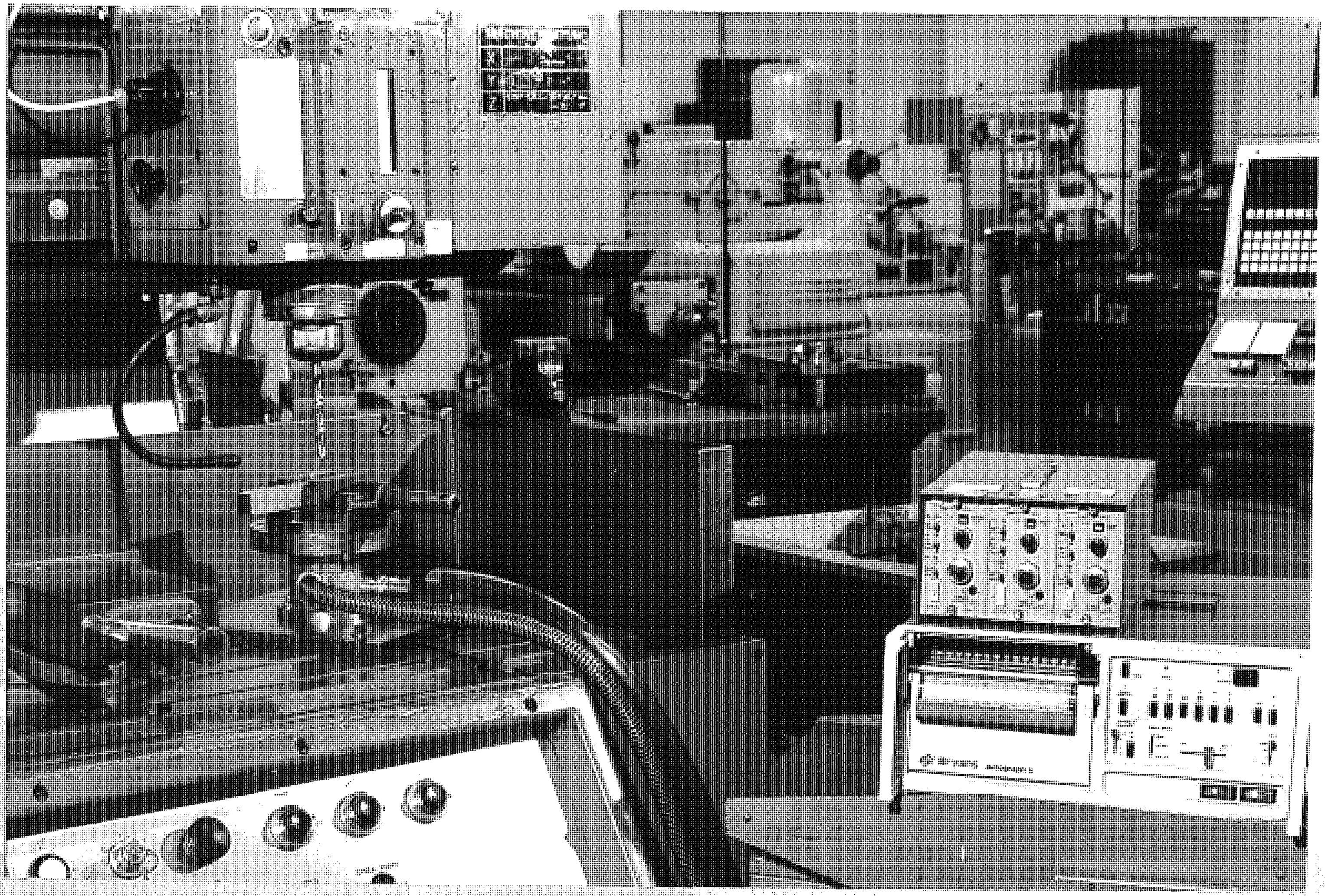


FIG 3.1 OLIVETTI NC MILLING MACHINE - SET UP FOR VERTICAL DRILLING TRIALS

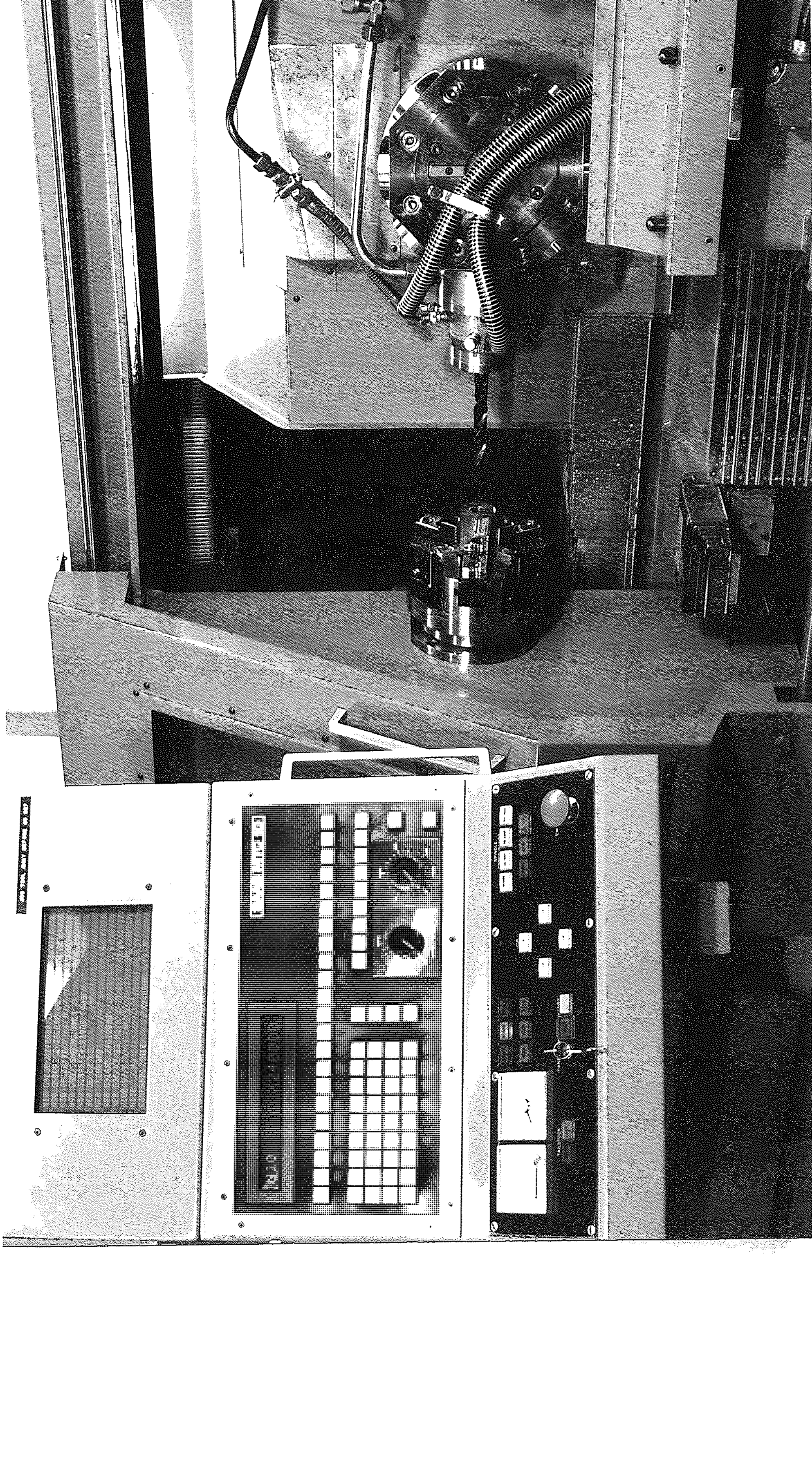


FIG 3.2 TORSHALLA CNC LATHE -SET UP FOR HORIZONTAL DRILLING TRIALS

FIG 3.3 THE MICRON DRILL POINT GRINDING MACHINE

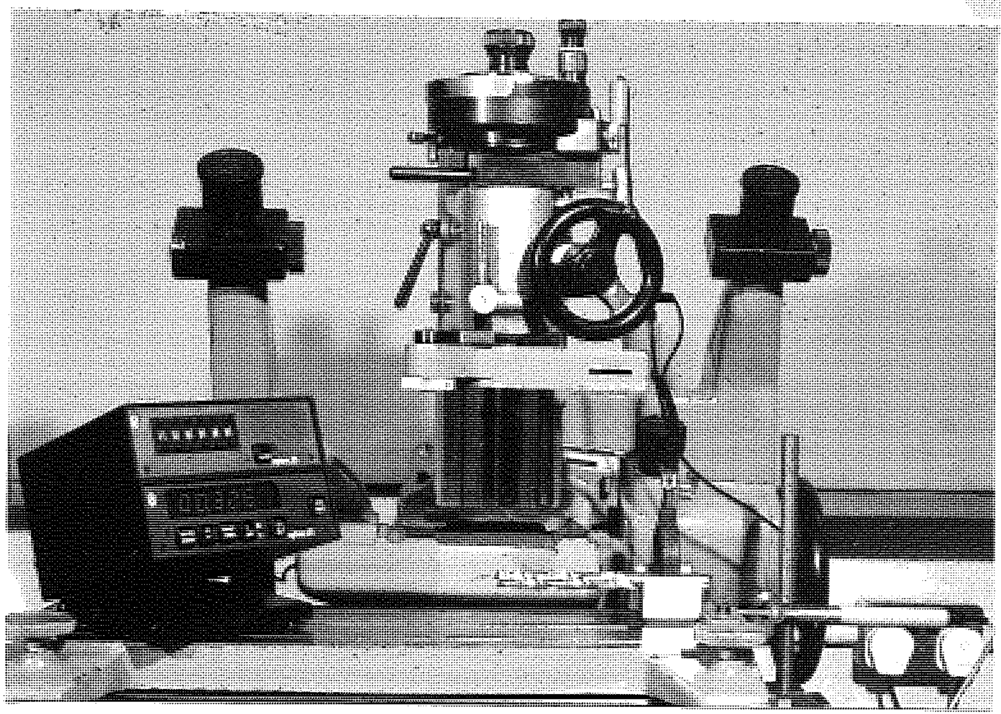


FIG 3.4 THE UNIVERSAL MEASURING MACHINE

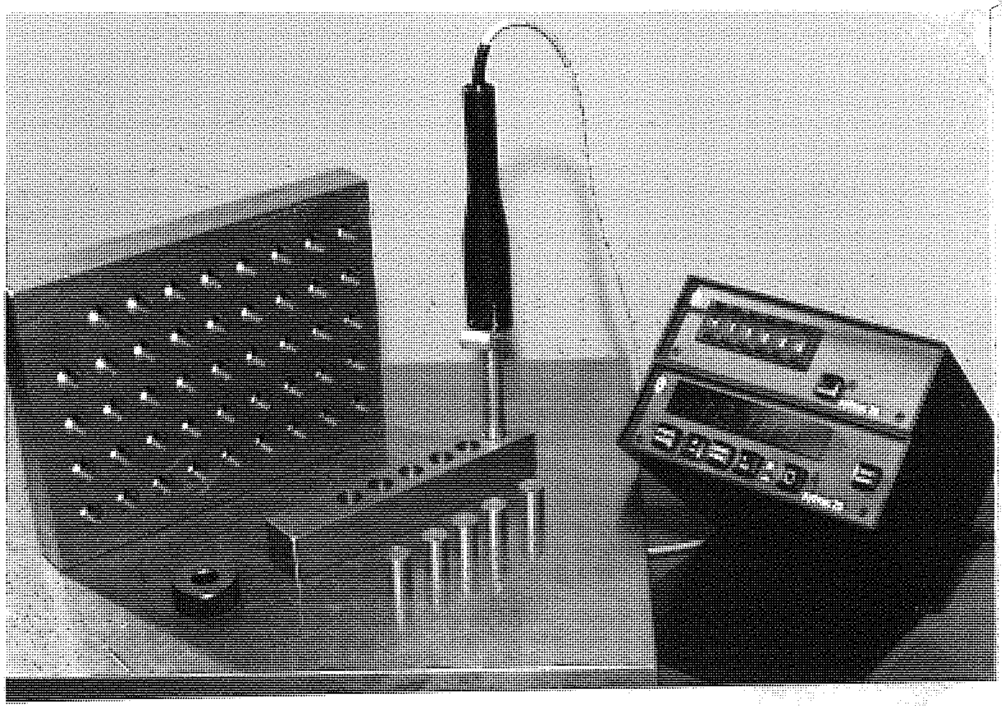


FIG 3.5 THE "SYLVAC" BORE GAUGE AND DIGITAL DISPLAY UNIT

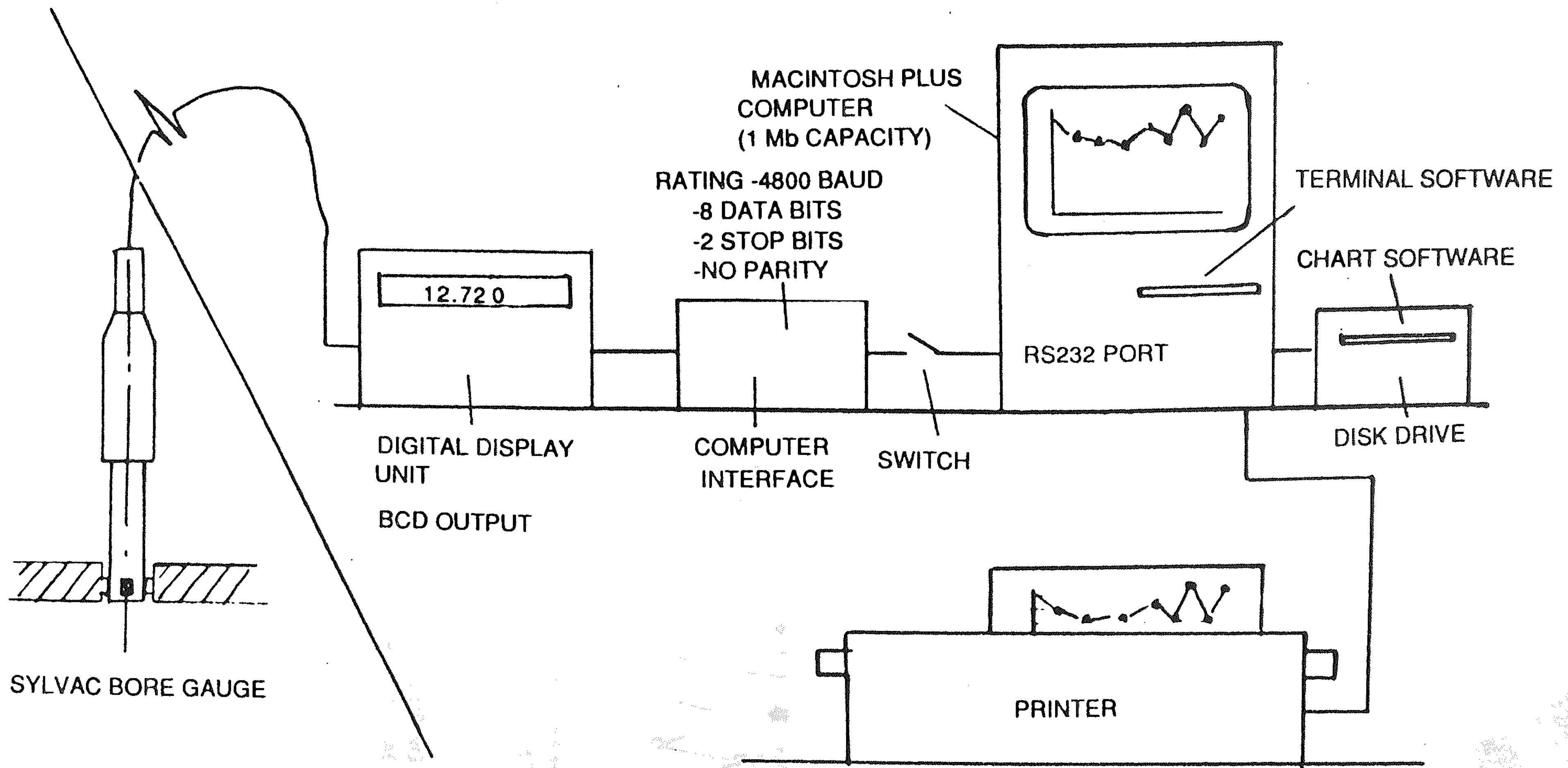



FIG 3.6 COMPUTER AIDED HOLE MEASUREMENT SYSTEM

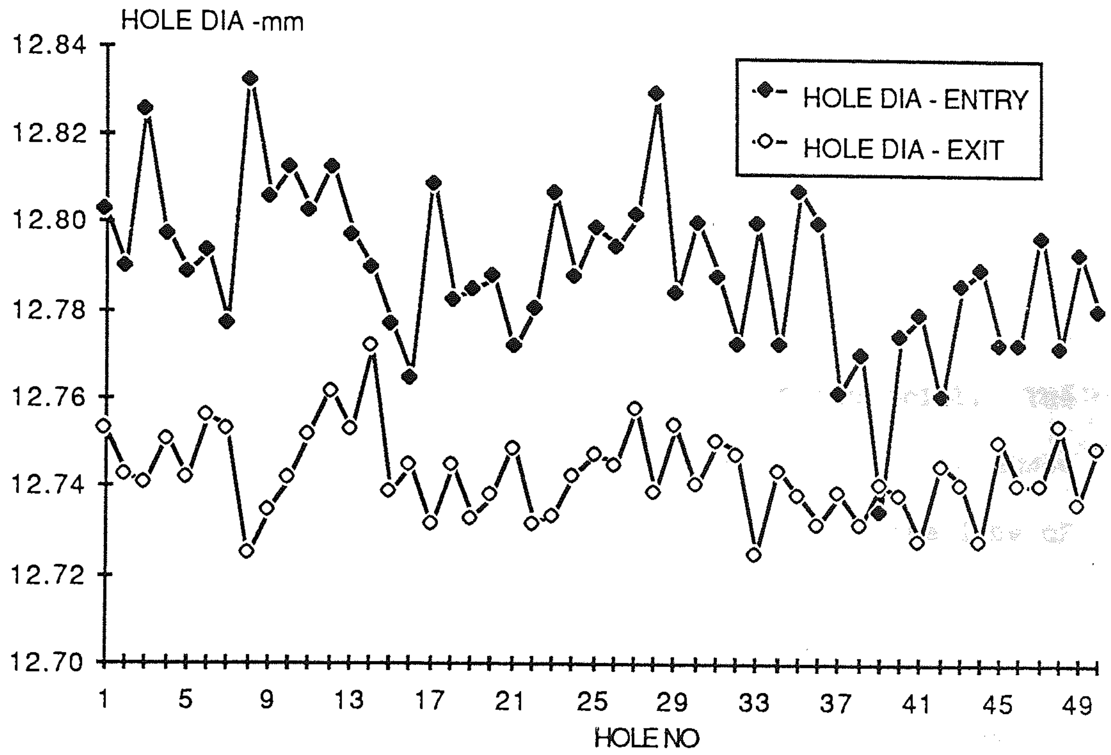



FIG 3.7 12.70 mm DIA STEAM TEMPERED TWIST DRILL
EXAMPLE OF COMPUTER PLOT OF HOLE DIAMETERS USING "SYLVAC" DIGITAL BORE GAUGE AND COMPUTER INTERFACE

# CHAPTER FOUR

## IMPORTANT ASPECTS OF TWIST DRILL GEOMETRY AND SYMMETRY

### 4.1 INTRODUCTION

The basic geometry and point configuration of a twist drill is specified in BS328-1985. This standard covers all the geometrical features and nomenclature of twist drills that are manufactured to a "conventional" geometry (Fig.4.1).

The conventional geometry incorporates a straight cutting lip which extends from the chisel edge to the land of the drill. The straight lip is generated from the intersection of the flute shape and point angle in grinding. Each lip lies above the centre line of the drill by an amount equal to half the web thickness.

It is important to maintain a symmetrical configuration at the drill point in order to balance the cutting forces acting on each lip (Fig.4.2). Any out of balance may contribute to unequal wear rates on the lips or run out of the drill. An asymmetric point may arise in drill manufacture through unequal fluting and this can lead to an eccentric chisel edge. Alternatively the asymmetry may be generated in point grinding and differences in lip height may contribute to poor drill performance, [25],[26],[27].

In order to obtain the straight cutting lip the drill must be ground to the specified point angle. A common point angle used is 118° (ie point half angles of 59°). When the point angle is ground much greater than 118°, the cutting lip will tend to become concave and for point angles less than 118° the lip will tend to become convex (Fig 4.3).

In this chapter the effect of point grinding errors with respect to lip height differences and also errors in point angle are considered.

## 4.2 POINT GRINDING ERRORS AND THE EFFECT ON FEED RATE PER LIP FOR DIFFERENCES IN LIP HEIGHT

In conventional drill point grinding a common error occurs when the drills are ground to the correct point angle but the lips are asymmetric such that one lip leads the other. This configuration leads to the chisel edge point becoming eccentric by an amount 'e' for a difference in lip height 'h' (Fig. 4.4) [28].

It is also important for the drill point half angle (x) to be ground equal or this again will produce a difference in lip height.

When the drill is ground with equal half angles 'x' on each lip; but one lip leads the other by an amount 'h' the feed (f) instead of being equally divided between each lip i.e. $\frac{f}{2}$ will increase to $\frac{f}{2} + \frac{h}{2}$ for the leading lip; and decrease to $\frac{f}{2} - \frac{h}{2}$ for the trailing lip. In the limiting condition only one lip and the chisel edge will cut, leaving the other lip to rub.

For a difference in lip height 'h', the chisel eccentricity e is given by $e = \frac{h}{2} \tan x$.

The feed rate per lip $f_1$ and $f_2$ can then be expressed as:-

$$f_1 = \frac{f}{2} + e \cot x$$

$$f_2 = \frac{f}{2} - e \cot x$$

In the limiting condition for only one lip cutting, $f_1 = f$ and $f_2 = 0$

$$\therefore e_{lim} = \frac{f}{2} \tan x.$$

where $e_{lim}$ is the limiting chisel eccentricity.

In general one lip will cut when $e \geq e_{lim}$.

The effect of the point eccentricity is also to increase the diameter of the drilled hole by 2e.

i.e. hole oversize = $2e = h \tan x$.

## 4.3 EXPERIMENTAL DESIGN

In order to establish the importance of correct drill point grinding on drill performance only two aspects of the point grind were investigated as follows:-

### 4.3.1. Lip Height Variation

The effect of three lip height errors of 0.05, 0.10 and 0.18 mm were compared with a correctly ground drill with no lip height difference.

### 4.3.2. Point Angle Variation

The effect of drilling with 112° and 124° point angles were compared to the specified point angle of 118°. (All other variables eg. clearance angle and chisel edge angle were maintained constant).

## 4.4 TEST EQUIPMENT

### 4.4.1 Drills - Measurement and Inspection

All tests were performed with 19.05 mm dia conventional twist drills. To establish the drill point parameters, detailed measurement and inspection procedures were undertaken with a Universal Measuring Machine that incorporated a "goniometer" eyepiece for measuring angles. A Sylvac linear transducer with digital readout was used to establish lip height differences and used in conjunction with the Universal Measuring Machine.

The end view of the drill and details of the chisel edge were obtained from a Shadow Graph Projection.

4.4.2. Drill Grinding

All drills were ground on Micron Model 108 Drill Point Grinding Machine.

4.4.3. Drill Testing

All tests were performed on the Torshalla CNC Lathe, (see Appendix II). Horizontal drilling trials were undertaken with the drill mounted in an adaptor on the Lathe Turret which also included a Kistler Drilling Dynamometer for Cutting Force Measurement. (APP.III).

The workpiece, 38 mm lengths of EN 1A mild steel was gripped in the Lathe Chuck and 2d deep holes were produced with an external supply of suds coolant.

4.4.4. Hole Measurement

The measurement of the hole diameters at drill entry and exit from the workpiece were made with a bore gauge probe coupled to the Sylvac Digital Readout.

## 4.5 TEST PROCEDURE

All 19.05 mm dia test drills were ground on the Micron Drill Point Grinding Machine and then carefully inspected to ensure that the desired lip height differences were obtained for the first test. In the second test the drill point angles were also modified on the Micron Machine.

Drilling Tests were performed at 600 rpm and feed rates of 0.1-0.4 mm/rev for the lip height trials.

The feed range was extended to cover 0.1-0.6 mm/rev for the trials with different drill point angles whilst maintaining the same speed of 600 rpm.

The Drill Torque, Thrust and Out of Balance force was recorded for all tests. Hole diameter measurements were also undertaken.

## 4.6 TEST RESULTS

Details of the Drill Point Geometries are presented in Table 4.1.

The performance results and hole oversize at different lip height errors are presented in Table 4.2. The Torque, Thrust and Out of Balance Force results are plotted in Fig.4.5.

The hole oversize at different feed rates is plotted in Fig.4.6. Table 4.3 shows the feed taken by each cutting lip and point eccentricity for different lip height errors together with the theoretical hole oversize.

Comparison of the actual and theoretical hole oversize are given in Fig.4.7.

The drill performance at different point angles is presented in Table 4.4 and Fig.4.8.

## 4.7 DISCUSSION OF RESULTS

### 4.7.1 Drilling Trials with Different Lip Height Errors

Dynamometer results for the torque, thrust and out of balance force are shown in Fig.4.5. From the torque plot it will be observed that small lip errors of up to .05 mm did not apparently affect the torque and hence the power consumption in drilling for the range of feeds considered. At lip height errors of 0.18 mm a torque increase of 7.5 - 10% was recorded compared to the torque with an equal lip height configuration. This was probably due to the eccentric running of the chisel edge rather than the unequal chip thickness distribution on the cutting lips.

The total drill thrust force remained nearly constant even when the drill was cutting on only one lip, or when the lip feed distribution was uneven (see Table 4.2). The effect of small lip height errors did not lead to significant increases in the thrust force. A high percentage of the total thrust can be attributed to the chisel edge, which continued to cut, albeit eccentricly (see Chapter 5) when there was a lip height difference.

The maximum out of balance force, which usually occurred at drill entry to the workpiece was consistently highest at 0.1 mm/rev and the magnitude did tend to increase with increasing lip height errors. These results confirmed that there was a much greater tendency for the drill to deflect or "walk" at low feed rates at drill entry. The presence of lip height errors and an eccentric chisel edge tended to exacerbate the problem.

The effect of the out of balance forces can be directly related to the amount of hole oversize generated at different feed rates (Fig.4.6). The maximuim oversize occurred with the largest lip height errors of 0.18 mm and the amount of hole oversize at drill entry, where the point was unsupported, exceeded 0.8 mm at 0.2 mm/rev.

At drill exit the maximum hole oversize of 0.25 mm was recorded at 0.1 mm/rev with 0.18 mm lip height difference despite the additional land support on the drill, which was provided by the drilled hole.

All the holes produced were essentially bell mouthed in form. The effect of lip height errors increased the amount of oversize generated and the choice of feed rate also contributed to the hole oversize. Other factors like unsupported drill length and torsional stiffness also probably contributed to oversize.

The hole oversize was compared with the theoretical value (h tan x) at different lip height errors (see Fig.4.7). At 0.3 ands 0.4

mm/rev feed rates there was a good correlation between the actual and theoretical oversize at drill entry. For feed rates of 0.1 and 0.2 mm/rev the actual oversizes tended to rapidly diverge from the theoretical value, particularly at 0.18 mm lip height difference.

At drill exit most of the hole oversize generated was below the theoretical value and the theoretical line (h tan x) tended to form a boundary, which inidicated the likely maximum hole oversize at exit from the 2D deep holes.

### 4.7.2 The Effect of Different Point Angles

The test results for the 19.05 mm dia twist drills ground at incorrect point angles were plotted in Fig.4.8. Note that there was little or no change in the drilling torque for point angles in the range 112° - 124° at a given feed rate. This was to be expected because the metal removal rate was constant and the drill chip thickness would only be expected to vary by about ±3% for point angle changes of ±6°.

Changes in the drill point angle from 118° resulted in small changes in the thrust force in the order of + 5% at 124° point angle and -5% at 112° point angle.

Inspection of the tested drills showed that at a 112° point angle, extensive overheating and built up edge occurred at the chisel edge whereas this wear was transferred almost entirely to the drill lips with a 124° point angle. The conventional 118° point geometry by comparison showed a more uniform wear pattern across the lips and chisel edge. The choice of a 118° point angle therefore probably represented a compromise between optimum cutting conditions and good tool life. (The effect of further changes in drill point geometry are also reported in Chapter 11).

## 4.8 CONCLUSIONS

(i) Precision drill point grinding and particularly accurate control of lip height to within .05 mm were essential; to produce precision holes with twist drills. Hole oversizes at drill entry of up to 0.838 mm were measured for a nominal hole size of 19.05 mm, when the lip height error was 0.18 mm.

(ii) In the limiting condition where only one lip of the 19.05 mm dia drill was cutting at feed rates of 0.1 mm/rev, lip height errors of 0.10 and 0.18 mm resulted in hole oversizes of 0.279 and 0.660 mm respectively at drill entry.

(iii) The combination of large lip height errors and fine feed rates should be avoided in order to produce precision holes.

(iv) It is unlikely that twist drills ground by hand will produce precision holes.

(v) Hole oversize was usually much greater at drill entry and the use of higher feed rates may help to reduce this problem without the need of resorting to centre drills.

(vi) Conventional drills that are incorrectly point ground may result in reduced tool life.

(vii) The amount of hole oversize generated in drilling was consistent with theory, but the value also depended upon hole depth, feed rate, drill length and the rigidity of the drilling set up.

| | |
|---|---|
| Point Angle | 118° |
| Clearance Angle | 10° |
| Helix Angle | 32° |
| Chisel Edge Angle | 120° |
| Web Thickness at Point | 2.5 mm |
| 4 Drills - Lip Height Differences of 0, 0.05, 0.10 and 0.18 mm | |

Point Angle Modifications
Point Angles of 112°, 118°, 124° - geometry as above with no lip height difference.

**TABLE No. 4.1**

**DETAILS OF 19.05 mm Dia. CONVENTIONAL TWIST DRILLS USED IN LIP HEIGHT AND POINT ANGLE MODIFICATIONS.**

| LIP HEIGHT ERROR (mm) | FEED RATE (mm/rev) | TORQUE (Nm) | THRUST (KN) | MAXIMUM OUT OF BALANCE FORCE (N) | HOLE OVERSIZE (mm) | | THEORETICAL OVERSIZE (mm) = h tan x |
|---|---|---|---|---|---|---|---|
| | | | | | ENTRY | EXIT | |
| 0 | 0.1 | 10.5 | 1.7 | 80 | .228 | .013 | 0 |
| | 0.2 | 19.0 | 2.6 | 40 | .165 | .013 | |
| | 0.3 | 25.0 | 3.5 | 50 | .064 | .040 | |
| | 0.4 | 34.0 | 4.9 | 40 | .064 | .040 | |
| 0.05 | 0.1 | 10.0 | 1.6 | 90 | .127 | .050 | .083 |
| | 0.2 | 19.0 | 2.5 | 75 | .100 | .050 | |
| | 0.3 | 27.0 | 3.5 | 45 | .076 | .050 | |
| | 0.4 | 34.0 | 4.9 | 20 | .076 | .076 | |
| 0.10 | 0.1 | 11.0 | 1.7 | 125 | .279 | .050 | .166 |
| | 0.2 | 20.5 | 2.7 | 75 | .279 | .050 | |
| | 0.3 | 27.0 | 3.4 | 75 | .200 | .025 | |
| | 0.4 | 35.0 | 4.9 | 80 | .200 | .050 | |
| 0.18 | 0.1 | 11.5 | 1.6 | 110 | .660 | .250 | .299 |
| | 0.2 | 21.0 | 3.0 | 55 | .838 | .089 | |
| | 0.3 | 28.5 | 3.6 | 50 | .400 | .076 | |
| | 0.4 | 36.5 | 5.2 | 60 | .300 | .050 | |

**TABLE No. 4.2**

**19.05 mm Dia. TWIST DRILL: PERFORMANCE TEST RESULTS AND HOLE OVERSIZE AT DIFFERENT LIP HEIGHT ERRORS.**

| FEED RATE mm/rev | ECCENTRICITY LIMIT $e_{lim}$ (mm) | FEED RATE DISTRIBUTION PER LIP (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | EQUAL LIPS | | .05 mm LIP HEIGHT DIFF | | .10 mm LIP HEIGHT DIFF | | .18 mm LIP HEIGHT DIFF | |
| | | $f_1$ | $f_2$ | $f_1$ | $f_2$ | $f_1$ | $f_2$ | $f_1$ | $f_2$ |
| 0.1 | .083 | .05 | .05 | .075 | .025 | .10* | 0 | .10* | 0 |
| 0.2 | .166 | .10 | .10 | .125 | .075 | .15 | .05 | .19 | .01 |
| 0.3 | .249 | .15 | .15 | .175 | .125 | .20 | .10 | .24 | .06 |
| 0.4 | .332 | .20 | .20 | .225 | .175 | .25 | .15 | .29 | .11 |
| Actual Eccentricity of chisel, e (mm) | | e = 0 | | e = .04 | | e = .083 | | e = .15 | |

TABLE No.4.3

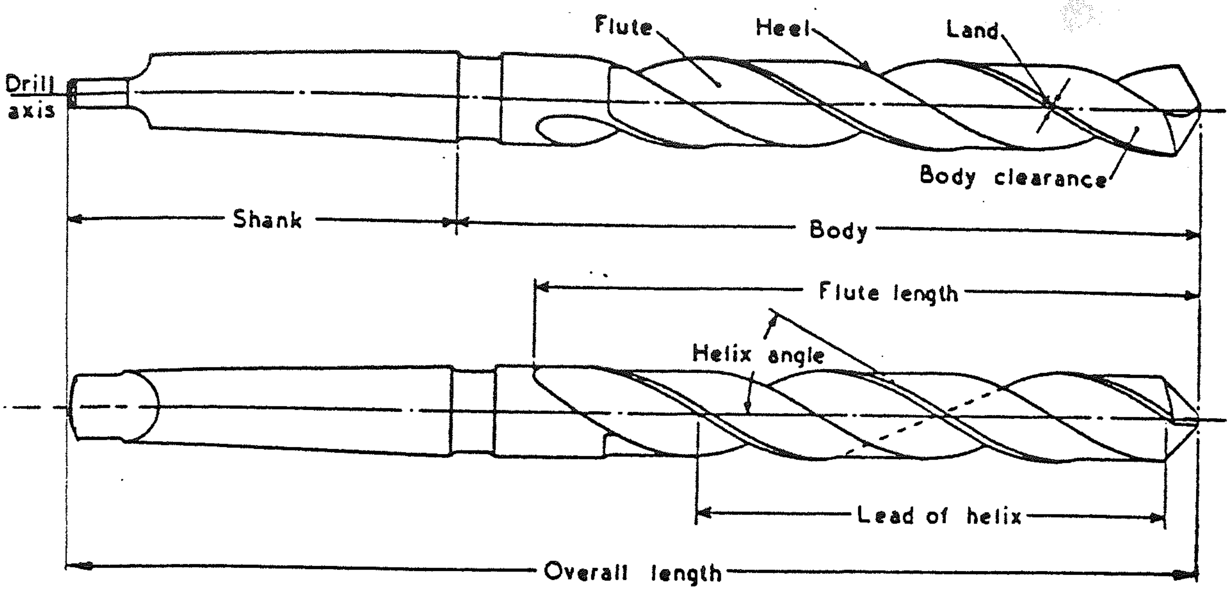
THE EFFECT OF LIP HEIGHT DIFFERENCE ON THEORETICAL FEED RATE PER LIP.

* N.B. Cutting on only one lip when $e \geq e_{lim}$.

| DRILL POINT ANGLE (Deg) | FEED RATE (mm/rev) | TORQUE (Nm) | THRUST (kN) |
|---|---|---|---|
| 112 | 0.1 | 10.5 | 1.5 |
| | 0.2 | 18.5 | 2.5 |
| | 0.3 | 26.0 | 3.6 |
| | 0.4 | 34.5 | 5.3 |
| | 0.5 | 44.0 | 7.2 |
| | 0.6 | 50.0 | 8.4 |
| 118 | 0.1 | 10.5 | 1.6 |
| | 0.2 | 18.5 | 2.8 |
| | 0.3 | 26.5 | 4.1 |
| | 0.4 | 34.0 | 5.5 |
| | 0.5 | 43.0 | 7.6 |
| | 0.6 | 52.0 | 9.2 |
| 124 | 0.1 | 11.0 | 1.8 |
| | 0.2 | 18.0 | 2.9 |
| | 0.3 | 26.0 | 4.0 |
| | 0.4 | 34.0 | 5.8 |
| | 0.5 | 44.0 | 8.0 |
| | 0.6 | 51.0 | 9.2 |

TABLE No.4.4

19.05 mm Dia. TWIST DRILL : THE EFFECT OF POINT ANGLE ON DRILL PERFORMANCE AT 600 rpm.



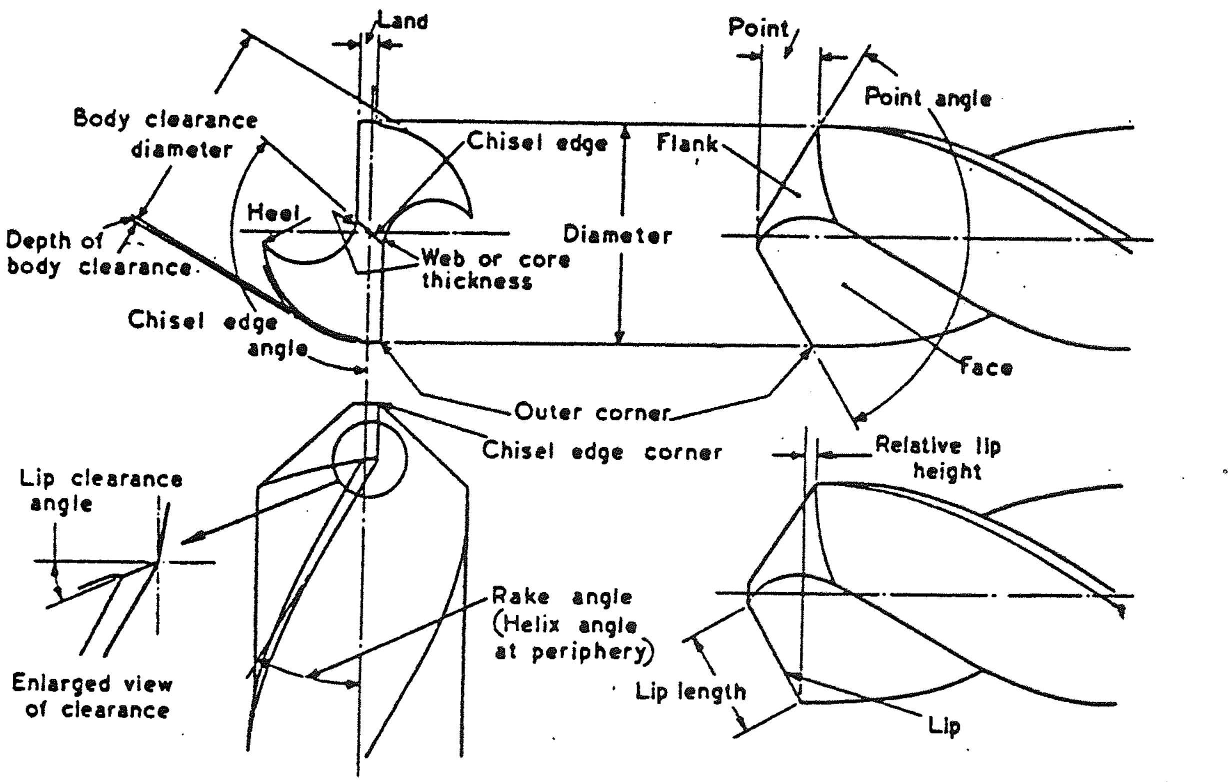




FIG 4.1 BASIC TWIST DRILL NOMENCLATURE

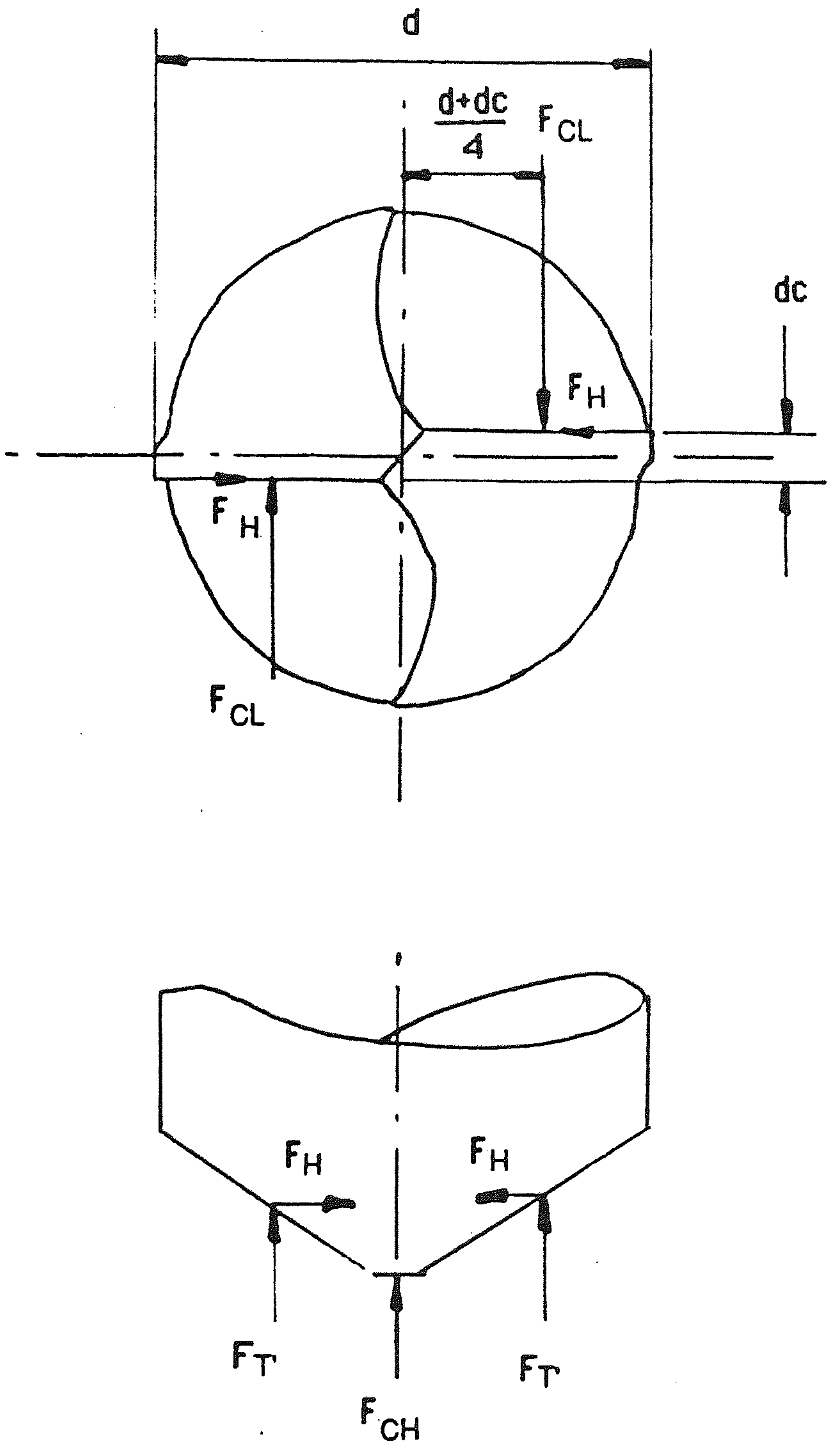
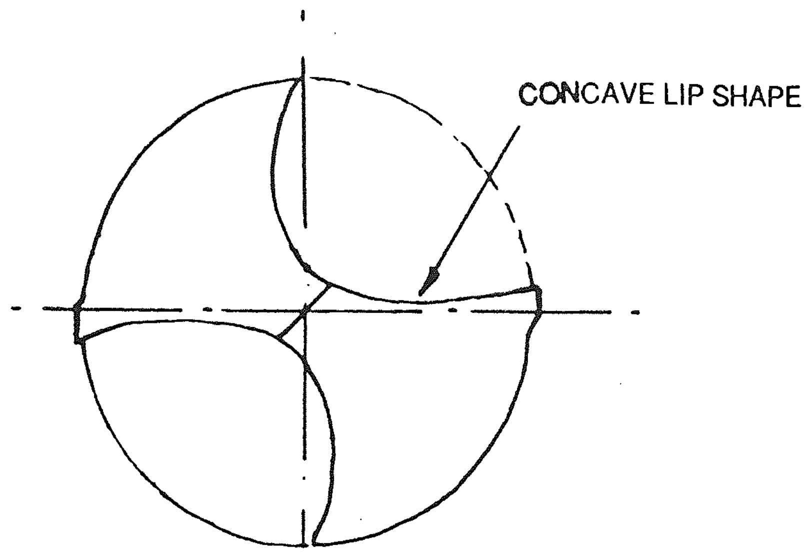
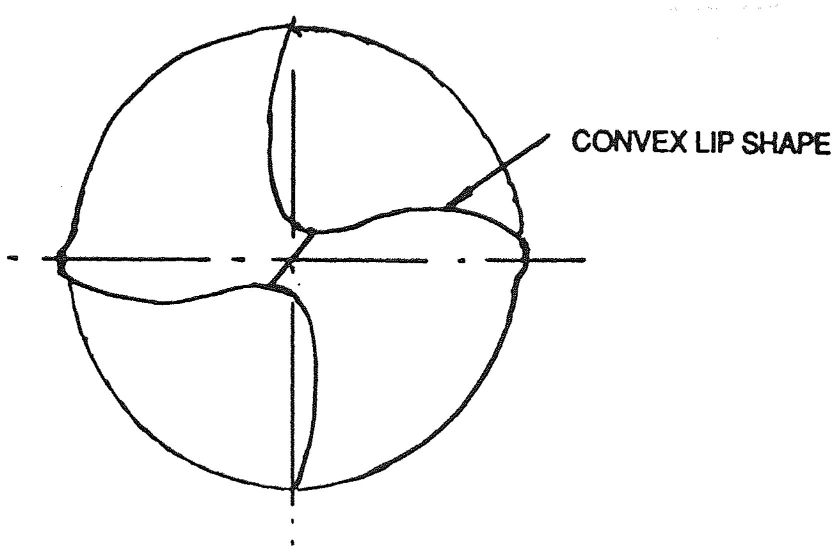



FIG 4.2 FORCE EQUILIBRIUM ON CUTTING LIPS OF TWIST DRILL GROUND WITH A SYMMETRICAL POINT CONFIGURATION

($F_H$ =NORMAL COMPONENT TO $F_T$)




POINT ANGLE GREATER THAN 118°




POINT ANGLE LESS THAN 118°

FIG 4.3 THE EFFECT OF GRINDING INCORRECT POINT ANGLES ON THE SHAPE OF THE TWIST DRILL CUTTING LIP

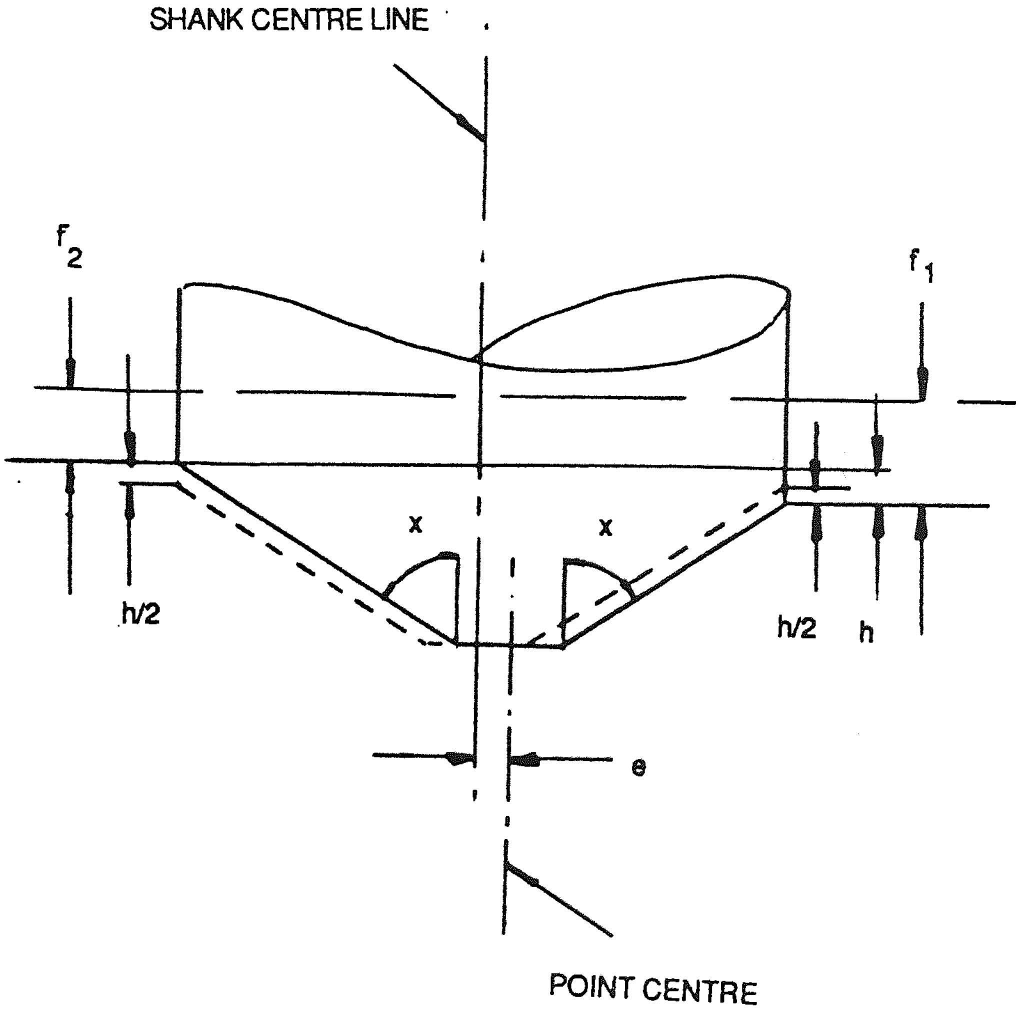



FIG 4.4 ERRORS IN DRILL POINT GRINDING - THE DIFFERENCE IN LIP HEIGHT "h" AND THE EFFECT ON FEED RATE PER LIP ($f_1$ & $f_2$) AND POINT ECCENTRICITY "e"

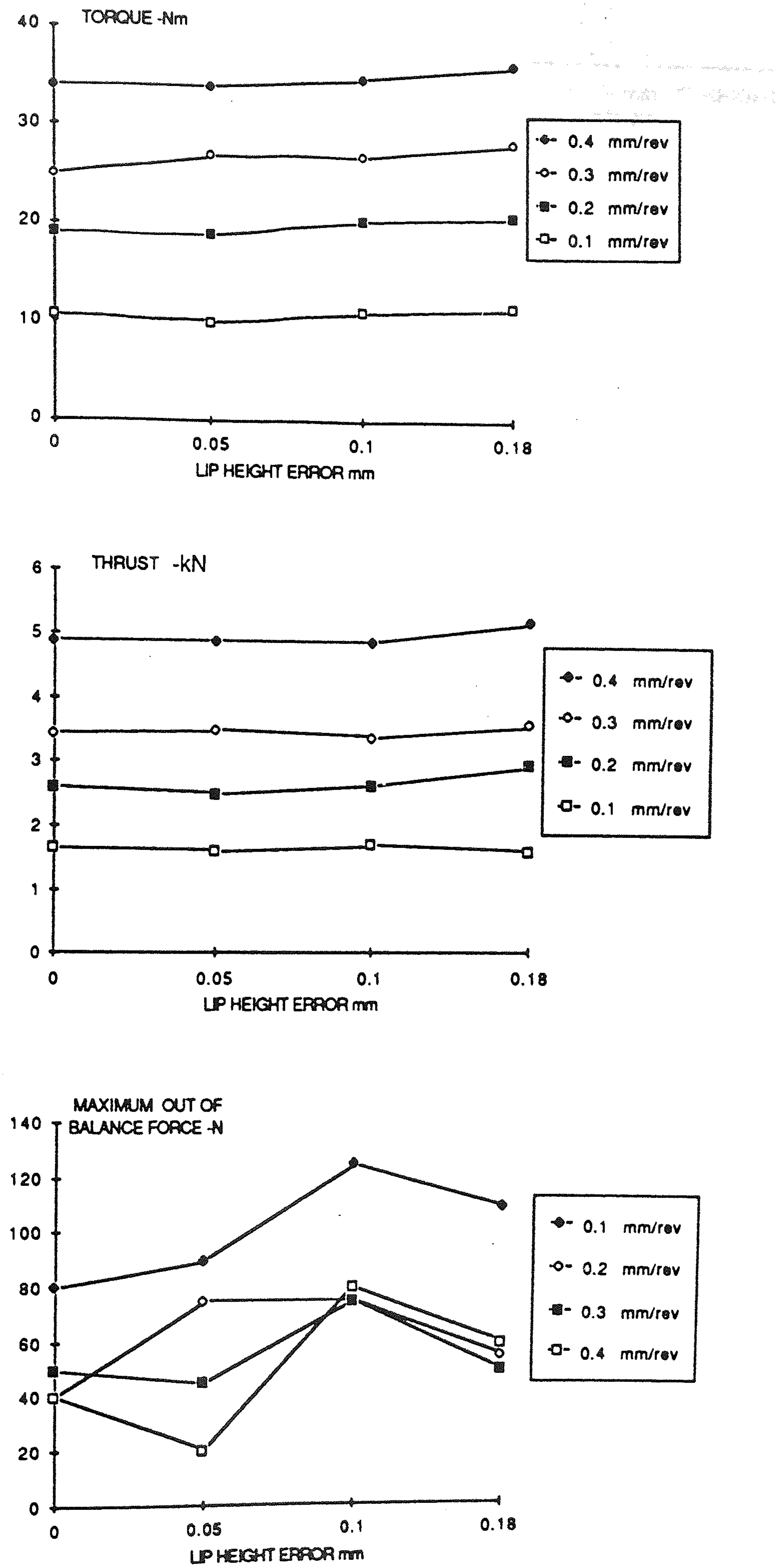
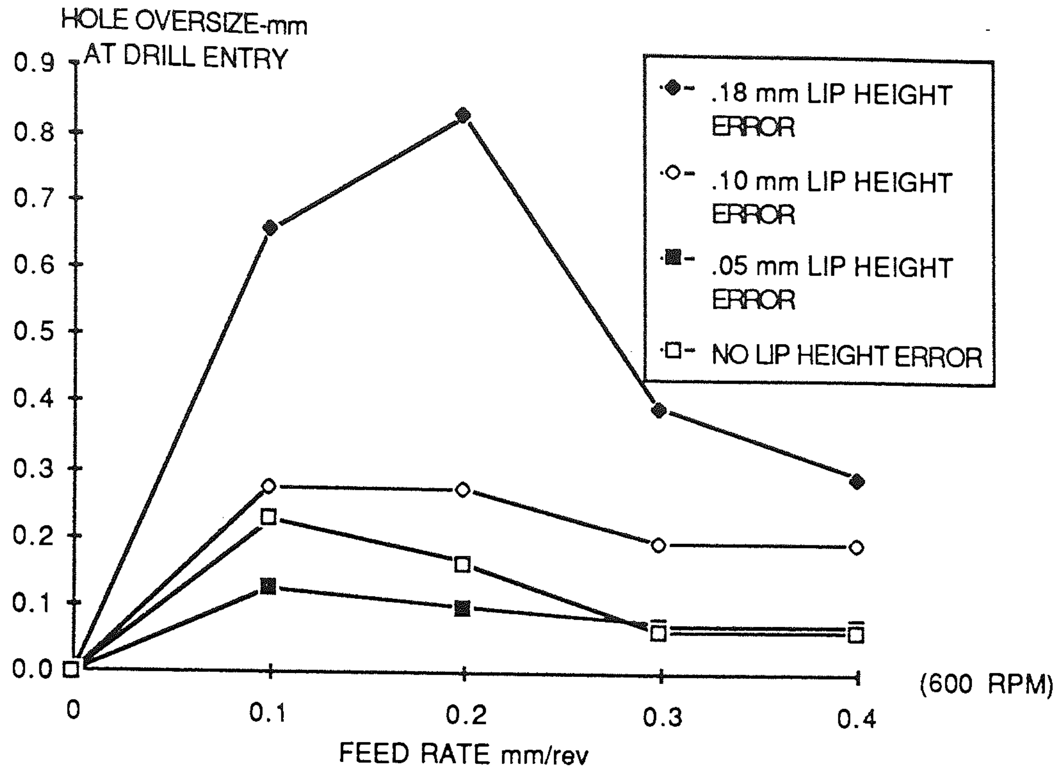



FIG 4.5 19.05 mm DIA TWIST DRILL THE EFFECT OF LIP HEIGHT ERRORS ON DRILL PERFORMANCE - COMPARISON OF TORQUE (Nm) THRUST (kN) AND OUT OF BALANCE FORCE (N) AT DIFFERENT FEED RATES (ALL TESTS AT 600 rpm)



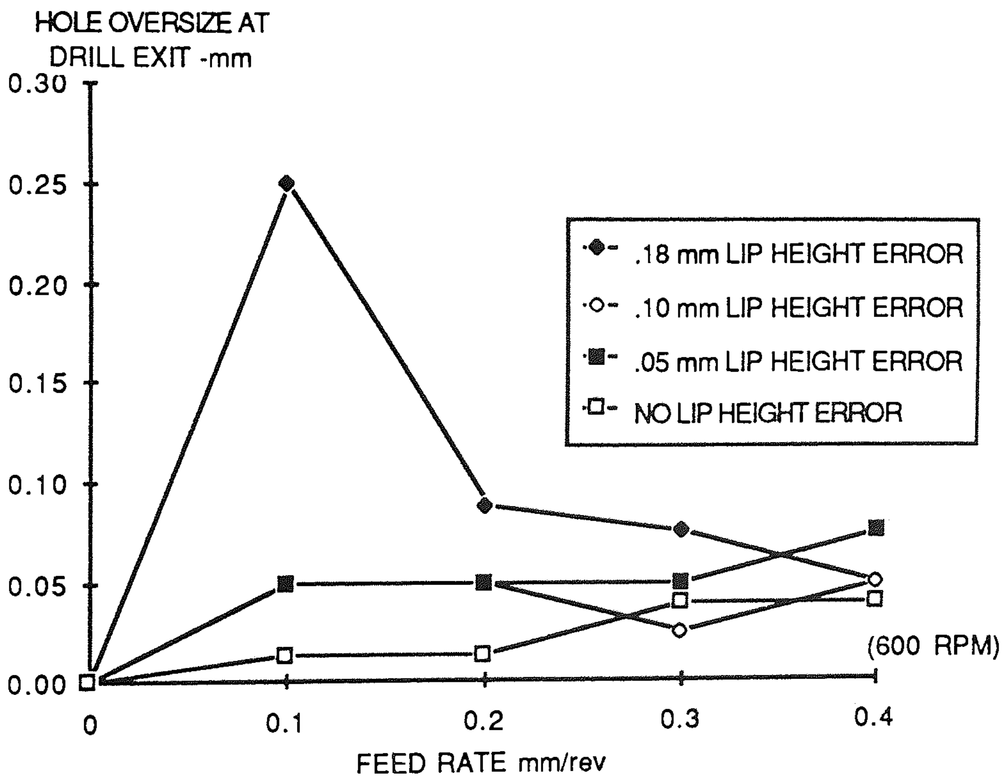
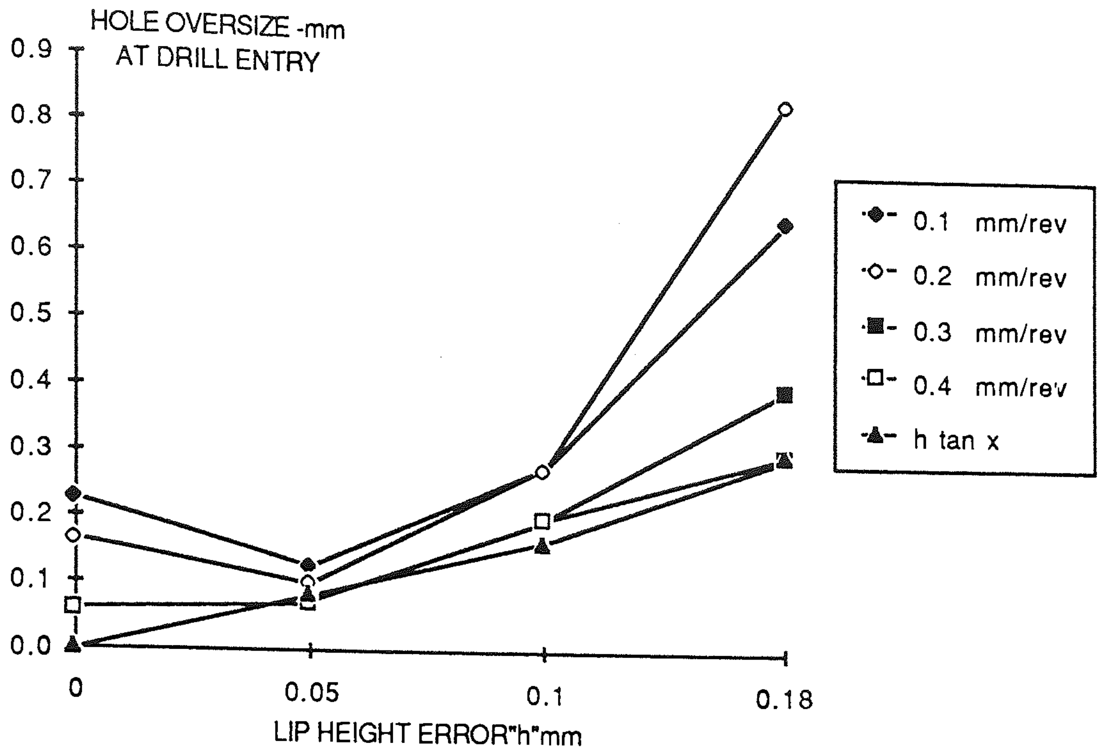




FIG 4.6 19.05 mm DIA TWIST DRILL
COMPARISON OF HOLE OVERSIZE AT DIFFERENT
FEED RATES FOR DIFFERENT LIP HEIGHT ERRORS



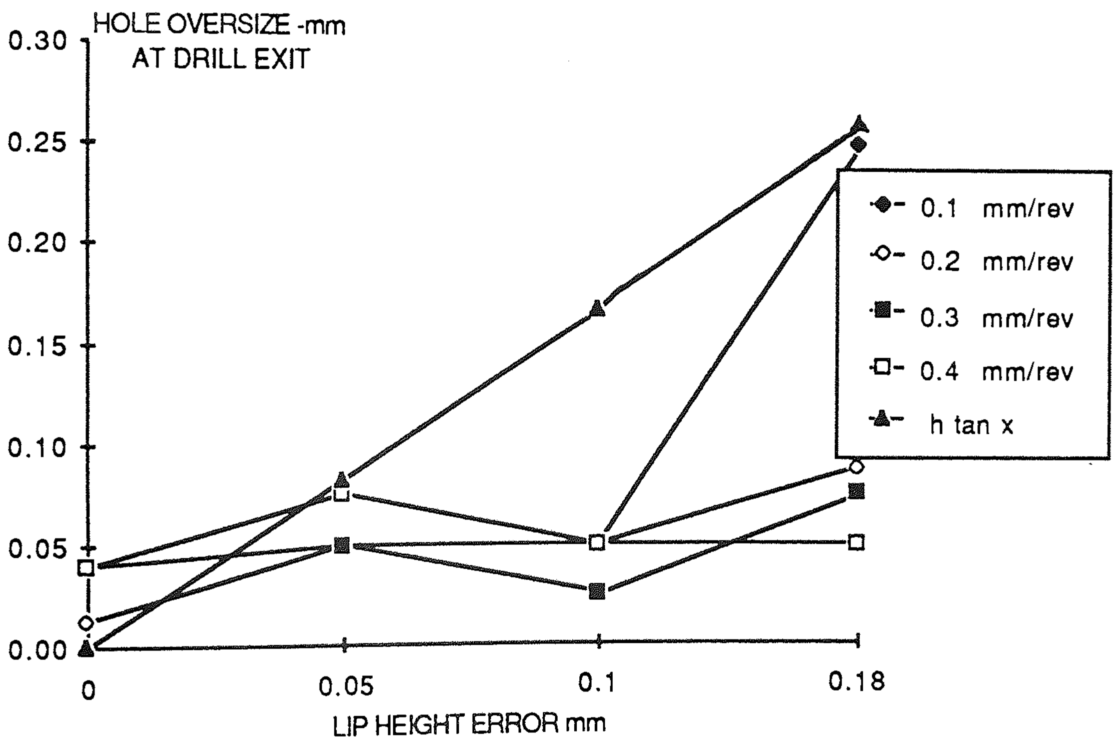
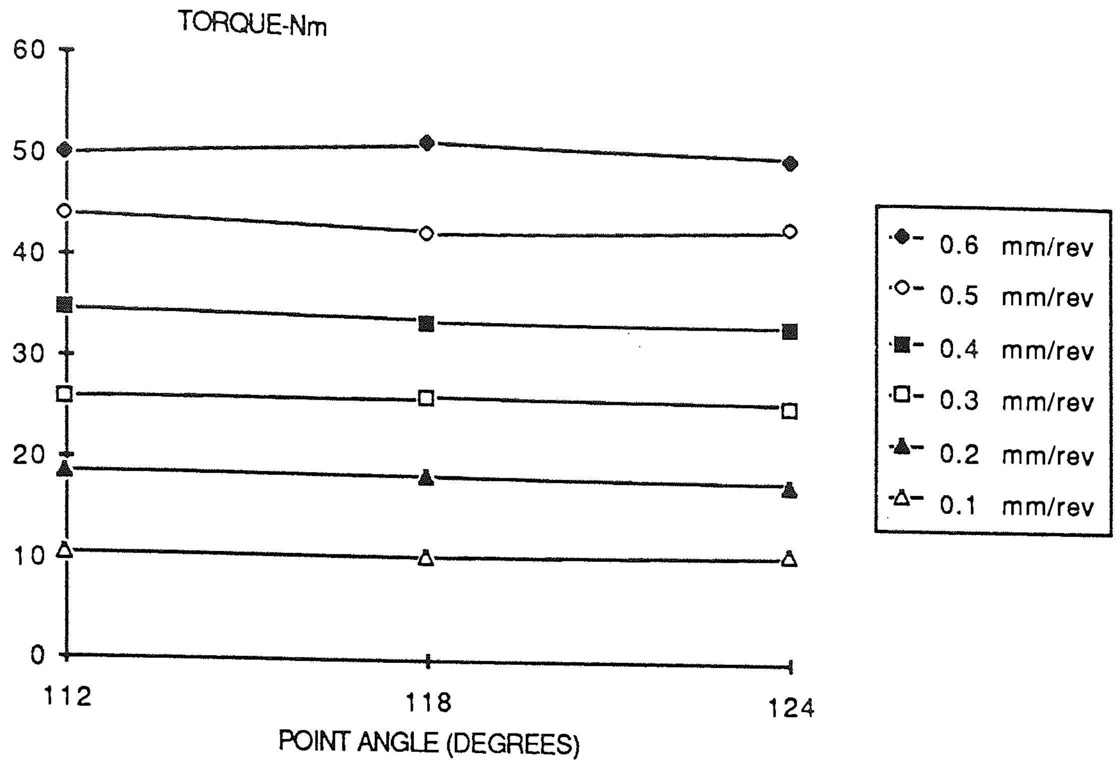




FIG 4.7 19.05 mm DIA TWIST DRILL COMPARISON HOLE OVERSIZE ( mm) AT DRILL ENTRY AND EXIT AT DIFFERENT FEED RATES AND DIFFERENT LIP HEIGHT ERRORS (THEORETICAL OVERSIZE= h tan x )



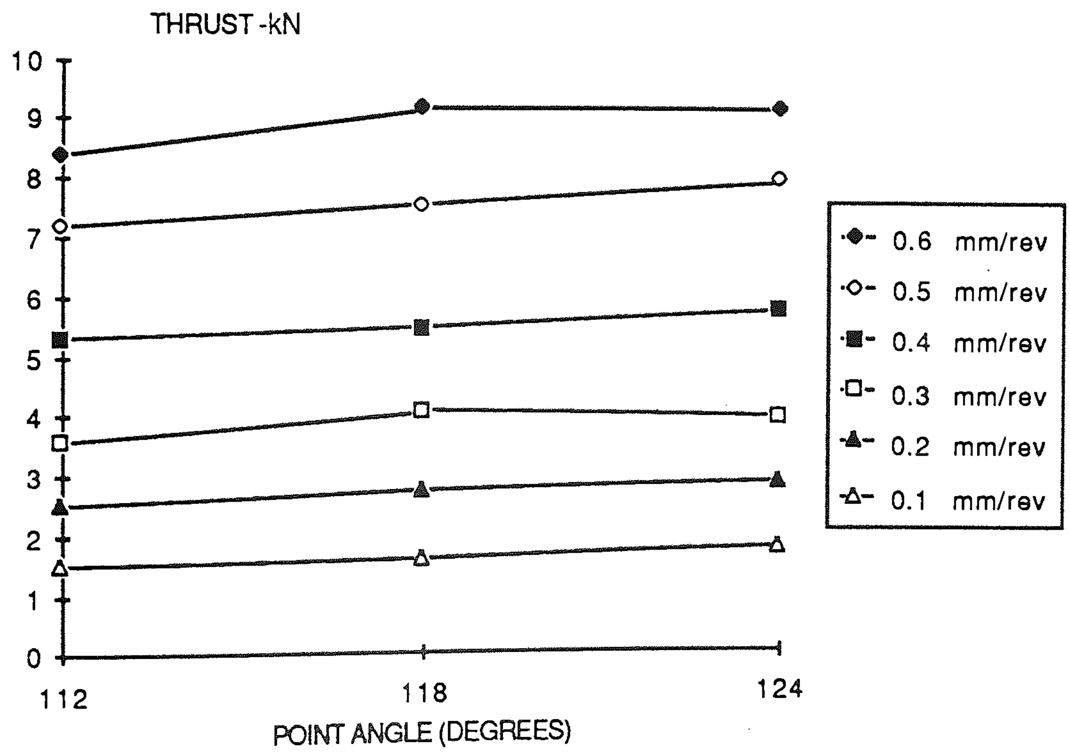




FIG 4.8 19.05 mm DIA TWIST DRILL -THE EFFECT OF POINT ANGLE ON DRILLING TORQUE AND THRUST AT DIFFERENT FEED RATES

# CHAPTER FIVE

# THE PREDICTION OF TORQUE AND THRUST IN DRILLING

## 5.1 INTRODUCTION

In this part of the research, equations were developed to enable the thrust and torque to be predicted. The basis for this work was the fundamental metal cutting equations used by Merchant [29] but suitably modified to account for the twist drill lip geometry. Empirical factors were also used to determine the thrust and torque at the chisel edge region of the drill.

In order to determine the basic orthogonal cutting data, cutting tests were performed on a D.S.G. Lathe. The results of this work, together with actual dynamometer readings of thrust and torque for a 19.05 mm and 12.70 mm dia twist drill provided the fundamental basis from which the predictive equations were developed.

The predictive equations were used to determine the thrust and torque of a 15.875 mm dia twist drill. Further drilling tests were then undertaken to compare the actual with the predicted values for 15.875 mm dia.

## 5.2 LITERATURE REVIEW

Various empirical equations have been developed that enable the torque and thrust in drilling to be determined. According to Kaczmarek [28] the general formulae for the axial thrust and torque in plain drilling are given by :-

$$F_z = C_F d^{b_F} f^{u_F} K_H$$

$$M = C_M d^{b_M} f^{u_M} K_H$$

where $C_F$ and $C_M$ are constants taking into account the influence of all factors not appearing in the formulae. $b_F$ and $b_M$ are exponents characterising the drill diameter 'd', $u_F$ and $u_M$ are exponents characterising the influence of feed rate 'f', $K_H$ is a correction coefficient taking into account the mechanical properties of the material.

From research undertaken by Oxford,[30] these equations for drills where the ratio of chisel edge diameter to overall diameter is 0.180 may be expressed as:

$$F_z = 0.195\, H_B\, d^{0.8} f^{0.8} + .0022\, H_B d^2$$

$$M = 0.087\, H_B\, d^{1.8} f^{0.8}$$

where $H_B$ is the Brinell hardness of the material.

More recent research by Bhattacharyya [31],[32] established, by analogy with a single point turning tool that the cutting force $F_C$ on the lip of a drill can be derived from basic orthogonal metal cutting equations for cutting force $F_C$., i.e.

$$F_C = \frac{\tau_S\, A \cos(\tau - \gamma)}{\sin\phi \cos(\phi + \tau - \gamma)}$$

where $\tau_S$ = shear stress of the material being cut.

$A$ = Cross sectional area of undeformed chip

$\tau$ = Friction Angle

$\gamma$ = Rake Angle

$\phi$ = Shear Angle

The torque 'M' in drilling can be estimated by assuming that the cutting force acts at the centre of cutting lip of the drill. The thrust force $F_Z$ can be similarly derived from $\frac{F_T}{F_C} = \tan(\tau - \gamma)$ where $F_T$ = Feed Force.

A knowledge of the basic orthogonal metal cutting parameters including shear angle, rake angle and friction angle are required together with the shear stress of the material [33]. To undertake this analysis for a drill it is important to determine the variation in rake angle along the cutting lip [34] and also understand the basic rules for chip formation in drilling [35],[36]. It is then possible to predict the thrust and torque in drilling by developing these basic equations for the drill geometry considered and this type of analysis is used in this chapter.

A detailed evaluation of the drill geometry was undertaken by Watson [37]. By considering incremental elements of the cutting lip and chisel edge he was also able to develop a model for the prediction of thrust and torque [38],[39],[40],[41].

## 5.3 ORTHOGONAL CUTTING TESTS

### 5.3.1 Test Equipment

For the orthogonal cutting tests a D.S.G. Centre Lathe was used. The cutting tool was clamped to the top face of a Kistler Turning Dynamometer Type No. 9259A, which was bolted onto the lathe saddle. The Dynamometer output signal was fed through Kistler Charge Amplifiers and presented on a U.V. Recorder Trace. Only two channels were used enabling the feed force $F_T$ and the cutting force $F_C$ to be measured.

A calibration test was performed on the Dynamometer before cutting tests were undertaken. This test on the Denison Testing Machine enabled the Dynamometer to be loaded in compression in 1kN increments up to a maximum of 5kN. Comparison between the U.V. trace output and the Denison Scale readings confirmed that the Dynamometer was accurate to +0 -2% of the Denison Indicated Values.

The cutting tools used were all H.S.S. of the "Knife edge type" ground with six different rake angles ranging from 0-30° in 5° increments. Each tool was ground to 10° clearance angle. All cutting tests were performed with a flood of suds coolant (Edgar Vaughan "Hocut Type 3210A" in a 10 to 1 dilution).

The workpiece material (mild steel EN 1A) was identical to that used for drilling. For the orthogonal cutting tests a piece of bored bar was used so that the width of the cut corresponded to the lip length of a 19.05 mm dia twist drill, which was used in the predictive equation tests.

5.3.2. Test Procedure

A constant cutting speed of 225 rpm was used because this corresponded to a surface speed of 36 m/min that was used in 19.05 mm dia twist drill trials. The feed range chosen was between .043 and .254 mm/rev to correspond as near as possible to the feed per lip for feeds of 0.1-0.6mm/rev on 19.05 mm dia drill (see Appendix IV). Care was taken to ensure that the orthogonal cutting test was performed with the cutting edge set on the centre line of the workpiece. A swarf sample was taken for each test, at the different combinations of rake angle and feed rate. The mean chip thickness "$t_2$" was found from micrometer readings. Feed rates of 0.254 mm/rev were not used for rake angles of 0° - 10° because the swarf tended to be discontinuous and the thickness $t_2$ was difficult to accurately determine.

### 5.3.3. Test Results

All the orthogonal cutting test results are shown in Table 5.1. The calculated results of $F_T/F_C$, friction angle $\tau$, cutting ratio $r_c$ and shear angle $\phi$ are given in Table 5.2. A plot of $\tau$ against rake angle and $\phi$ versus rake angle are given in Figs.5.1 and 5.2. A further plot (Fig.5.3) shows the relationship between the ratio $F_T/F_C$ and the rake angle $\gamma$.

### 5.3.4. Discussion of Results

Using the results in Table 5.1. The method of calculating the cutting ratio $r_c$, the friction angle $\tau$ and the shear angle $\phi$ are given in Appendix (V). The calculated results which are presented in Table 5.2 confirmed that:-

(i) From the relationship $F_T/F_C$ = tan $(\tau - \gamma)$ it was established that the friction angle $\tau$ tended to be constant across the range of rake angles and feed rates chosen. The mean friction angle was 31° and this value was used in subsequent predictive equations (see Fig 5.1).

(ii) The shear angle $\phi$ was directly proportional to the rake angle $\gamma$. The value of $\phi$ ranged from 13.59° at 0° rake angle to 30.35° at 30° rake (Fig 5.2). The average slope of the curve was 0.56° per degree increase in rake angle. This compared favourably with Merchants Modified Equation $2\phi + \tau - \gamma =$ constant where the theoretical slope = 0.5.(see Appendix V).).

(iii) The ratio of $F_T/F_C$ was inverseley proportional to the rake angle (see Fig. 5.3). At any given rake angle, the ratio of $F_T/F_C$ tended to be fairly constant across the range of feed rates chosen.

## 5.4 DRILLING TESTS TO ESTABLISH PREDICTIVE EQUATIONS FOR TORQUE AND THRUST.

In the first part of the analysis, drill tests were undertaken with 12.70 and 19.05 mm dia twist drills.

The torque and thrust results, together with the predictive Cutting Force Equations previously established from the Orthogonal Cutting Test, were used as a basis for determining the theoretical thrust and torque for 15.875 mm dia twist drill. The actual results for a 15.875 mm dia drill were then measured and compared with the theoretical, values.

### 5.4.1. Drill Geometry

Three drill sizes were considered, 12.70, 15.875 and 19.05 mm diameters and they were all individually inspected before testing. The point geometries were ground, such that the angles and proportions of each drill were very similar (see Table 5.3).

All measurements were made on the Universal Measuring Machine and/or Nikon Shadow Graph as previously described.

#### 5.4.1.1. Twist Drill Rake Angles

The helical flute and the centre web configuration produce a varying rake angle across the cutting lip of a twist drill. In order to determine the range of rake angles at the cutting lip, both along the drill axis and at right angles (orthogonally) to it, a sectional grinding procedure was adopted. This was designed to provide the information for use in the subsequent analysis and predictive equations.

Initially sections were ground axially at 0.75 mm increments across the cutting lip of a 19.05 mm dia twist drill. The rake angles were measured at each increment with the goniometer attachment on the Universal Measuring

Machine. The procedure was then repeated on the opposite lip but grinding at right angles to lip for the same equivalent radial distance i.e. 0.89 mm along the lip (Appendix VI). The results are presented in Table 5.4, Fig 5.4, for the entire lip length from the outside diameter to the chisel edge of the drill. The range of rake angles both axial and orthogonal varied from about 0° at the chisel edge to 30° at the circumference of the drill. Measurements on both the 12.70 and 15.875 mm dia drills confirmed that the same range of rake angles were applicable.

### 5.4.2. Test Material

All the test material used was mild steel type EN1A.

### 5.4.3. Test Procedure

#### 5.4.3.1. 12.70 mm Dia Twist Drills

The drilling trials were performed on an Olivetti N.C. Milling Machine (see Appendix I). The workpiece was clamped into a vice bolted on to the top face of the Kistler Drilling Dynamometer (see Appendix III).

A N.C. program was prepared which enabled a series of holes to be produced at 748 rpm and feed rates of 0.1 - 0.5 mm/rev in 0.1 mm/rev increments. The hole depth was two diameters. Torque and thrust values were obtained for the range of speeds and feeds chosen.

5.4.3.2. 19.05 mm Dia Twist Drills

The 19.05 mm dia twist drills were used on the Torshalla CNC Lathe because power limitations on the Olivetti Milling Machine caused the 19.05 mm to stall at high feed rates.

The torque and thrust force were measured from the U.V. recorder trace taken from Lathe Drilling trials at 600 rpm and 0.1 - 0.6 mm/rev feed rates at hole depths of two diameters. The lathe test programis described in Appendix II.

In further trials the contribution of the chisel edge region and drill lands was assessed. For the chisel edge, the percentage of total torque and thrust was determined from drilling trials with a 3.1 mm dia pilot hole, that was predrilled in the workpiece. Similarly the contribution to the overall torque and thrust of the drill lands was found by counter boring a 18.95 mm diameter hole so that the drill lands were doing all the effective cutting.

5.4.4. Drill Test Results : 12.70 and 19.05 mm Dia Drills

The torque and thrust force measured for the 12.70 mm dia drill are shown in Table 5.5 and the results for the 19.05 mm dia are given in Table 5.6. The percentage of torque and thrust attributable to the chisel edge and lands of the 19.05 mm dia drill are presented in Table 5.7 and Figs 5.6 and 5.7. Note that land thrust force is negligible.

### 5.4.5. Equations for Predicting Drill Torque

From Merchants Force Circle (Fig 5.5), the cutting force $F_C$ and Shear force $F_S$ can be expressed in terms of the resultant force R. i.e.,

$$F_C = R \cos (\tau - \gamma) \qquad \text{(i)}$$

$$F_S = R \cos (\phi + \tau - \gamma) \qquad \text{(ii)}$$

by combining (i) and (ii)

$$F_C = \frac{F_S \cos (\tau - \gamma)}{\cos (\phi + \tau - \gamma)} \qquad \text{(iii)}$$

also $F_S = \tau_S A_s$ (iv)

where $\tau_S$ = shear stress of material

$A_s$ = area in shear

$$A_s = \frac{A}{\sin \phi} \qquad \text{(v)}$$

A = normal cross sectional area of undeformed chip

$$\therefore F_C = \frac{\tau_S A \cos (\tau - \gamma)}{\sin\phi \cos (\phi + \tau - \gamma)} \qquad \text{(vi)}$$

For drilling the area $A_D$ of undeformed chip per lip equals the length of the cutting lip multiplied by the width of cut at a given feed rate.

i.e. $$A_D = \frac{f}{2} \sin x \cdot \frac{d - dc}{2 \sin x}$$

$$\therefore F_{CL} = \tau_{SE} \frac{f\,(d-dc)}{4} \frac{\cos(\tau - \gamma_E)}{\sin\phi \cos(\phi + \tau - \gamma_E)} \qquad \text{(vii)}$$

To determine the shear stress $\tau_{SE}$ it was necessary to determine the

Shear Force $F_S$. By resolving Forces from Merchants Circle

$$F_S = F_C \cos\phi - F_T \sin\phi \qquad \text{(viii)}$$

In order to determine the lip shear force $F_{SL}$, the lip cutting force $F_{CL}$ and the lip feed force $F_{TL}$ in drilling must be determined.

By resolving the lip thrust force $F_T'$ (see Appendix VII) the normal component $F_{TL}$ can be found from:-

$$F_{TL} = \frac{F_T'}{\sin x} \qquad \text{(ix)}$$

$$\therefore \quad F_{SL} = F_{CL} \cos\phi - \frac{F_T' \sin\phi}{\sin x} \qquad \text{(x)}$$

Also from Merchants Force Circle

$$\frac{F_T}{F_C} = \tan(\tau - \gamma) \qquad \text{(xi)}$$

For drilling and from (ix) and (xi)

$$\frac{F_{TL}}{F_{CL}} = \frac{F_T'}{F_{CL} \sin x} = \tan(\tau - \gamma_E)$$

$$\therefore \quad F_T' = F_{CL} \tan(\tau - \gamma_E) \sin x \qquad \text{(xii)}$$

The drill torque on the cutting lips

$$M_1 = F_{CL} \frac{(d + dc)}{4} 2 = F_{CL} \frac{(d + dc)}{2} \qquad \text{(xiii)}$$

This assumes that the cutting force acts at the mid point of the cutting lip

i.e. radius $= \frac{d + dc}{4}$ (see Appendix VII).

From the Cutting Test for the 19.05 mm dia twist drill the summation of chisel edge torque and land torque was 10% of the total torque across the range of feeds, (Fig.5.6).

If $M_2$ = chisel + land torque, then the total drill torque $M_P$ = $M_1 + M_2$. but $M_2 = 0.1\ M_P$.

$$\therefore M_P = \frac{M_1}{0.9} = 1.11\ M_1 \qquad \text{(xiv)}$$

5.4.6. Equations for Predicting Drill Thrust

The total thrust force $F_{ZP}$ for drilling at a given feed rate $= 2F_T' + F_{CH}$.

where $F_{CH}$ = chisel edge thrust force

$F_T'$ = axial thrust force per lip

(land thrust is negligible).

From Fig.5.7 the mean chisel thrust for 19.05 mm dia drill was found to be about 75% of the total thrust force $F_{ZP}$, ie $F_{CH} = 0.75\ F_{ZP}$.

$$\therefore \text{Axial Thrust per lip } F_T' = \frac{F_{ZP}}{8}$$

$$\text{and} \quad F_{ZP} = 8F_T' \qquad \text{(xv)}.$$

5.4.7. Using the Test Results and Predictive Equations to confirm the Torque and Thrust for the 12.70 and 19.05 mm dia Drills.

In order to confirm that the predictive equations were consistent with the results for 12.70 and 19.05 mm dia drills, the torque and thrust were both calculated using the equations developed above. The predicted values were then compared with the actual results. The basis for the prediction was the Orthogonal Cutting Test Results.

5.4.7.1. Determining an Effective Rake Angle ($\gamma_E$)

From Fig . 5.4 it was confirmed that both the orthogonal rake angle and axial rake angle were almost identical at any given radius on the cutting lip.

The empirical equations (xiv) and (xv) were used to determine the lip torque $M_1$ and the thrust $F_T'$. The cutting force $F_{CL}$ was then calculated directly from equation (xiii) and the ratio of $F_T'/F_{CL}$ found. From Merchants Modified Equation (xii) the value of $(\tau - \gamma_E)$ was established. The friction angle, however, was found to be almost constant at 31° ( see Fig 5.1). It was therefore possible to determine the effective rake angle for both the 12.70 and 19.05 mm dia drills. see Tables 5.8 and 5.9. The mean effective rake angles were 16.65° and 15.25° respectively.

A mean effective rake angle of 15° was therefore used in all predictive equations because this also corresponded to the mean orthogonal/axial rake angle of the drill.

5.4.7.2. Effective Shear Angle ($\phi$)

From the orthogonal cutting test data, the shear angle was shown to increase linearly with rake angle (see Fig 5.2). At a 15° rake angle the corresponding shear angle was 21.75° and this value was used in all subsequent calculations to determine the effective shear stress.

5.4.7.3. Effective Shear Stress ($\tau_{SE}$)

Using the above data for rake and shear angle the shear stress $\tau_{SE}$ was calculated from equations (iv), (v) and (x). The shear stress which varied with feed rate was plotted for both the 12.70 and 19.05mm dia twist drills (Fig 5.8).

5.4.7.4. Cutting Force Prediction($F_{CL}$)

The prediction of cutting force was made from equation (vii).

5.4.7.5. Torque Prediction ($M_P$)

The total predicted torque ($M_P$) was found from equations (xiii) and (xiv). A plot of the actual and predicted torques for both 12.70 and 19.05 mm dia drills is shown in Fig 5.9.

5.4.7.6. Thrust Prediction ($F_{ZP}$)

Predicted thrust values were found from equation (xii) to firstly establish the axial thrust per lip and then secondly equation (xv) for the total thrust $F_{ZP}$. A plot of the actual and predicted thrust forces for both 12.70 and 19.05 mm dia drills is shown in Fig 5.10.

5.4.8. Predicted Results

The results of Effective Shear Stress, Predicted Cutting Force, Predicted Torque and Predicted Thrust are shown in Tables 5.10/5.11. for 12.70 and 19.05 mm dia drills, together with the actual measured values of torque and thrust.

5.4.9. Predicting the Torque and Thrust for a 15.875 mm dia drill

In order to completely verify the predictive equations a 15.875 dia Dormer twist drill was obtained and the geometrical proportions measured to ensure that it corresponded to those for the 12.70 and 19.05 mm dia drills (Table 5.3).

The predicted cutting Force $F_{CL}$ was then calculated by using an interpolated value for the shear stress from Fig.5.8 and equation (vii). The torque predicted $M_P$ was established from equations (xiii) and (xiv). The Thrust prediction $F_{ZP}$ was obtained from (xii) and (xv). These results are presented in Table 5.12.

5.5 DRILLING TESTS FOR 15.875 mm dia DRILL

In order to confirm the accuracy of the predicted results for the 15.875 dia drill a new set of drilling tests were undertaken on the Olivetti Milling Machine at 748 rpm and 0.1-0.5 mm/rev.

The results are listed in Table 5.12 alongside the predicted values. A plot of the actual and predicted torques is shown in Fig.5.11 and the corresponding thrust forces are shown in Fig.5.12.

## 5.6 DISCUSSION OF RESULTS

The fundamental basis of this analysis was the hypothesis that the drill chip flow could be considered as orthogonal and therefore analysed by Modified Merchants Equations.

To confirm and verify this hypothesis it was first necessary to determine the direction of chip flow at the cutting lip. The mean chip flow angle was found by superimposing samples of the spiral drilling swarf on the cutting lip and observing that the direction of chip flow was initially towards the web of the drill at approximately right angles to the cutting lip (Fig.5.13). It was further necessary to establish the range of orthogonal rake angles across the cutting lip of the drill. The important finding to emerge from (Fig.5.4) was that at any point on the cutting lip both the axial rake angle and orthogonal rake angle were almost identical, ranging from 0° at the drill chisel edge to 30° at the outside diameter.

From these results it was then necessary to establish an effective rake angle for the drill.

For the 12.70 and 19.05 mm dia drills it was established that after allowances were made for the chisel edge and drill lands the calculated ratio of the lip feed to cutting force, $F_{TL}/F_{CL}$, were nearly constant across the range of feed (see Tables 5.8 and 5.9). Furthermore, if the mean values of $F_{TL}/F_{CL}$ were superimposed on the Orthogonal Cutting Test Plot of $F_T/F_C$ against rake angle (Fig.5.3), the effective rake angle lay between 15.6 and 17° for the two drills considered. Similarly if the coefficient of friction was considered as constant and of the same value as in the Orthogonal Test i.e., ($\tau$ = 31°), then for both drills 12.70 and 19.05 mm dia the effective rake angle ranged from 15.25° and 16.65° (Tables 5.8 and 5.9). In both cases, therefore the effective rake angle corresponded very closely to the mean axial and orthogonal rake angle.

In developing the predictive equations it was therefore considered reasonable to adopt 15° as the effective rake angle ($\gamma_E$) which corresponded to a shear angle at 21.75° from the Orthogonal Cutting Test (Fig 5.2).

The prediction of torque at a given feed rate was simplified providing that, firstly a value for the Effective Shear Stress could be determined. The shear stress was established as outlined in previously and plotted in Fig.5.8. Note that the values obtained were about 50% greater than those obtained from the Orthogonal Cutting Test on the lathe. The reasons for this were probably attributable to the combined effects of shear and torsional effects on the chip. The effective shear stress was not constant, and it tended to increase at both low and high feed rates.

At low feed rates this was probably due to the tool rubbing and tending to compress rather than shear the material. At high feed rates the increased shear stress may be due to increased resistance caused by built up edge.

The second assumption associated with torque prediction was the position at which the cutting force ($F_{CL}$) acted on the cutting lip. The distance was chosen to be midway between the outside radius and the chisel edge radius.

From the comparison of the actual and predicted torques for the 12.70 and 19.05 mm dia drills (Fig.5.9), the above assumption would seem reasonable. It also followed that the estimate of 10% additional torque for the drill chisel edge and lands was applicable to the 12.70 mm dia drill.

In the case of drill thrust the predicted values for the 19.05 mm were close to the actual value. The predicted thrust for 12.70 mm based on the 19.05 mm drill model produced values up to 15% greater (Fig.5.10). This may have been due to the slightly different ratio of chisel diameter to overall drill diameter for the 12.70 dia drill. Another factor likely to influence the thrust is the chisel edge angle because this alters the direction of chip flow in the chisel region of the drill. At higher feed rates 0.4-0.6mm/rev the presence of built up edge on the chisel edge and cutting lips also tends to lead to increases in thrust force.

When taking all these additional factors into consideration, the predicted thrust values were considered to be satisfactory.

In order to test the validity of the predictive equations a 15.875 mm dia twist drill was chosen for a set of prediction results. These were calculated and listed in Table 5.12. A set of actual results taken are included for comparison purposes. The basis for these results was that a value for effective shear stress could be directly interpolated from mid way between the values for 19.05 mm and 12.70 mm as in Fig.5.8.

The plot of actual torque versus predicted torque for the 15.875 mm dia drill showed a very good correlation (Fig.5.11)

The thrust comparisons, however, were less close and the predicted thrust was up to 14% greater than the actual thrust. (Fig.5.12)

## 5.7 CONCLUSIONS

(i) Empirical equations were used to confirm that a mean effective rake angle of 15° could be adopted for the cutting lip of both 19.05 and 12.70 mm dia twist drills.

(ii) The calculated effective shear stress in drilling tended to be high at feed rates of 0.1 mm/rev and this was probably due to increased friction caused by the drill rubbing as well as cutting. High effective shear stress was also calculated at 0.6 mm/rev and this was probably due to built up edge effects.

(iii) Higher values of effective shear stress were obtained for drilling than those recorded in orthogonal cutting and this was attributed to the three dimensional nature of the chip formation in drilling.

(iv) The shear stress used for a 15.875 mm dia drill was determined by direct linear interpolation between the values for 12.70 mm and 19.05 mm dia.

(v) The torque predicted for a 15.875 mm dia drill was very close to the actual value.

(vi) Predicted thrust forces were up to 14% greater than actual recorded values.

(vii) Orthogonal cutting tests confirmed that a constant friction angle could be assumed over the range of rake angles considered.

| RAKE ANGLE (γ) | TEST RESULTS | FEED RATE mm/rev .043 | .089 | .127 | .178 | .221 | .254 |
|---|---|---|---|---|---|---|---|
| 0° | $F_T$ | 0.59 | 0.76 | 1.28 | 1.63 | 1.95 | - |
| | $F_C$ | 1.10 | 1.65 | 2.40 | 3.05 | 3.50 | - |
| | $t_2$ | 0.254 | 0.381 | 0.533 | 0.635 | 0.762 | - |
| 5° | $F_T$ | 0.37 | 0.66 | 0.78 | 1.25 | 1.70 | - |
| | $F_C$ | 0.86 | 1.59 | 2.20 | 3.00 | 3.50 | - |
| | $t_2$ | 0.152 | 0.330 | 0.457 | 0.762 | 0.889 | - |
| 10° | $F_T$ | 0.30 | 0.50 | 0.66 | 0.80 | 1.00 | - |
| | $F_C$ | 0.70 | 1.30 | 1.72 | 2.30 | 2.75 | - |
| | $t_2$ | 0.152 | 0.254 | 0.406 | 0.546 | 0.736 | - |
| 15° | $F_T$ | 0.23 | 0.30 | 0.44 | 0.60 | 0.75 | 0.85 |
| | $F_C$ | 0.66 | 1.15 | 1.58 | 2.05 | 2.60 | 2.85 |
| | $t_2$ | 0.102 | 0.241 | 0.330 | 0.444 | 0.546 | 0.609 |
| 20° | $F_T$ | 0.12 | 0.20 | 0.29 | 0.42 | 0.50 | 0.55 |
| | $F_C$ | 0.60 | 1.07 | 1.45 | 2.00 | 2.40 | 2.70 |
| | $t_2$ | 0.089 | 0.216 | 0.279 | 0.406 | 0.508 | 0.584 |
| 25° | $F_T$ | 0.14 | 0.20 | 0.20 | 0.25 | 0.28 | 0.30 |
| | $F_C$ | 0.66 | 1.05 | 1.35 | 1.80 | 2.20 | 2.45 |
| | $t_2$ | 0.089 | 0.178 | 0.355 | 0.432 | 0.508 | 0.533 |
| 30° | $F_T$ | 0.08 | 0.12 | 0.11 | 0.12 | 0.13 | 0.14 |
| | $F_C$ | 0.52 | 0.90 | 1.24 | 1.65 | 2.00 | 2.30 |
| | $t_2$ | 0.076 | 0.178 | 0.267 | 0.368 | 0.444 | 0.495 |

**TABLE No.5.1**

**ORTHOGONAL CUTTING TEST RESULTS : 0° - 30° RAKE ANGLE**

**Key:-**
$F_T$ = Feed Force (kN)
$F_C$ = Cutting Force (kN)
$t_2$ = Mean Chip Thickness (mm)

| RAKE ANGLE | CALCULATED RESULTS | FEED RATE mm/rev .043 | .089 | .127 | .178 | .221 | .254 | MEAN VALUES |
|---|---|---|---|---|---|---|---|---|
| 0° | $F_T/F_C$ | 0.536 | 0.460 | 0.533 | 0.534 | 0.557 | - | 0.524 |
| | $\tau$ | 28.20 | 24.73 | 28.07 | 28.12 | 29.12 | - | 27.65 |
| | $r_c$ | 0.170 | 0.233 | 0.238 | 0.280 | 0.290 | - | - |
| | $\phi$ | 9.65 | 13.11 | 13.39 | 15.64 | 16.17 | - | 13.59 |
| 5° | $F_T/F_C$ | 0.430 | 0.415 | .354 | 0.416 | 0.485 | - | 0.420 |
| | $\tau$ | 28.28 | 27.54 | 24.50 | 27.62 | 30.90 | - | 27.77 |
| | $r_c$ | 0.283 | 0.269 | 0.263 | 0.233 | 0.248 | - | - |
| | $\phi$ | 16.17 | 15.35 | 15.01 | 13.35 | 14.20 | - | 14.81 |
| 10° | $F_T/F_C$ | 0.428 | 0.384 | 0.384 | 0.347 | 0.364 | - | 0.381 |
| | $\tau$ | 33.2 | 31.0 | 31.0 | 29.2 | 29.9 | - | 30.87 |
| | $r_c$ | 0.283 | 0.350 | 0.313 | 0.325 | 0.300 | - | - |
| | $\phi$ | 16.35 | 20.15 | 18.02 | 18.76 | 17.31 | - | 18.12 |
| 15° | $F_T/F_C$ | 0.348 | 0.261 | 0.278 | 0.293 | 0.289 | 0.298 | 0.294 |
| | $\tau$ | 34.21 | 29.62 | 30.56 | 31.31 | 31.09 | 31.60 | 31.40 |
| | $r_c$ | 0.425 | 0.368 | 0.384 | 0.400 | 0.404 | 0.416 | - |
| | $\phi$ | 24.76 | 21.47 | 22.32 | 23.31 | 23.58 | 24.27 | 23.28 |
| 20° | $F_T/F_C$ | 0.200 | 0.186 | 0.200 | 0.210 | 0.208 | 0.204 | 0.201 |
| | $\tau$ | 31.31 | 30.58 | 31.31 | 31.85 | 31.76 | 31.51 | 31.38 |
| | $r_c$ | 0.485 | 0.412 | 0.454 | 0.437 | .435 | 0.434 | - |
| | $\phi$ | 28.67 | 24.25 | 26.75 | 25.72 | 25.67 | 25.59 | 26.11 |
| 25° | $F_T/F_C$ | 0.212 | 0.190 | 0.148 | 0.139 | 0.127 | 0.122 | 0.156 |
| | $\tau$ | 36.98 | 35.78 | 33.26 | 32.90 | 32.25 | 31.98 | 33.86 |
| | $r_c$ | 0.485 | 0.500 | 0.357 | 0.411 | 0.435 | 0.476 | - |
| | $\phi$ | 30.04 | 29.86 | 29.23 | 24.22 | 25.77 | 28.34 | 27.91 |
| 30° | $F_T/F_C$ | 0.155 | 0.111 | 0.087 | 0.072 | 0.065 | 0.061 | 0.092 |
| | $\tau$ | 38.82 | 36.34 | 35.06 | 34.15 | 33.71 | 33.48 | 35.26 |
| | $r_c$ | 0.566 | 0.500 | 0.476 | 0.482 | 0.497 | 0.513 | - |
| | $\phi$ | 34.35 | 29.99 | 28.40 | 28.78 | 29.76 | 30.82 | 30.35 |

**TABLE No.5.2** ORTHOGONAL CUTTING TEST CALCULATED RESULTS

**Key:-**

$F_T/F_C$ = Ratio Feed Force to Cutting Force
$\tau$ = Friction Angle
$r_c$ = Cutting Ratio
$\phi$ = Shear Angle

| | DRILL DIAMETER (mm) | | |
|---|---|---|---|
| DRILL GEOMETRY | 12.70 | 15.875 | 19.05 |
| Point Angle | 118° | 117° | 118° |
| Helix Angle | 31° | 30°40' | 32° |
| Clearance Angle | 12° | 10°50' | 10° |
| Chisel Edge Angle | 127° | 126° | 122° |
| Lip Height Difference (mm) | nil | nil | nil |
| Web Dia. (mm) | 1.83 | 2.29 | 2.54 |
| Ratio Web/overall dia | 0.144 | 0.144 | 0.133 |

(All drills had Steam Tempered Finish)

**TABLE No.5.3**

**MEASUREMENTS OF TWIST DRILLS USED IN TORQUE AND THRUST PREDICTIONS.**

| RADIAL DISTANCE FROM CHISEL EDGE (mm) | ORTHOGONAL RAKE ANGLE (Deg) | AXIAL RAKE ANGLE (Deg) |
|---|---|---|
| 0 | 0 | 2.66 |
| 0.75 | 8.16 | 6.66 |
| 1.50 | 13.50 | 10.66 |
| 2.25 | 14.50 | 13.58 |
| 3.00 | 15.00 | 16.75 |
| 3.75 | 18.00 | 19.00 |
| 4.50 | 21.16 | 21.50 |
| 5.25 | 25.33 | 25.08 |
| 6.00 | 26.50 | 26.50 |
| 6.75 | 28.66 | 28.92 |
| 7.50 | 30.00 | 30.00 |
| 8.25 | 30.00 | 30.00 |

TABLE No. 5.4

COMPARISON OF ORTHOGONAL AND AXIAL RAKE ANGLES AT DIFFERENT SECTIONS ALONG THE CUTTING LIP.

| FEED RATE mm/rev | TORQUE (Nm) M | THRUST FORCE $F_Z$ (kN) |
|---|---|---|
| .1 | 5.5 | 1.35 |
| .2 | 10.0 | 2.10 |
| .3 | 14.0 | 3.05 |
| .4 | 19.5 | 4.00 |
| .5 | 24.0 | 5.00 |

TABLE No. 5.5

12.70 mm Dia. TWIST DRILL : DYNAMOMETER RESULTS FOR VERTICAL DRILLING AT 748 rpm

| FEED RATE mm/rev | TORQUE (Nm) M | THRUST FORCE $F_Z$ (kN) |
|---|---|---|
| .1 | 10.5 | 1.6 |
| .2 | 18.5 | 2.75 |
| .3 | 26.5 | 4.1 |
| .4 | 34.0 | 5.5 |
| .5 | 43.0 | 7.6 |
| .6 | 53.0 | 9.2 |

TABLE No. 5.6

19.05 mm Dia TWIST DRILL : DYNAMOMETER RESULTS FOR HORIZONTAL DRILLING AT 600 rpm

| DRILL FEED RATE mm/rev | THRUST CHISEL % | TORQUE CHISEL % | TORQUE LANDS % |
|---|---|---|---|
| 0.1 | 61.8 | 9.5 | - |
| 0.2 | 67.2 | 7.8 | 1.3 |
| 0.4 | 73.9 | 8.3 | 1.5 |

TABLE No. 5.7

PERCENTAGE OF TOTAL THRUST AND TORQUE TAKEN BY CHISEL EDGE AND LANDS OF A 19.05 mm DRILL AT 600 rpm
(Pilot Hole 3.1mm dia)

(N.B. Land Thrust was negligible)

| FEED RATE mm/rev | MEASURED TORQUE M Nm | TORQUE LESS 10% | CUTTING FORCE/LIP $F_{CL}$ (N) | MEASURED THRUST $F_z$(kN) | $F_T'$ = AXIAL THRUST PER LIP = $F_z/8$ | $\frac{F_{TL}}{F_{CL}}$ | $(\tau-\gamma_E)$ | EFFECTIVE RAKE ANGLE $\gamma_E$ |
|---|---|---|---|---|---|---|---|---|
| .1 | 5.5 | 4.95 | 681 | 1.35 | 169 | .289 | 16.15 | 14.85 |
| .2 | 10.0 | 9.00 | 1238 | 2.10 | 262 | .247 | 13.89 | 17.13 |
| .3 | 14.0 | 12.60 | 1734 | 3.05 | 381 | .256 | 14.38 | 16.62 |
| .4 | 19.5 | 17.55 | 2415 | 4.00 | 500 | .241 | 13.58 | 17.42 |
| .5 | 24.0 | 21.60 | 2973 | 5.00 | 625 | .245 | 13.78 | 17.22 |
| | | | | | | .255 (mean) | | 16.65° ($\gamma_E$ mean) |

$\frac{F_{TL}}{F_{CL}} = \tan(\tau - \gamma_E) \sin x \qquad \tau = 31°$

TABLE No.5.8

BASIS FOR DETERMINING THE EFFECTIVE RAKE ANGLE $\gamma_E$ FOR 12.70 mm Dia DRILL

| FEED RATE mm/rev | MEASURED TORQUE M (Nm) | TORQUE LESS 10% | CUTTING FORCE/LIP $F_{CL}$ (N) | MEASURED THRUST $F_Z$(kN) | AXIAL THRUST PER LIP $F_T'$ = $F_Z/8$(N) | $\frac{F_{TL}}{F_{CL}}$ | $(\tau - \gamma_E)$ | EFFECTIVE RAKE ANGLE $\gamma_E$ |
|---|---|---|---|---|---|---|---|---|
| .1 | 10.5 | 9.45 | 875 | 1.60 | 200 | .266 | 14.93 | 16.07 |
| .2 | 18.5 | 16.65 | 1542 | 2.75 | 344 | .259 | 14.55 | 16.45 |
| .3 | 26.5 | 23.85 | 2209 | 4.10 | 512 | .270 | 15.13 | 15.87 |
| .4 | 34.0 | 30.6 | 2835 | 5.50 | 687 | .283 | 15.79 | 15.21 |
| .5 | 43.0 | 38.7 | 3585 | 7.60 | 950 | .309 | 17.17 | 13.83 |
| .6 | 53.0 | 47.7 | 4419 | 9.20 | 1150 | .303 | 16.89 | 14.11 |
| N.B. $\frac{F_{TL}}{F_{CL}} = \frac{F_T'}{F_{CL}} = \tan(\tau-\gamma_E)\sin x, \tau = 31°$ | | | | | | .282 (mean) | | 15.25° ($\gamma_E$ mean) |

**TABLE No. 5.9**

**BASIS FOR DETERMINING THE EFFECTIVE RAKE ANGLE $\gamma_E$ FOR 19.05 mm Dia. DRILLS**

| FEED RATE mm/rev | SHEAR FORCE $F_{SL}$(N) | AREA IN SHEAR $A_s$mm² | SHEAR STRESS $\tau_{SE}$N/mm² | PREDICTED CUTTING FORCE $F_{CL}$ (N) | PREDICTED LIP TORQUE $M_1$(Nm) | PREDICTED TOTAL TORQUE $M_P$(Nm) | ACTUAL TORQUE M(Nm) | PREDICTED FEED FORCE $F_T$'(N) | TOTAL PREDICTED THRUST $F_{ZP}$(N) | ACTUAL THRUST $F_Z$(N) |
|---|---|---|---|---|---|---|---|---|---|---|
| .1 | 557 | .733 | 759 | 668 | 4.9 | 5.4 | 5.5 | 164 | 1312 | 1350 |
| .2 | 1031 | 1.466 | 702 | 1236 | 9.0 | 10.0 | 10.0 | 303 | 2424 | 2100 |
| .3 | 1446 | 2.200 | 657 | 1734 | 12.6 | 14.0 | 14.0 | 425 | 3400 | 3050 |
| .4 | 1969 | 2.934 | 671 | 2362 | 17.2 | 16.0 | 19.5 | 579 | 4632 | 4000 |
| .5 | 2376 | 3.667 | 648 | 2851 | 20.7 | 23.0 | 24.0 | 698 | 5584 | 5000 |

$F_T' = F_{CL} \tan(\tau - \gamma_E) \sin x$

TABLE No.5.10

COMPARISON OF ACTUAL AND PREDICTED TORQUE AND THRUST 12.70 mm Dia. DRILL.

| FEED RATE mm/rev | SHEAR FORCE $F_{SL}$(N) | AREA IN SHEAR $A_s$mm² | SHEAR STRESS $\tau_{SE}$(N/mm²) | PREDICTED CUTTING FORCE $F_{CL}$ (N) | PREDICTED LIP TORQUE $M_1$ (Nm) | PREDICTED TOTAL TORQUE $M_P$ (Nm) | ACTUAL TORQUE M (Nm) | PREDICTED FEED FORCE $F_T'$ (N) | TOTAL PREDICTED THRUST $F_{ZP}$(N) | ACTUAL THRUST $F_Z$ (N) |
|---|---|---|---|---|---|---|---|---|---|---|
| .1 | 726 | 1.114 | 652 | 869 | 9.4 | 10.4 | 10.5 | 213 | 1704 | 1600 |
| .2 | 1284 | 2.228 | 576 | 1537 | 16.6 | 18.4 | 18.5 | 376 | 3008 | 2750 |
| .3 | 1830 | 3.342 | 547 | 2193 | 23.7 | 26.3 | 26.5 | 537 | 4296 | 4100 |
| .4 | 2335 | 4.456 | 524 | 2801 | 30.2 | 33.6 | 34.0 | 686 | 5488 | 5500 |
| .5 | 2918 | 5.570 | 524 | 3507 | 37.9 | 42.1 | 43.0 | 859 | 6872 | 7600 |
| .6 | 3607 | 6.684 | 540 | 4320 | 46.6 | 51.8 | 53.0 | 1058 | 8464 | 9200 |

TABLE No. 5.11

COMPARISON OF ACTUAL AND PREDICTED TORQUE AND THRUST - 19.05 mm Dia. DRILL.

| FEED RATE mm/rev | PREDICTED SHEAR STRESS N/mm² $\tau_{SE}$ | PREDICTED LIP TORQUE $M_1$(Nm | PREDICTED TOTAL TORQUE $M_p$(Nm) | ACTUAL TORQUE M(Nm) | PREDICTED FEED FORCE $F_T$'(N) | TOTAL PREDICTED THRUST $F_{ZP}$(N) | ACTUAL THRUST $F_Z$(N) |
|---|---|---|---|---|---|---|---|
| .1 | 705 | 7.1 | 7.8 | 8.6 | 190 | 1520 | 1650 |
| .2 | 639 | 12.8 | 14.2 | 14.6 | 344 | 2752 | 2500 |
| .3 | 602 | 18.0 | 20.0 | 21.0 | 487 | 3896 | 3500 |
| .4 | 483 | 23.3 | 25.9 | 27.0 | 628 | 5024 | 4550 |
| .5 | 586 | 29.3 | 32.5 | 32.0 | 789 | 6312 | 5550 |

TABLE No.5.12

PREDICTION OF TORQUE AND THRUST FOR 15.875 mm Dia. DRILL AND COMPARISON WITH ACTUAL RESULTS.

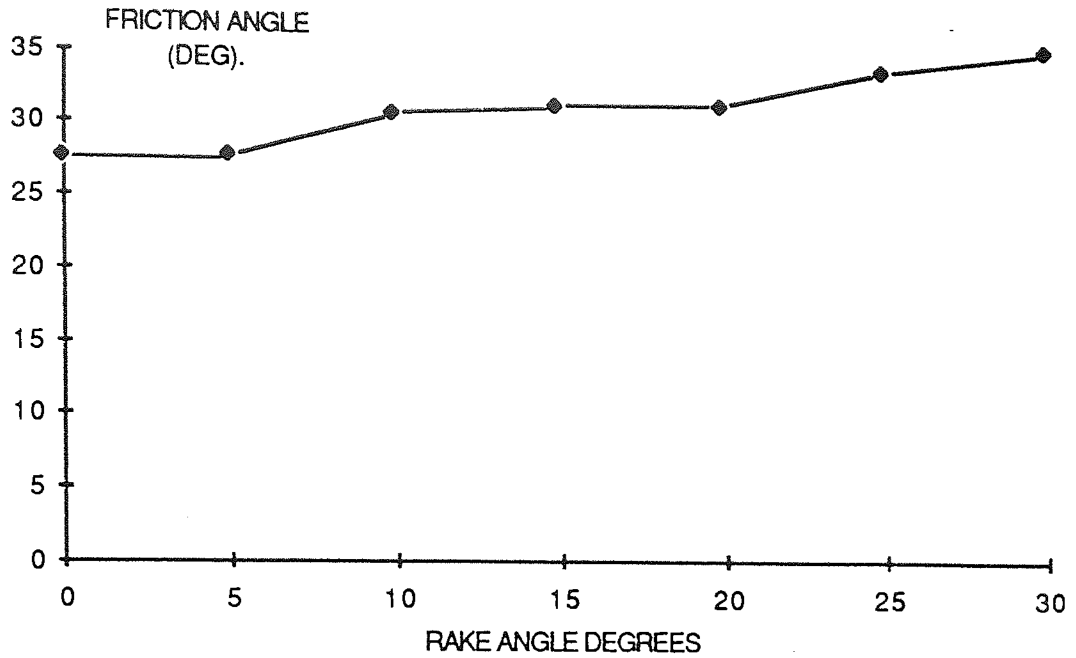



FIG 5.1 ORTHOGONAL CUTTING TEST
GRAPH OF FRICTION ANGLE AGAINST RAKE ANGLE

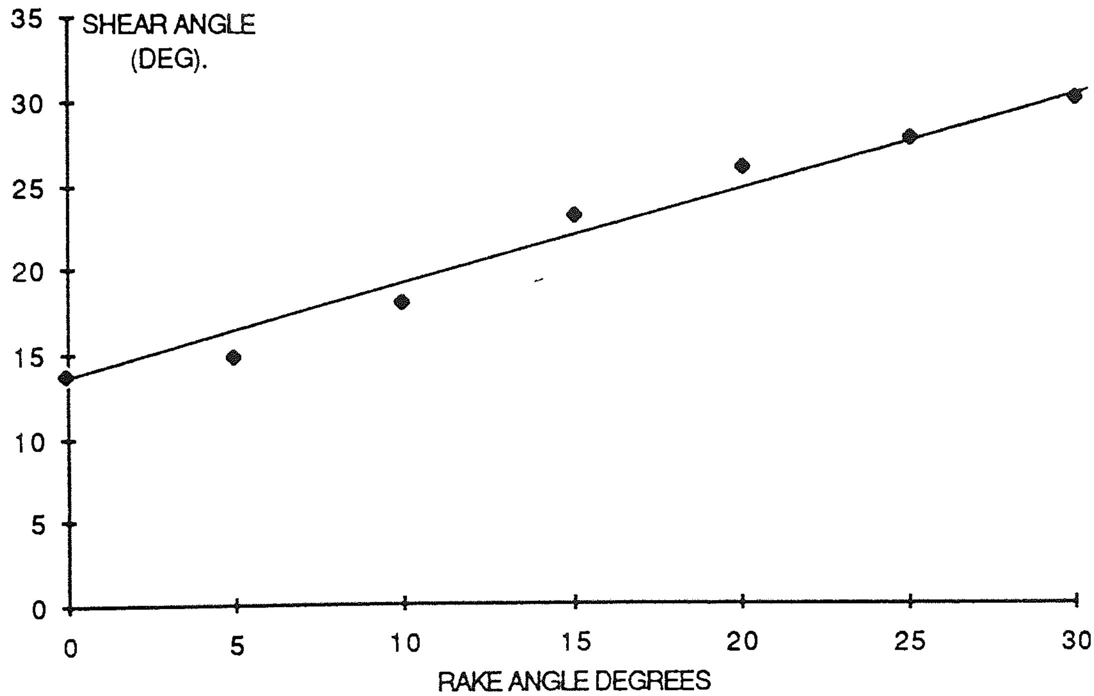



FIG 5.2 ORTHOGONAL CUTTING TEST
GRAPH OF SHEAR ANGLE AGAINST RAKE ANGLE

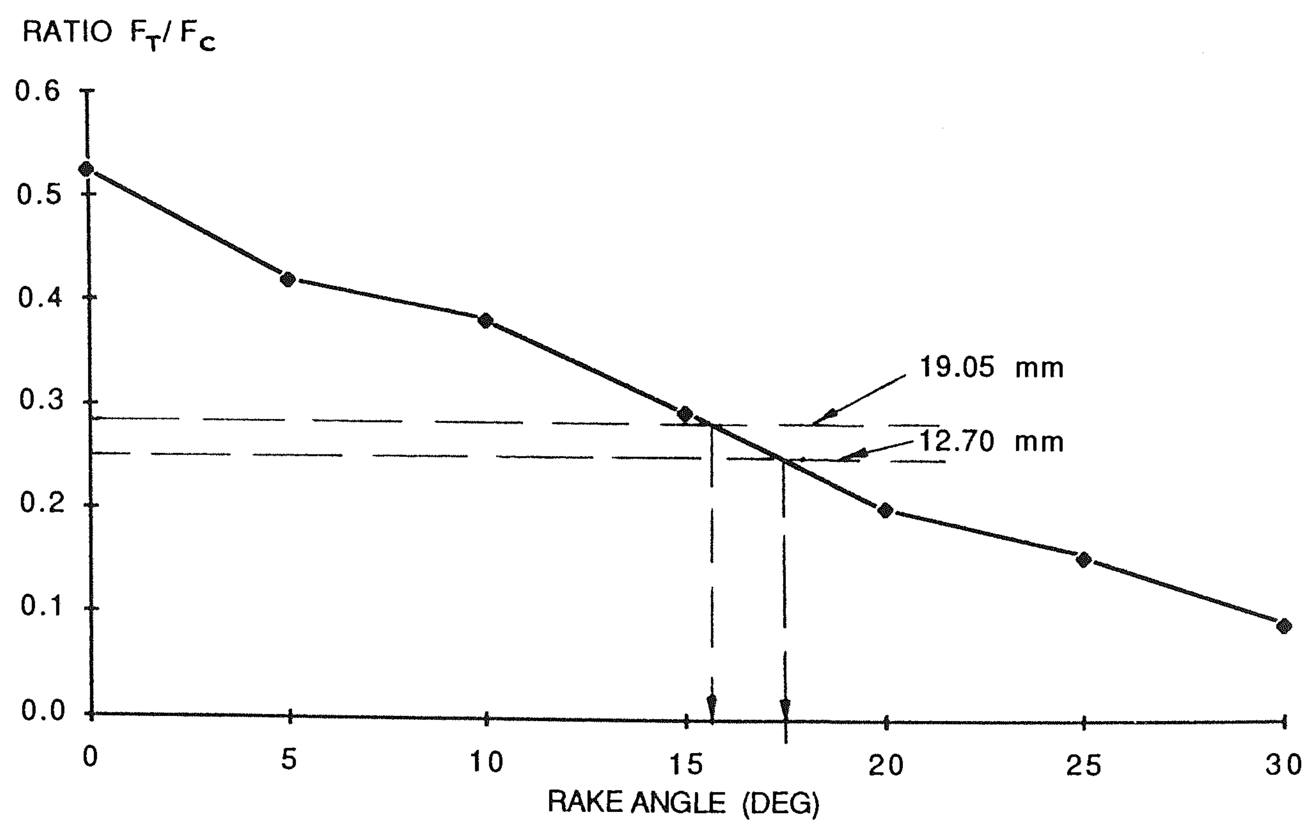



FIG 5.3 ORTHOGONAL CUTTING TEST GRAPH OF $F_T / F_C$ VERSUS RAKE ANGLE (RATIO OF $F_{TL} / F_{CL}$ SUPERIMPOSED FOR 19.05 mm & 12.70 mm DIA TWIST DRILLS )

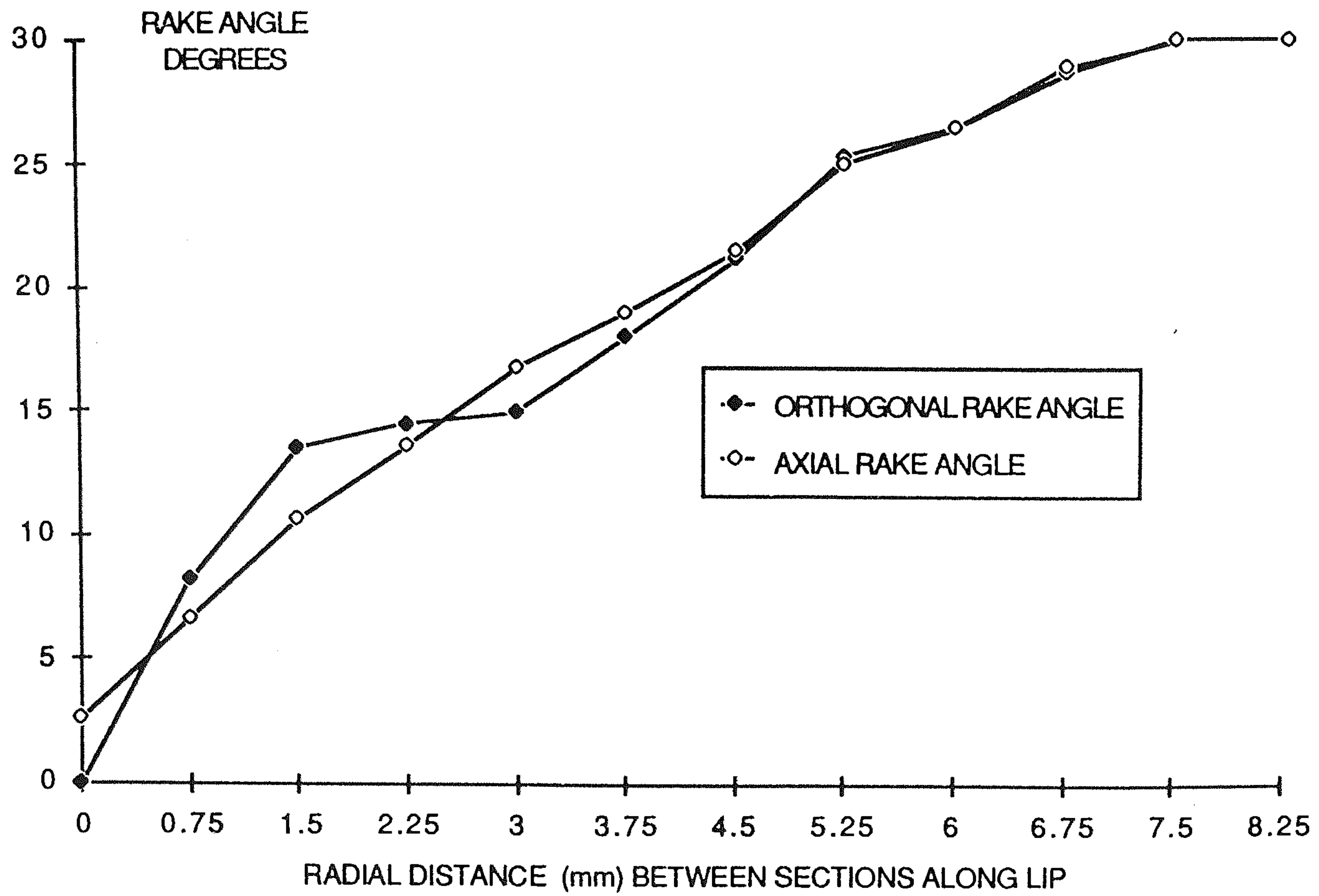
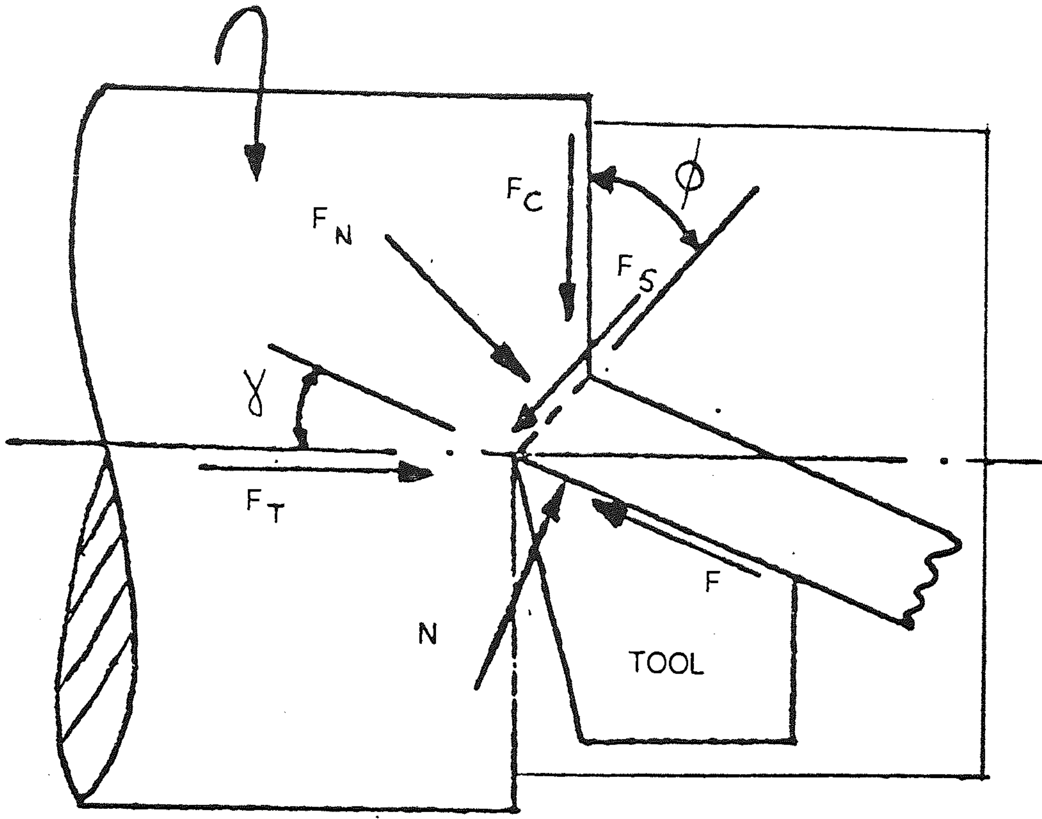
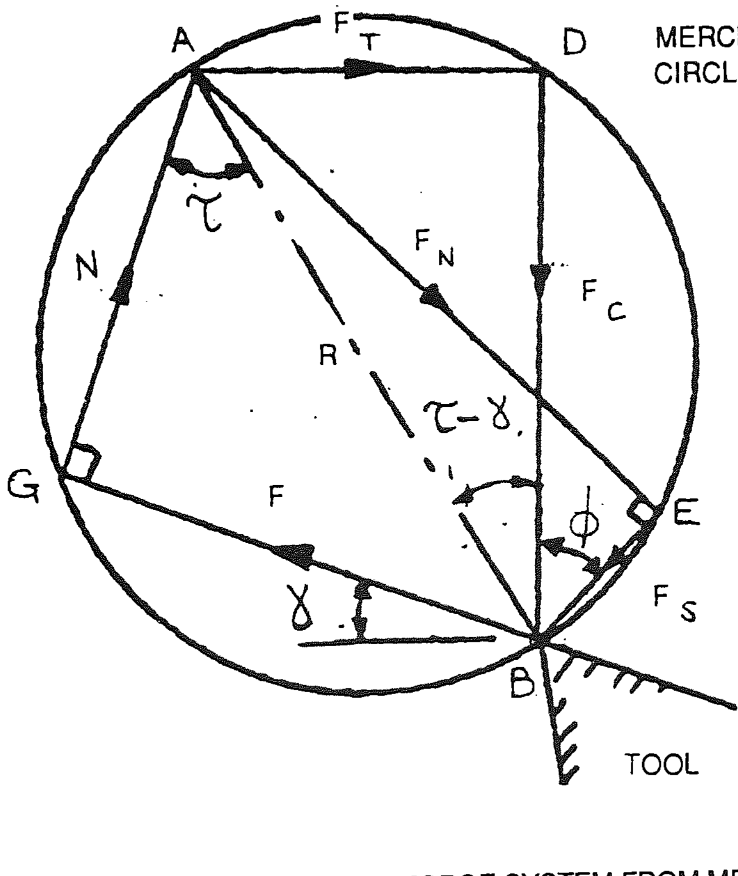



FIG 5.4 19.05 mm DIA TWIST DRILL -COMPARISON OF ORTHOGONAL AND AXIAL RAKE ANGLES AT DIFFERENT SECTIONS ON THE LIP




CHIP FORMATION MECHANISM
AND FORCE SYSTEM




MERCHANTS FORCE
CIRCLE

FIG 5.5 CHIP FORMATION AND FORCE SYSTEM FROM MERCHANTS ANALYSIS OF ORTHOGONAL CUTTING

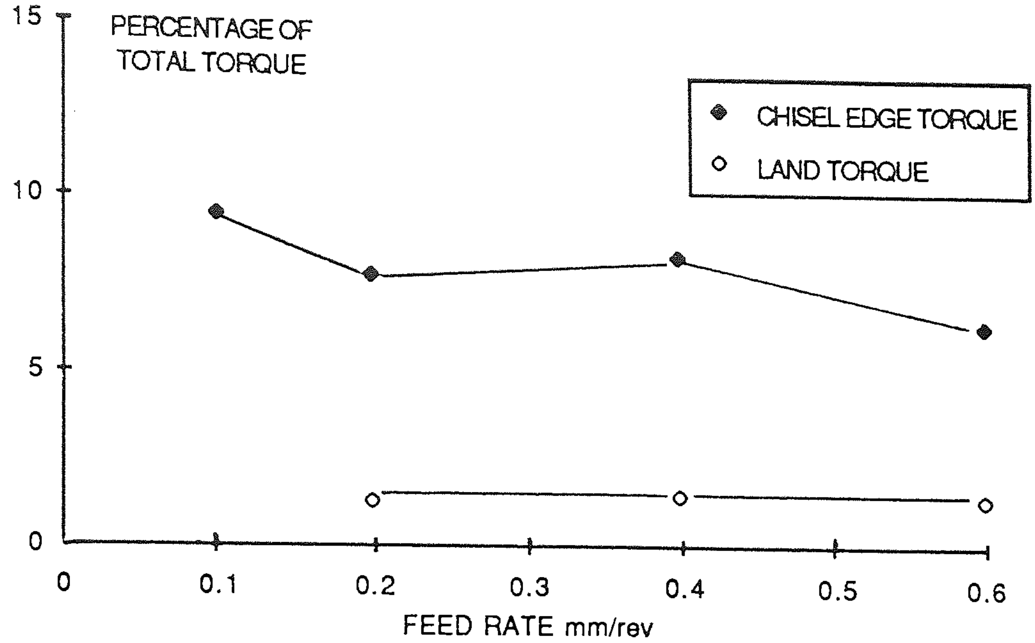



FIG 5.6 19.05 mm DIA TWIST DRILL
PERCENTAGE OF TOTAL TORQUE
ATTRIBUTABLE TO CHISEL EDGE AND LANDS

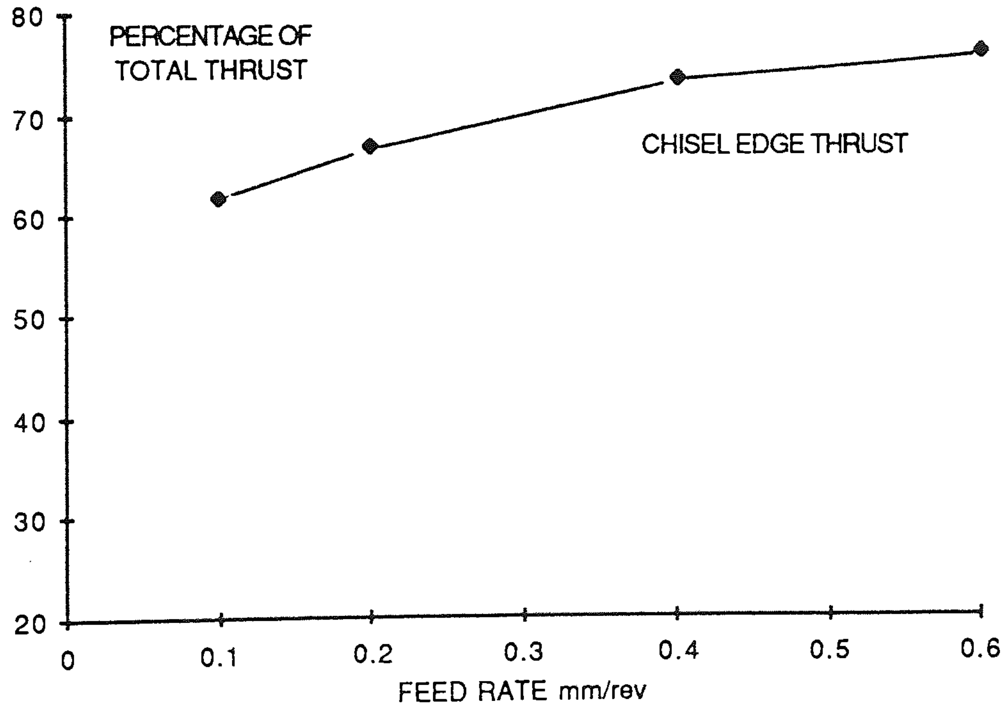



FIG 5.7 19.05 mm DIA TWIST DRILL
PERCENTAGE OF TOTAL THRUST ATTRIBUTABLE TO
THE CHISEL EDGE (LAND THRUST IS NEGLIGIBLE)

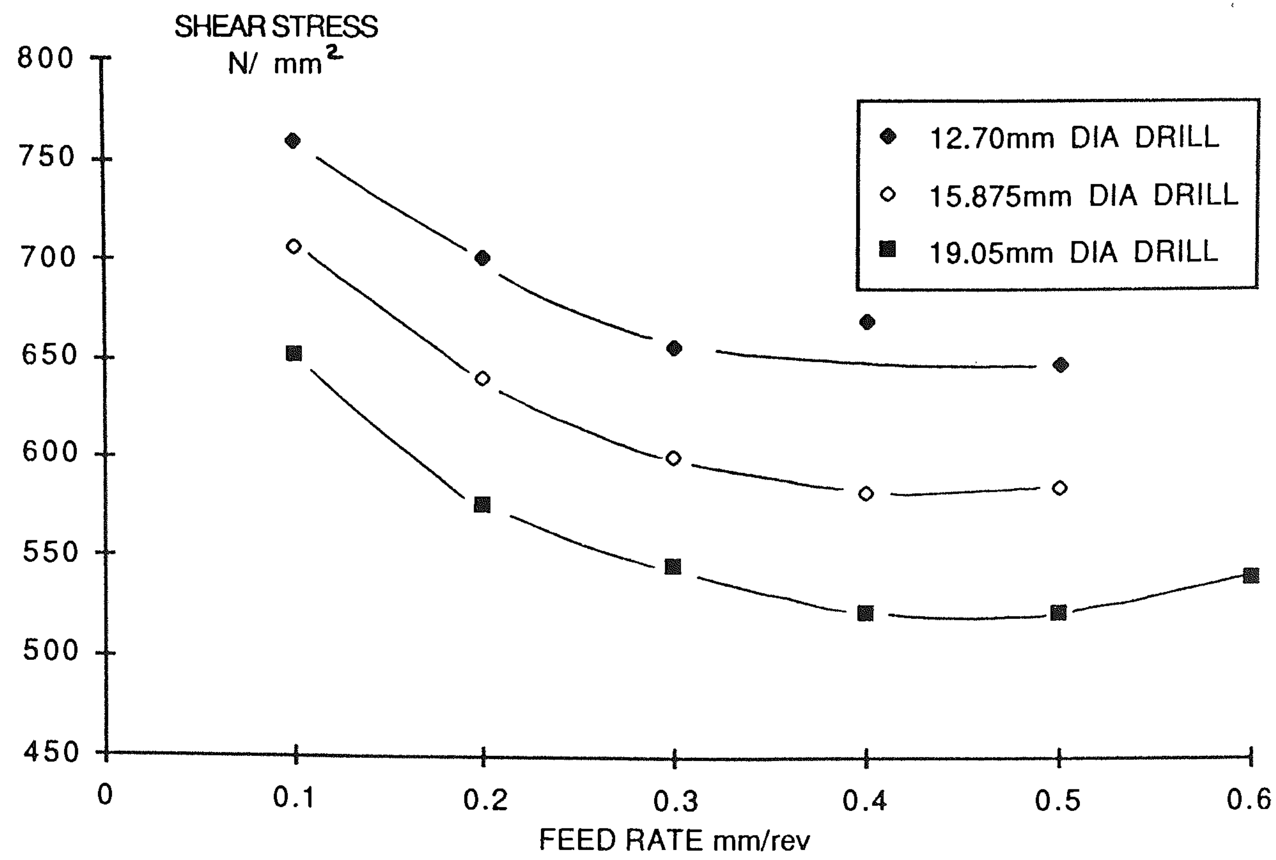



FIG 5.8 EFFECTIVE SHEAR STRESS ( $N/mm^2$ ) 12.70 &19.05 mm DIA TWIST DRILLS (15.875 mm DIA STRESS BY INTERPOLATION )

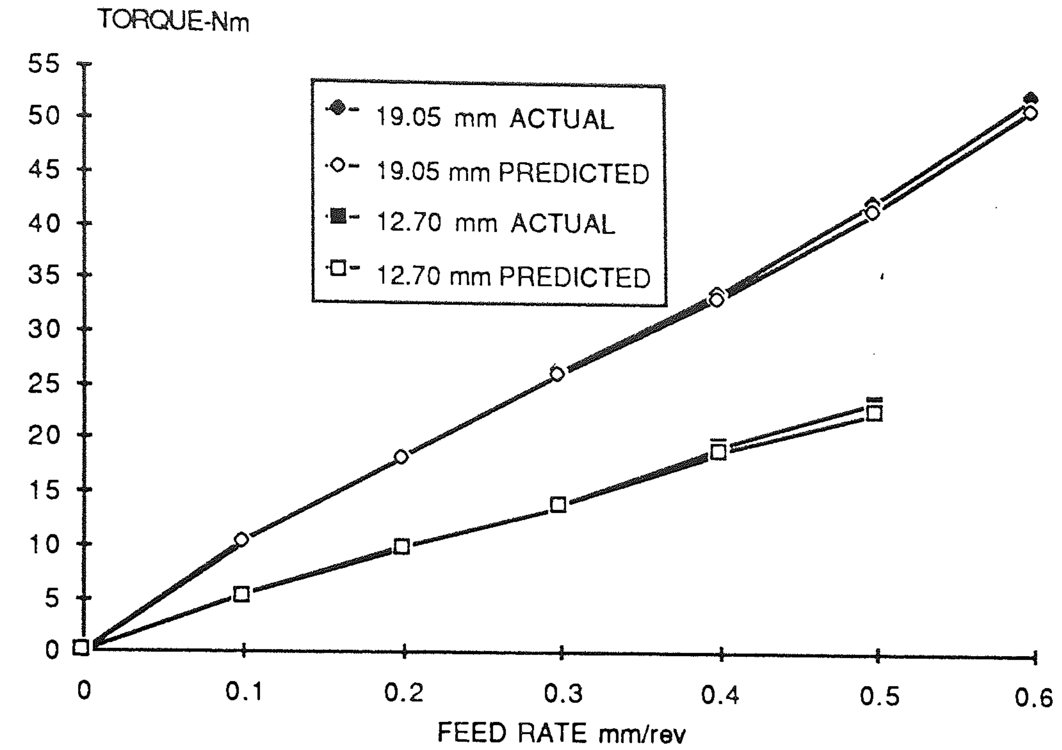



FIG 5. 9 COMPARISON OF ACTUAL AND PREDICTED TORQUE (Nm)
19.05 &12.70 mm DIA TWIST DRILLS

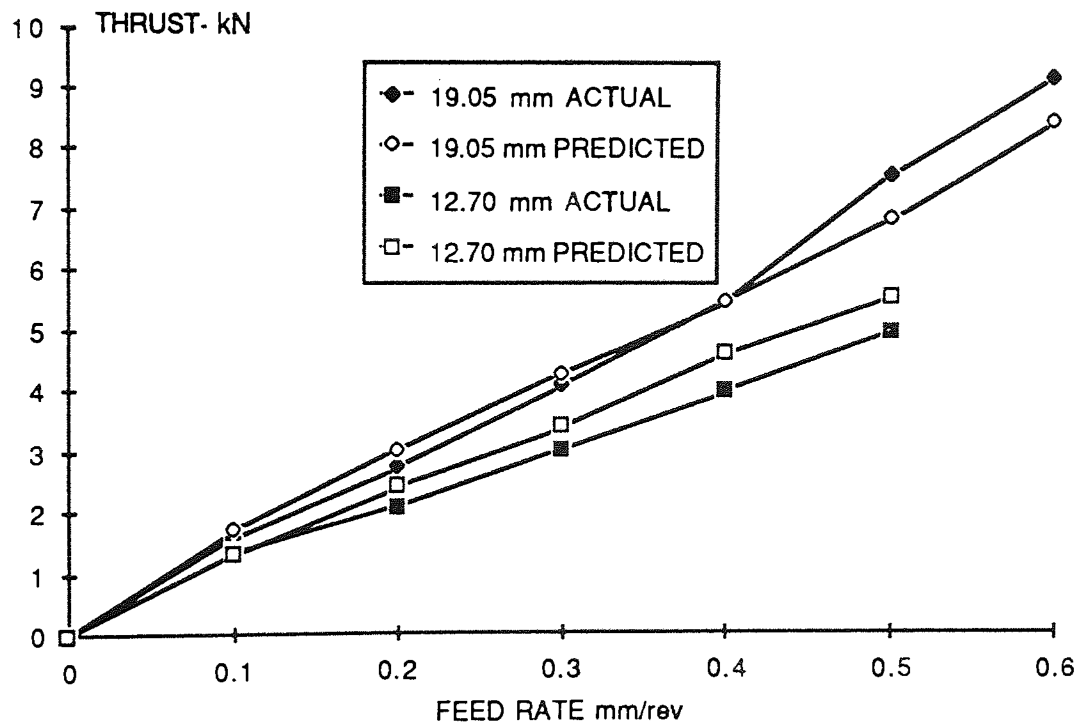



FIG 5.10 COMPARISON OF ACTUAL AND PREDICTED THRUST (kN)
19.05 &12.70 mm DIA TWIST DRILLS

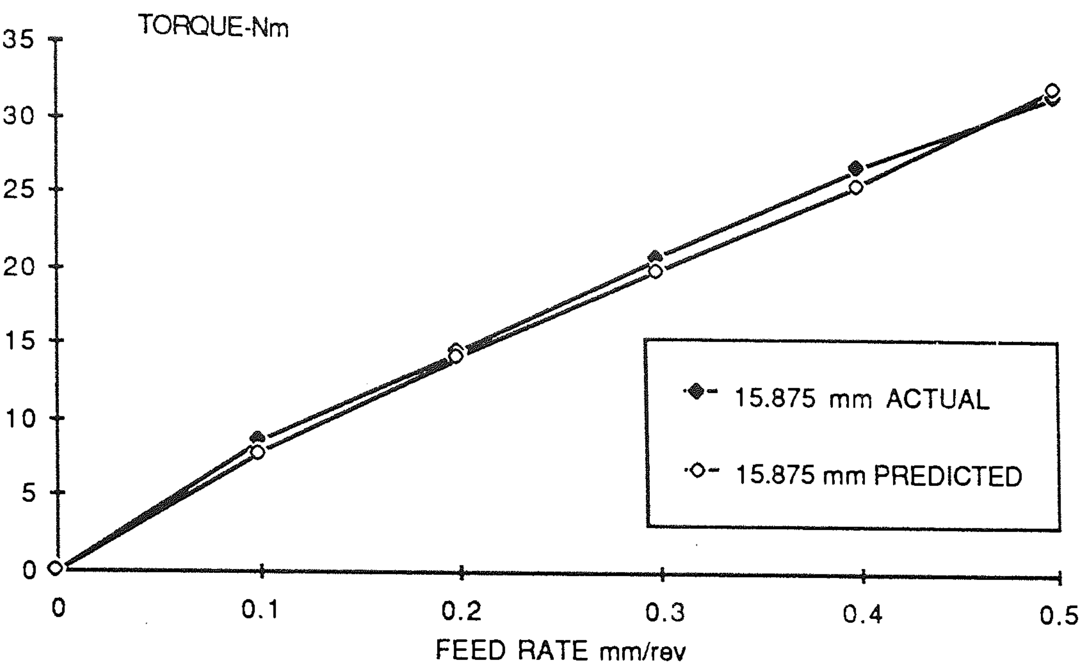



FIG 5.11 15.875 mm DIA TWIST DRILL
COMPARISON OF ACTUAL AND PREDICTED TORQUE (Nm)

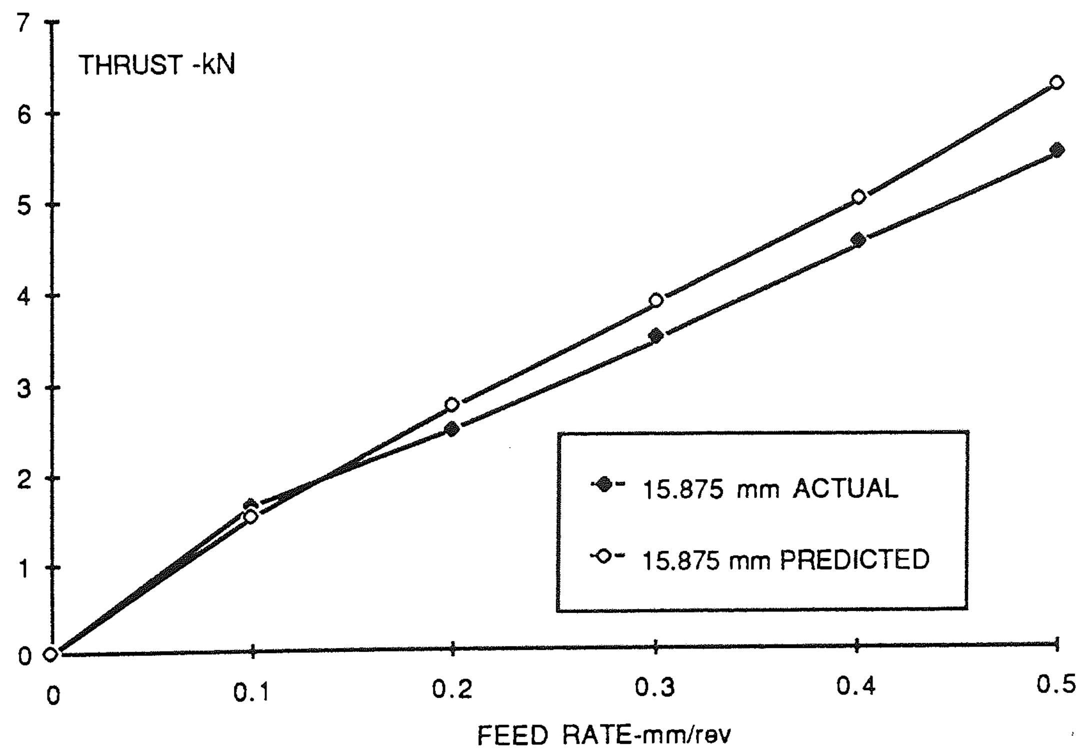



FIG 5.12 15.875 mm DIA TWIST DRILL
COMPARISON OF ACTUAL AND PREDICTED THRUST (kN)

FIG 5.13 19.05 mm Dia TWIST DRILL WITH SPIRAL CHIP SUPERIMPOSED TO SHOW DIRECTION OF CHIP FLOW AT THE CUTTING LIP

# CHAPTER SIX

# THE ADVANTAGES OF COOLANT FED TWIST DRILLS

## 6.1 INTRODUCTION

A major disadvantage of conventional twist drills is that coolant cannot effectively penetrate to the bottom of the hole being drilled once the hole depth has reached about one diameter deep. With increasing hole depth there may be a tendency for swarf clogging [42] to occur in the flutes of the drill. Periodic withdrawal of the drill or "wood pecking" is therefore necessary in order to clear the flutes. The problem becomes acute when the hole depth exceeds 3 diameters deep [43]. The upward spiral of swarf in the drill flutes serves to effectively block any coolant passage to the drill tip and ultimate failure of the cutting lips may occur through overheating. The mode of failure is inherently temperature dependent [44], which in turn depends upon the speed and feed of the drill and the drilling time [45].

A High Speed Steel twist drill will tend to lose its point hardness through "tempering back" at temperatures of about 550°C [46].

The tool life may be further reduced in horizontal drilling because any external coolant supply may not reach the bottom of the drilled hole through assistance from gravity.

## 6.2 COOLANT FED TWIST DRILLS

To overcome some of the overheating problems associated with conventional twist drills coolant fed drills were introduced [47].

A coolant fed drill usually incorporates internal passageways in the body of the drill which enable pressurised fluid, gas or a mist to be delivered to the tip of the drill [48] (Fig.6.1). Alternatively tubes may be brazed into slots milled in the flutes. The application of coolant by pulsed pressure techniques has also been considered [49].

The most common coolant is soluble oil or "suds" which is delivered under pressure to a hole in the shank of the drill via a coupling to a coolant inducer ring. This ring is usually sealed by 'O' rings and retained by circlips on the drill shank. Alternatively for horizontal drilling the coolant can be supplied axially through a hole in the Morse taper shank, with the supply being piped to the Morse taper housing.

The optimum design and application of coolant fed drills should take into account the nature of the material being cut. Low helix angles may be preferred in horizontal drilling because the swarf will have less distance to travel through the flutes of the drill to emerge from the hole.

Higher "fast" helix angles may assist in swarf ejection for rotating applications [50].

## 6.3 THE USE AND APPLICATION OF COOLANT FED DRILLS

Whilst coolant fed twist drills have been available for a number of years their potential has not been fully realised and this is due to a number of factors, i.e.:-

(i) Lack of knowledge of the potential advantages and the operating conditions which may result in improved drill performances.

(ii) Reluctance of engineering companies to invest in more expensive tooling and associated coolant systems for use with coolant fed drills.

(iii) Availability of coolant fed drills. (These drills have not universally been produced or marketed by UK drill manufacturers).

With the advent of CNC and more advanced machining systems, machining centres and Flexible Manufacturing Systems a new approach has emerged which places much greater emphasis on improved tooling systems. Unmanned systems require drills that have consistent and more predictable tool life [51], as well as the capability for increased penetration rates [52],[53]. Whilst some published material does attempt to identify the benefits of coolant fed drills in deep holes [54],[55],[56], there is only limited information available.

Some application requirements (eg speed, feed, coolant pressure) have been identified [57], but further detailed research is required to determine the optimum operating conditions for a coolant fed drill and the advantages compared with conventional drills.

## 6.4 ESTABLISHMENT OF TEST FACILITIES

All tests were undertaken on a Torshalla CNC Lathe (see Fig.6.2 and Appendix II). A special mounting block was bolted onto the lathe turret to carry the Kistler Drilling Dynamometer (Appendix III).

A Morse Taper adaptor was designed so that the drill shank was supported inside the Dynamometer body.

The high pressure coolant was supplied by a Grundfoss Multistage centrifugal pump Type CP2-200K at pressures of up to 16 bar. The pump was mounted near the bed of the machine and was used instead of the existing lathe suds pump when drilling with the coolant fed drill. For conventional drilling the existing lathe pump was used to supply an external "flood" of coolant.

For the high pressure pump a new coolant supply pipe was installed so that an independent system could be utilised. A pressure gauge was incorporated near to the drill mounting block (Fig.6.3).

A CNC program was written so that an automatic drilling cycle was performed. Each mild steel blank was individually loaded into the chuck and the lathe screen guard served to contain the excessive splash of coolant that was created. The high pressure pump was operated manually from a switch for each hole drilled.

## 6.5 CHARACTERSTICS OF THE COOLANT SYSTEM.

In order to adjust the coolant pressure at the drill, a flow control valve was incorporated in the supply line. Reductions in coolant flow rate were accompanied by a corresponding fall in pressure downstream from the valve. A flow meter was connected to the drill outlet so that the range of flow rates corresponding to the coolant pressures could be established (Table 6.1 and Fig.6.4) before testing commenced.

## 6.6 EXPERIMENTAL DESIGN

In order to establish the performance characteristics of a 19.05 mm dia coolant fed drill, the following tests were undertaken to determine:-

(i) The effect of coolant pressure on drill performance and hole quality.

(ii) The performance of coolant fed drills compared with conventional drills at different speeds and feeds.

(iii) The tool life of coolant fed drill compared with a conventional drill over 150 holes (All tests were restricted to drilling hole depths of two diameters deep in mild steel EN1A).

## 6.7 COOLANT FED DRILL GEOMETRY

The geometry of the 19.05 mm dia coolant fed drill and the conventional drill, used in these trials, were identical at the point. Each drill was ground to the same point angle of 118° with the clearance angle (10°) and chisel edge angle (120°) also being identical. The only difference in the two drills was in the web section. Both drills had similar 2.5 mm parallel web thicknesses over 13 mm of the flute length near the drill tip. The coolant fed drill web then tapered to a maximum thickness of 7 mm, whilst the conventional drill web was only 6.25 mm. Although the increased web thickness on the coolant fed drill might tend to restrict the swarf in deeper holes, this was thought unlikely to present a problem on the 38 mm hole depths used.

## 6.8 TEST PROCEDURE

The following tests were undertaken:-

### 6.8.1. Coolant Fed Drill Performance For Changes in Operating Pressure

Limited tests were undertaken to assess the coolant fed drill performance at different coolant supply pressures. The test was performed at 500 rpm x 0.4 mm/rev [58]. Torque and thrust measurements were taken starting at 9.33 bar pressure and then reducing in increments of 1.33 bar.

### 6.8.2. Comparison of Conventional and Coolant Fed Drill at Different Speeds and Feeds.

A series of tests was undertaken to compare the performance of a conventional and coolant fed drill at 600 rpm (36 m/min) across a range of feeds from 0.1 - 0.6 mm/rev.

Similar trials were then made at 1000 rpm to assess the higher speed capabilities of both drills. A constant coolant pressure of 6.50 bar was maintained for the coolant fed drill and the existing lathe suds pump coolant supply used for the conventional drill.

### 6.8.3. Comparison of Conventional and Coolant Fed Drill Over 150 Hole Tool Life Test.

In order to compare the performance of the coolant fed and conventional drills for repeated hole drilling, a tool life test over 150 holes was undertaken.

Identical speeds and feeds of 600 rpm x 0.6 mm/rev were used for each drill.

The coolant fed drill was operated at 6.50 bar coolant pressure and the Lathe suds pump cooling used for the conventional drill.

The torque and thrust traces were measured for each drill at every tenth hole. The drilled holes were also examined and the worn drills inspected at the end of the test.

## 6.9 RESULTS

The test results to show the effects of operating pressure on hole surface finish and thrust force for coolant fed drills, are presented in Table 6.2 and Figs.6.5 and 6.6.

The torque comparison results of a steam tempered conventional drill and a coolant fed drill at both 600 and 1000 rpm are shown in Table 6.3 and Figs.6.7 and 6.8.

The thrust results to complement the above torques at 600 and 1000 rpm are shown in Table 6.4 and Figs.6.9 and 6.10.

For the 150 hole tool life test the torque and thrust results for the conventional and coolant fed drills are presented in Table 6.5 and Figs.6.11 and 6.12, and an end view of the worn drills is shown in Fig.6.13.

The hole surface finish comparison results over 150 holes are presented in Table 6.6 and Fig.6.14 and the hole diameters at both drill entry and exit are given in Table 6.7 and Figs.6.15 and 6.16.

## 6.10 DISCUSSION OF RESULTS

From the tests undertaken in previous research [58] it was established that for coolant fed drills the coolant pressure had a significant effect on drill performance and hole quality, providing that moderate feed rates were used. Tests at 500 rpm x 0.4 mm gave significant improvements in hole surface finish when the coolant pressure reached 4 bar (Fig.6.5). Further increases in pressure did not result in any further improvement in hole finish. Increases in coolant pressure did not result in any reduction in drill torque, but the drill thrust force was reduced by up to 12.5% for pressures above 8 bar (Fig.6.6).

The improved hole quality and decrease in thrust force were attributed to reduction in built up edge on the drill due to lower cutting lip temperatures and also improved swarf evacuation from the hole with coolant fed drills.

These results were obtained for hole depths of 2 diameters (i.e. 38.1 mm) and in all subsequent tests a coolant pressure of 6.50 bar was used because this was judged to be sufficient for this hole depth. For deeper holes or other materials higher pressures would probably be required.

In the second phase of the work the performance of a coolant fed drill was compared with that of a conventional steam tempered twist drill across a range of feeds and at both 600 and 1000 rpm. The higher speed was chosen to investigate the opportunities for increased cutting speeds with coolant fed drills.

In comparing the torque results (Figs.6.7 and 6.8) it was established that at 600 rpm the torque for the coolant fed drill was actually between 5% and 10% higher than the conventional drill. The reasons for this were attributed to the lower temperatures in the cutting zone of the coolant fed drill. The lower temperature may have contributed to an effective increase in tensile strength in the cutting zone.

At 1000 rpm the torque for the coolant fed drill remained almost identical to that at 600 rpm, but the conventional drill torque increased so that curves were almost identical. The torque increase for the conventional drill was probably due to built up edge along the cutting lips and chisel edge, particularly at high feed rates [59].

The thrust force comparisons shown in Figs. 6.9 and 6.10 demonstrated that at 600 rpm there was very little difference between the thrust taken by both the steam tempered conventional drill and the coolant fed drill. The advantage of the coolant fed drill became apparent at 1000 rpm at feed rates of 0.1 - 0.4 mm/rev, when the conventional drill thrust force increased by about 25% compared to that measured for the coolant fed drill. The thrust increase was probably due to the built up edge formation that was exacerbated by the increased heat generation at the higher cutting speed.

At feed rates of 0.5 and 0.6 mm/rev the thrust forces generated by the conventional and coolant fed drills are similar. It is suggested that the ability of the coolant fed drill to prevent built up edge formation and assist swarf ejection was limited by the metal removal rate. At higher metal removal rates the increase in cutting temperatures and high chip thicknesses cannot be effectively countered by the coolant fed drill at 6.5 bar pressure.

Increases in coolant pressure or pulsed pressure feeding of the coolant may help to extend the effective operating range of the coolant fed drill particularly on increased hole depths.

When the performance of the conventional and coolant fed drill was compared over a 150 hole test to determine the drill wear characteristics, a feed of 0.6 mm/rev at 600 rpm was chosen to provide accelerated wear data. The difference in the performance of the two drills, which appeared small in the initial speed and feed test, became more apparent.

Dynamometer results confirmed that the conventional drill was inferior in performance. This was demonstrated by the torque and thrust traces (Figs.6.11 and 6.12). The torque for the conventional drill was generally between 5% and 10% higher than that for the coolant fed drill. The thrust force for the conventional drill was up to 10% greater than that for the coolant fed drill throughout the

150 hole test.

Comparison of the worn drills after testing (Fig.6.13) showed that the built up edge and heat affected zone on the conventional drill was much more pronounced to that observed on the coolant fed drill.

Comparison of the hole surface finishes over 150 holes (Fig.6.14) confirmed that the coolant fed drill achieved finishes of about 2μm Ra over the first 100 holes, but this deteriorated to about 4μm Ra over the final 50 holes. The conventional steam tempered drill produced holes with a surface finish of about 4μm Ra throughout the test.

The same trend was recorded for the hole diameters (Figs.6.15 and 6.16). The coolant fed drill generally produced holes to within 0.07 mm of nominal size, although this deteriorated to 0.10 over the final 50 holes. The conventional steam tempered drill hole diameters were more variable and up to 0.18 mm oversize at drill entry.

## 6.11 CONCLUSIONS

(i) Coolant fed drills successfully reduced the cutting lip temperatures and formation of built up edge when drilling hole depths of 2 diameters in mild steel providing that coolant pressures were maintained at or above 4 bars.

(ii) Speed increases of up to 66% were utilised without any significant increase in thrust force or torque at feed rates of up to 0.4 mm/rev for the coolant fed drill.

(iii) The torque taken by a coolant fed drill may sometimes be higher than that for an equivalent steam tempered conventional drill and this can be attributed to the lower temperatures at the cutting lip.

(iv) The use of coolant fed drills enabled improved hole tolerances and surface finishes to be achieved compared with a conventional drill for up to 100 holes. Some deterioration in coolant fed drill performance occurred after this.

(v) Minimum coolant pressures of about 4 bars were required to ensure improved hole quality and tool life for the coolant fed drill. High pressure coolant also provided rapid swarf evacuation.

(vi) Correct drill point grinding was essential to maintain the hole quality and improved drill performance of the coolant fed drill.

(vii) The same basic wear and failure mechanisms that occur with conventional twist drills can still be expected with coolant fed twist drills, but the onset of failure will occur after a greater number of holes.

| PRESSURE (bar) | COOLANT FLOWRATE (l/min) |
|---|---|
| 3.33 | 6.14 |
| 6.66 | 8.42 |
| 10.00 | 10.00 |
| 13.33 | 11.15 |
| 16.00 | 13.42 |

TABLE No. 6.1

CHARACTERISTICS OF THE COOLANT SYSTEM FOR
19.05 mm Dia. COOLANT FED DRILL.
THE EFFECT OF LINE PRESSURE ON COOLANT FLOW RATE.

| PRESSURE (bar) | HOLE SURFACE FINISH (μm Ra) | THRUST FORCE (kN) |
|---|---|---|
| External Coolant | 4.5 | 7.3 |
| 1.33 | 5.0 | 7.0 |
| 2.66 | 4.1 | 6.8 |
| 4.00 | 1.8 | 6.7 |
| 5.33 | 2.0 | 6.7 |
| 6.66 | 1.8 | 6.5 |
| 8.00 | 1.5 | 6.4 |
| 9.33 | 1.8 | 6.4 |

TABLE No. 6.2

19.05 mm Dia. COOLANT FED TWIST DRILL.
THE EFFECT OF LINE PRESSURE ON HOLE SURFACE FINISH
(μmRa) AND THRUST FORCE AT 500 rpm x 0.4 mm/rev.

| FEED RATE (mm/rev) | CONVENTIONAL STEAM TEMPERED DRILL TORQUE (Nm) | | COOLANT FED DRILL TORQUE (Nm) * | |
|---|---|---|---|---|
| | 600 rpm | 1000 rpm | 600 rpm | 1000 rpm |
| 0.1 | 10.5 | 11.0 | 11.0 | 11.0 |
| 0.2 | 18.5 | 20.0 | 21.0 | 20.0 |
| 0.3 | 26.5 | 28.0 | 29.0 | 29.0 |
| 0.4 | 34.0 | 38.0 | 37.0 | 37.0 |
| 0.5 | 43.0 | 48.0 | 46.0 | 47.0 |
| 0.6 | 52.0 | 60.0 | 53.0 | 55.0 |

TABLE No. 6.3 * Coolant Pressure 6.5 bar.

COMPARISON OF TORQUE (Nm) FOR STEAM TEMPERED AND COOLANT FED DRILL (19.05 mm Dia) AT 600 AND 1000 rpm AND SELECTED FEED RATES.

| FEED RATE (mm/rev) | CONVENTIONAL STEAM TEMPERED DRILL THRUST (kN) | | COOLANT FED DRILL* THRUST (kN) | |
|---|---|---|---|---|
| | 600 rpm | 1000 rpm | 600 rpm | 1000 rpm |
| 0.1 | 1.6 | 1.9 | 1.8 | 1.7 |
| 0.2 | 2.8 | 3.8 | 2.9 | 2.7 |
| 0.3 | 4.1 | 4.3 | 4.2 | 3.9 |
| 0.4 | 5.5 | 7.2 | 5.3 | 5.6 |
| 0.5 | 7.6 | 8.3 | 7.0 | 8.3 |
| 0.6 | 9.2 | 9.6 | 9.1 | 9.8 |

TABLE No. 6.4 * Coolant Pressure 6.5 bar.

COMPARISON OF THRUST (kN) FOR STEAM TEMPERED AND COOLANT FED DRILL (19.05 mm Dia) AT 600 AND 1000 rpm AND SELECTED FEED RATES.

| HOLE No. | CONVENTIONAL STEAM TEMPERED DRILL | | COOLANT FED DRILL | |
|---|---|---|---|---|
| | TORQUE(Nm) | THRUST(kN) | TORQUE(Nm) | THRUST (kN) |
| 1 | 50 | 9.6 | 49 | 8.6 |
| 20 | 50 | 10.0 | 51 | 8.8 |
| 40 | 52 | 10.0 | 52 | 9.2 |
| 60 | 52 | 10.2 | 50 | 9.0 |
| 80 | 53 | 10.2 | 51 | 9.0 |
| 100 | 52 | 10.0 | 51 | 9.0 |
| 120 | 55 | 10.5 | 52 | 9.0 |
| 140 | 51 | 10.3 | 52 | 9.2 |
| 150 | 52 | 10.2 | 52 | 9.2 |

TABLE No. 6.5

19.05 mm Dia. TWIST DRILL: COMPARISON OF TORQUE (Nm) AND THRUST (kN) FOR CONVENTIONAL AND COOLANT FED DRILL (6.50 bar COOLANT PRESSURE) OVER 150 HOLES AT 600 rpm x 0.6 mm/rev.

| HOLE No. | HOLE SURFACE FINISH (μmRa) | |
|---|---|---|
| | CONVENTIONAL STEAM TEMPERED DRILL (μmRa) | COOLANT FED DRILL (μmRa) |
| 1 | 1.4 | 2.1 |
| 20 | 3.8 | 1.5 |
| 40 | 3.3 | 2.2 |
| 60 | 3.7 | 1.8 |
| 80 | 3.1 | 1.8 |
| 100 | 4.0 | 1.8 |
| 120 | 3.2 | 4.1 |
| 140 | 5.0 | 3.2 |
| 150 | 3.2 | 3.5 |

TABLE No. 6.6

19.05 mm Dia. TWIST DRILL: COMPARISON OF HOLE SURFACE FINISH (μmRa) FOR CONVENTIONAL AND COOLANT FED DRILL (6.50 bar COOLANT PRESSURE ) OVER 150 HOLES AT 600 rpm x 0.6 mm/rev.

| HOLE No. | HOLE DIAMETERS (mm) | | | |
|---|---|---|---|---|
| | CONVENTIONAL STEAM TEMPERED DRILL (ENTRY) | (EXIT) | COOLANT FED DRILL (ENTRY) | (EXIT) |
| 1 | 19.10 | 19.05 | 19.07 | 19.07 |
| 20 | 19.10 | 19.05 | 19.07 | 19.07 |
| 40 | 19.07 | 19.13 | 19.07 | 19.07 |
| 60 | 19.13 | 19.10 | 19.07 | 19.05 |
| 80 | 19.13 | 19.07 | 19.07 | 19.05 |
| 100 | 19.18 | 19.05 | 19.10 | 19.07 |
| 120 | 19.18 | 19.07 | 19.10 | 19.07 |
| 140 | 19.10 | 19.07 | 19.10 | 19.07 |
| 150 | 19.13 | 19.10 | 19.10 | 19.07 |

**TABLE No. 6.7**

**19.05 mm Dia. TWIST DRILL:**
**COMPARISON OF HOLE Dia. (mm) AT ENTRY AND EXIT FOR CONVENTIONAL AND COOLANT FED DRILL (6.50 bar PRESSURE) OVER 150 HOLES.**

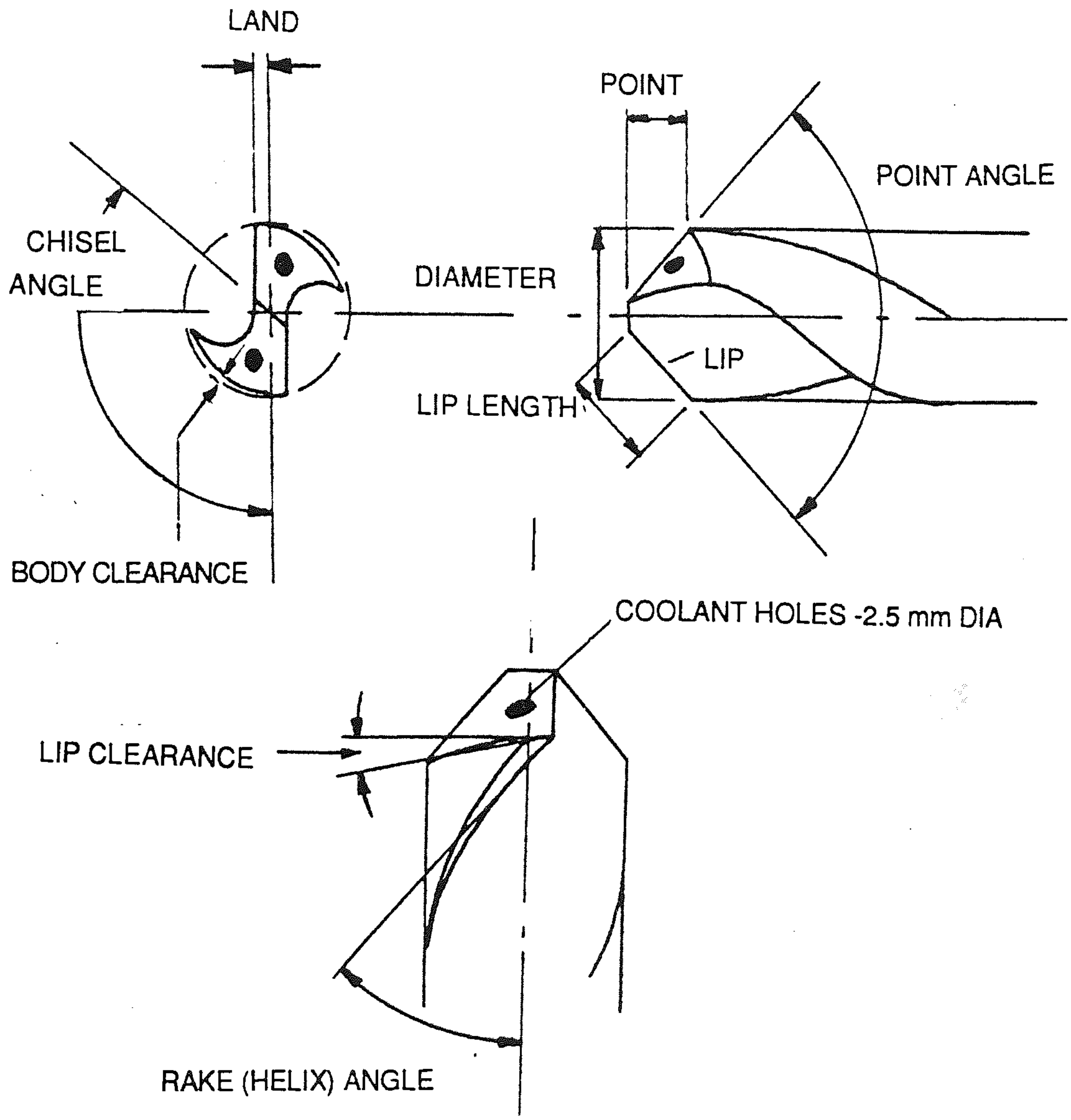



FIG 6.1 19.05 mm DIA COOLANT FED DRILL CONFIGURATION

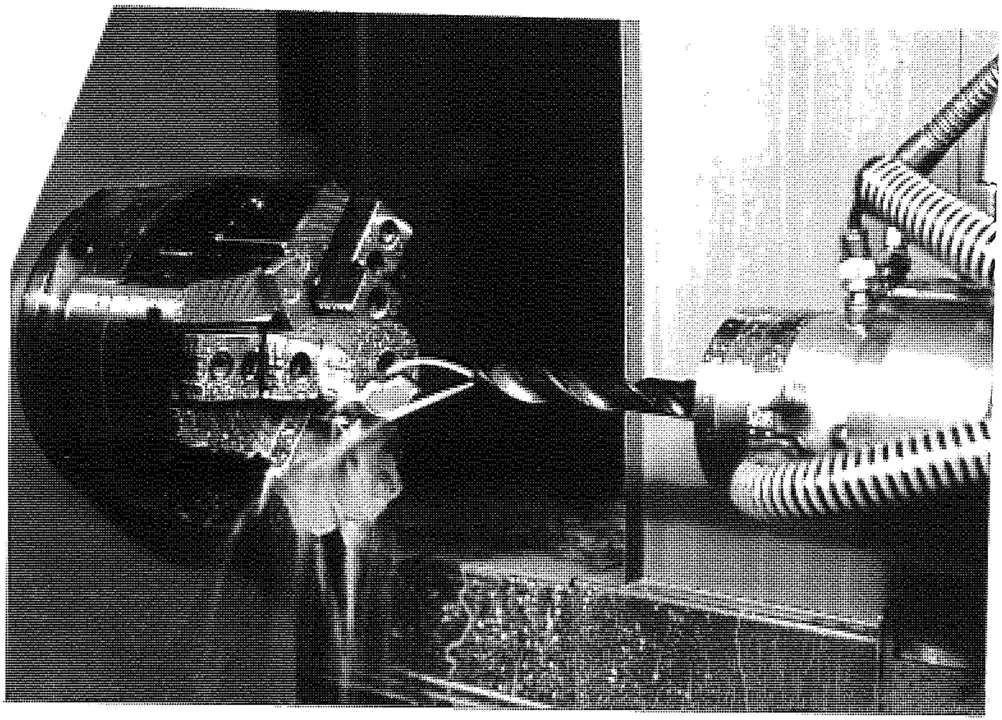


FIG 6.2 TORSHALLA CNC LATHE -DRILL TEST SET UP FOR COOLANT FED DRILL

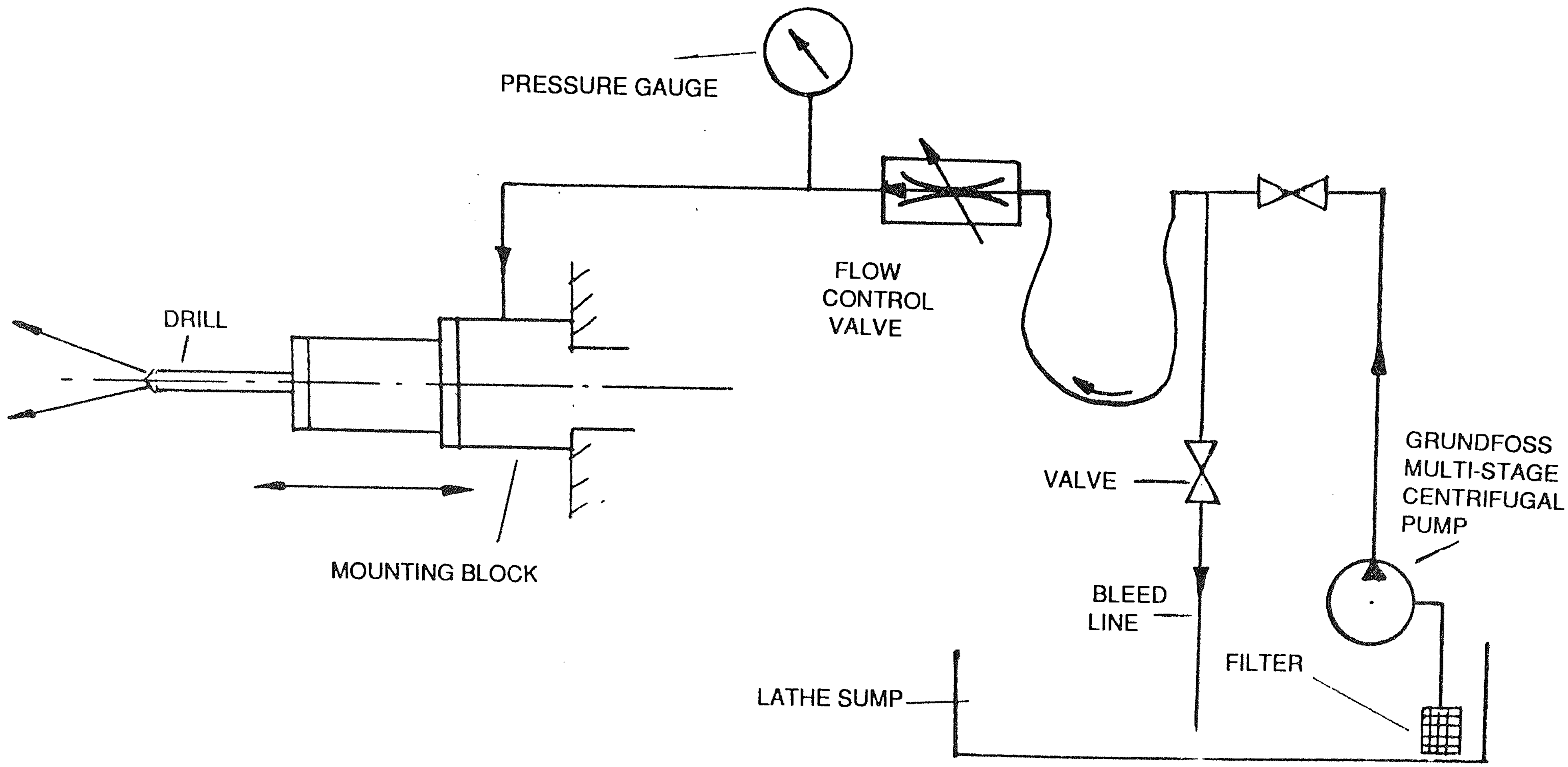



FIG 6.3 LINE DIAGRAM OF THE COOLANT FEED SYSTEM

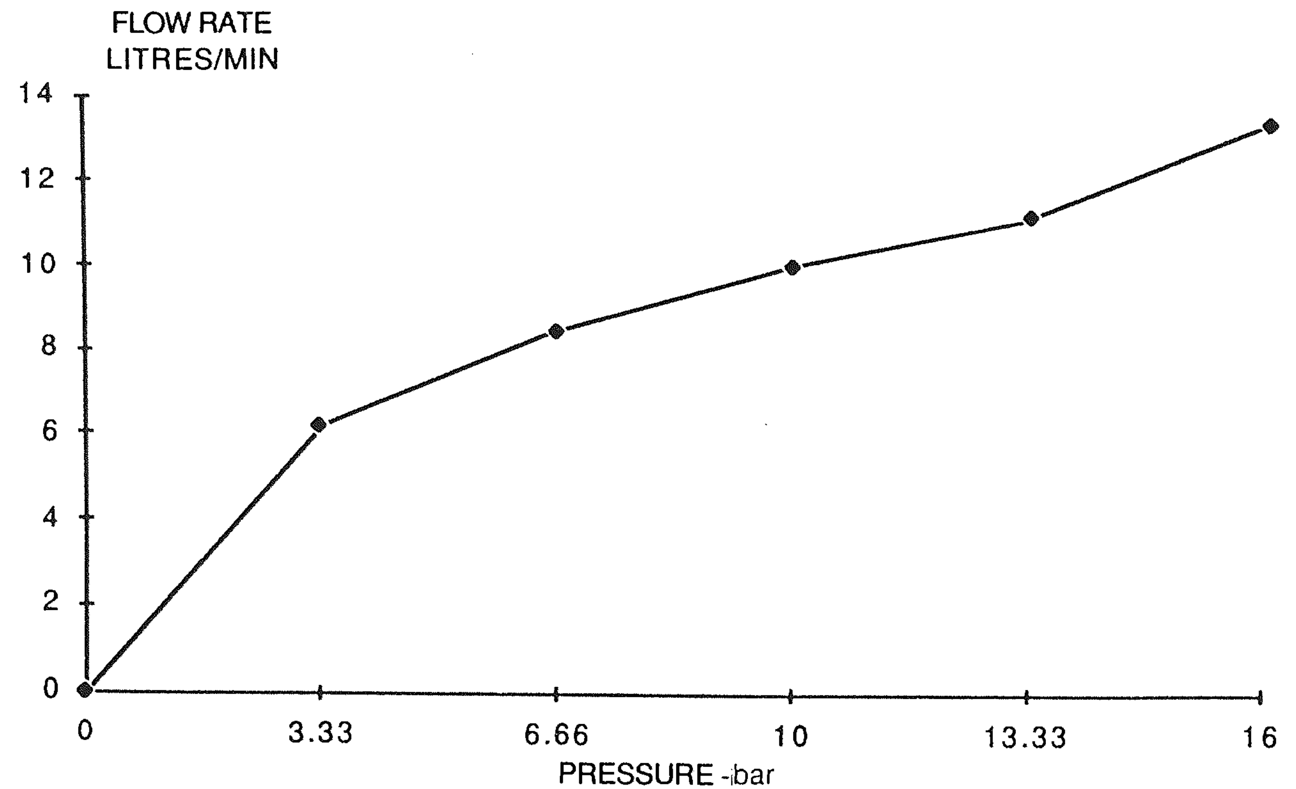



FIG 6.4 19.05 mm DIA COOLANT FED DRILL -GRAPH OF FLOW RATE VERSUS SUPPLY PRESSURE

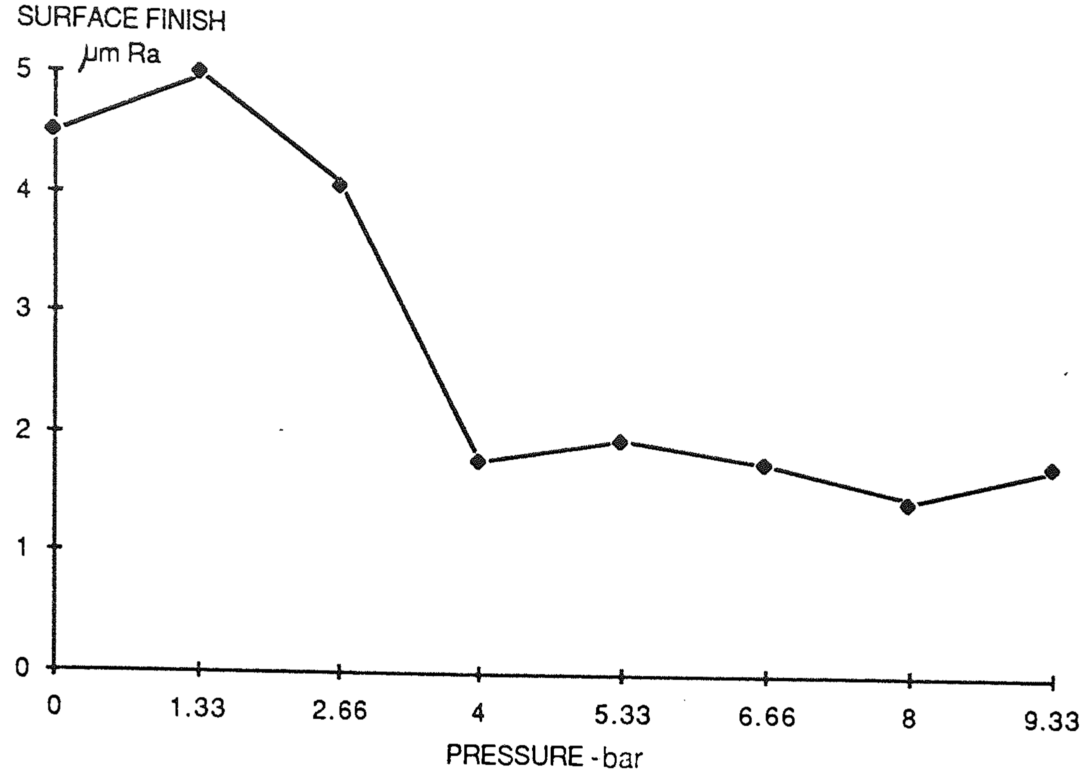



FIG 6.5 19.05 mm DIA COOLANT FED TWIST DRILL THE EFFECT OF PRESSURE ON HOLE SURFACE FINISH AT 500 rpm ,0.4 mm/rev

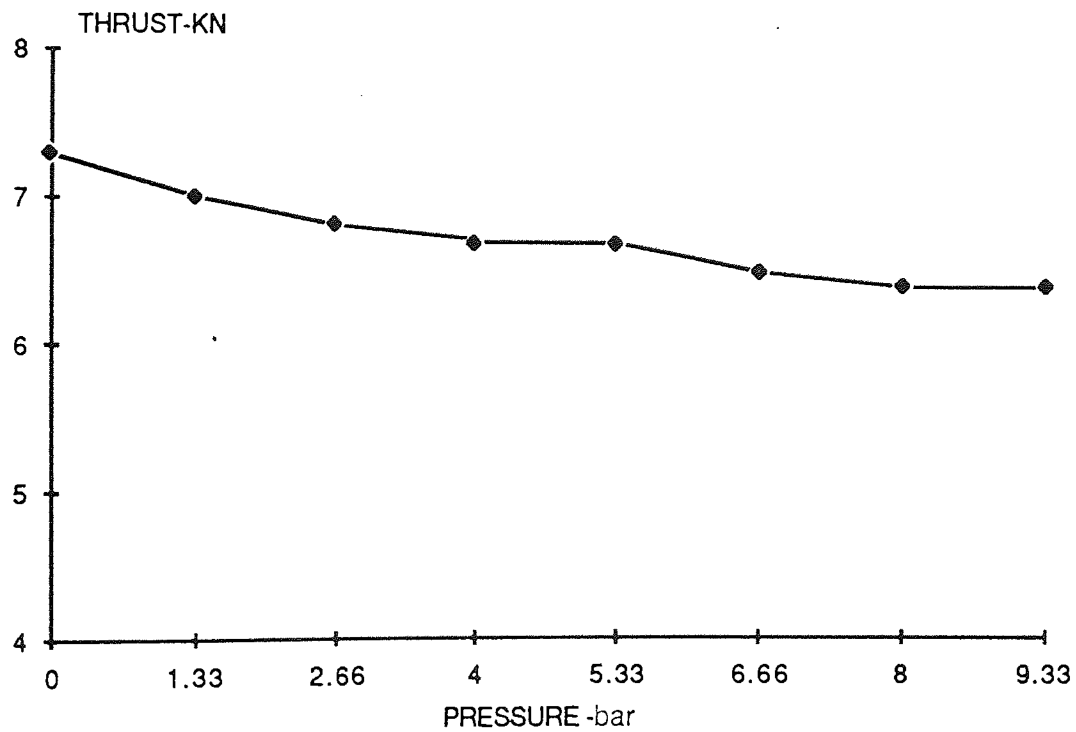



FIG 6.6 19.05 mm DIA COOLANT FED TWIST DRILL THE EFFECT OF PRESSURE ON THRUST AT 500 rpm ,0.4 mm/rev

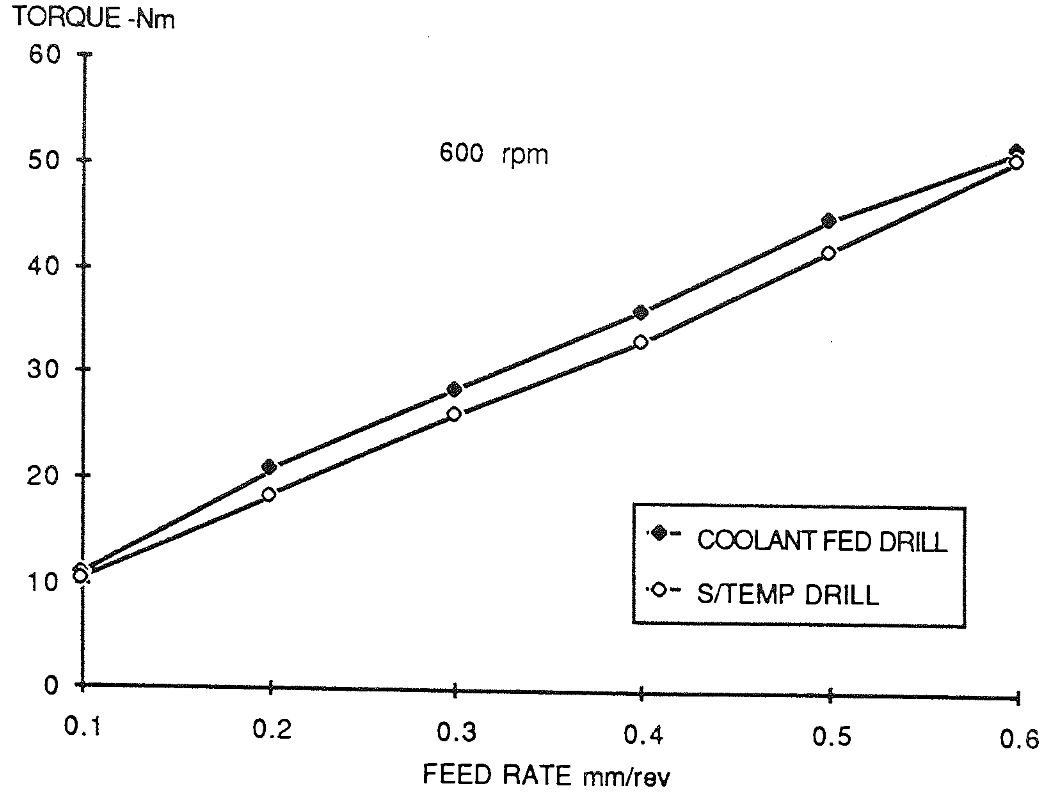



FIG 6.7 19.05 mm DIA TWIST DRILL -COMPARISON OF TORQUE (Nm) FOR A COOLANT FED DRILL (6.50 bar PRESSURE ) AND A STEAM TEMPERED DRILL AT 600 rpm AND SELECTED FEEDS

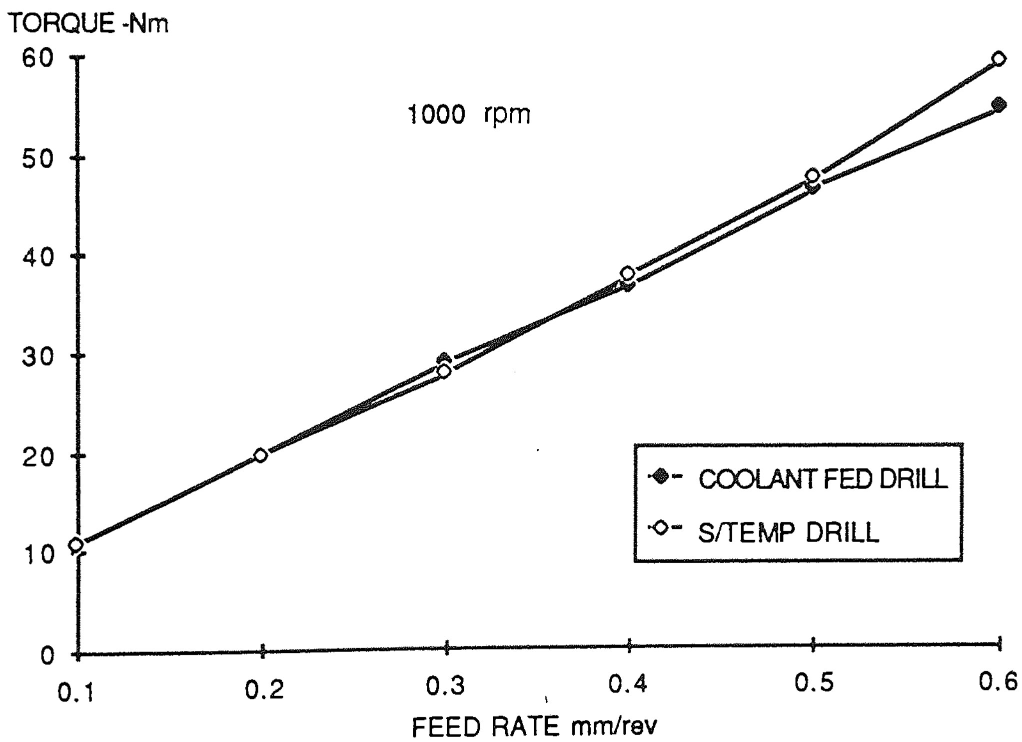



FIG 6.8 19.05 mm DIA TWIST DRILL -COMPARISON OF TORQUE (Nm) FOR A COOLANT FED DRILL (6.50 bar PRESSURE) AND A STEAM TEMPERED DRILL AT 1000 rpm AND SELECTED FEED RATES

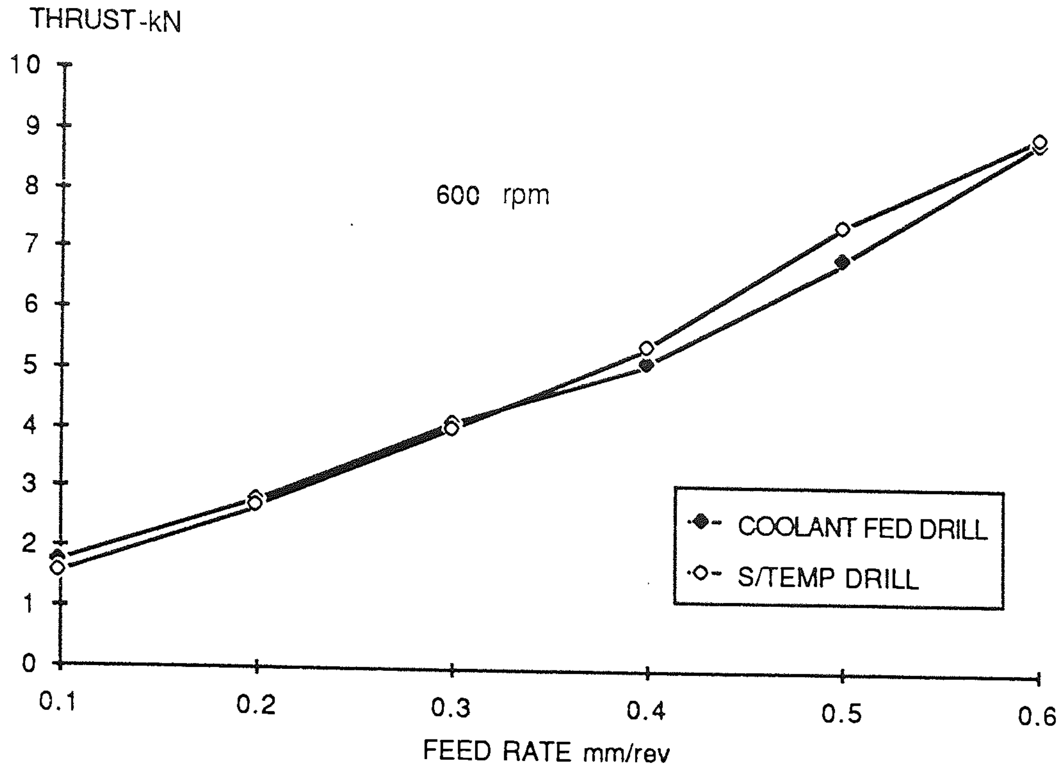



FIG 6.9 19.05 mm DIA TWIST DRILL - COMPARISON OF THRUST (kN) FOR A COOLANT FED DRILL (6.5 bar COOLANT PRESSURE) AND A CONVENTIONAL DRILL AT 600 rpm AND SELECTED FEEDS

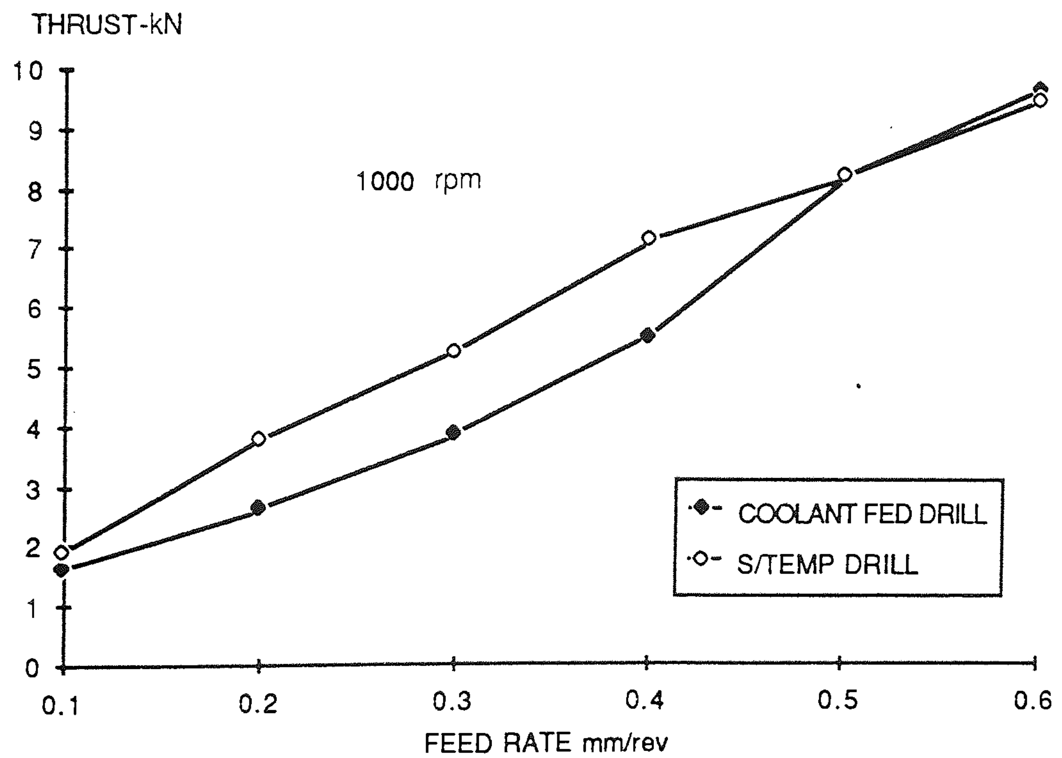



FIG 6.10 19.05 mm DIA TWIST DRILL-COMPARISON OF THRUST (kN) FOR A COOLANT FED DRILL (6.5 bar COOLANT PRESSURE) AND A STEAM TEMPERED DRILL AT 1000 rpm AND SELECTED FEEDS

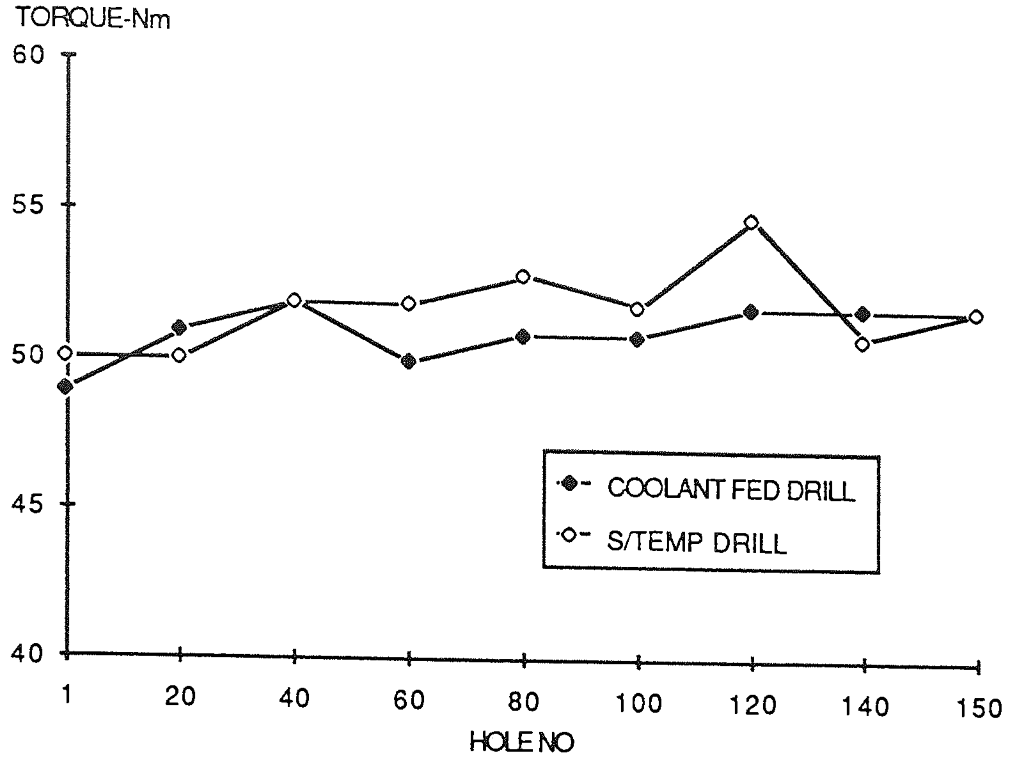



FIG 6.11 19.05 mm DIA TWIST DRILL - COMPARISON OF TORQUE (Nm) FOR A COOLANT FED AND STEAM TEMPERED DRILL OVER 150 HOLES AT 600 rpm,0.6 mm/rev

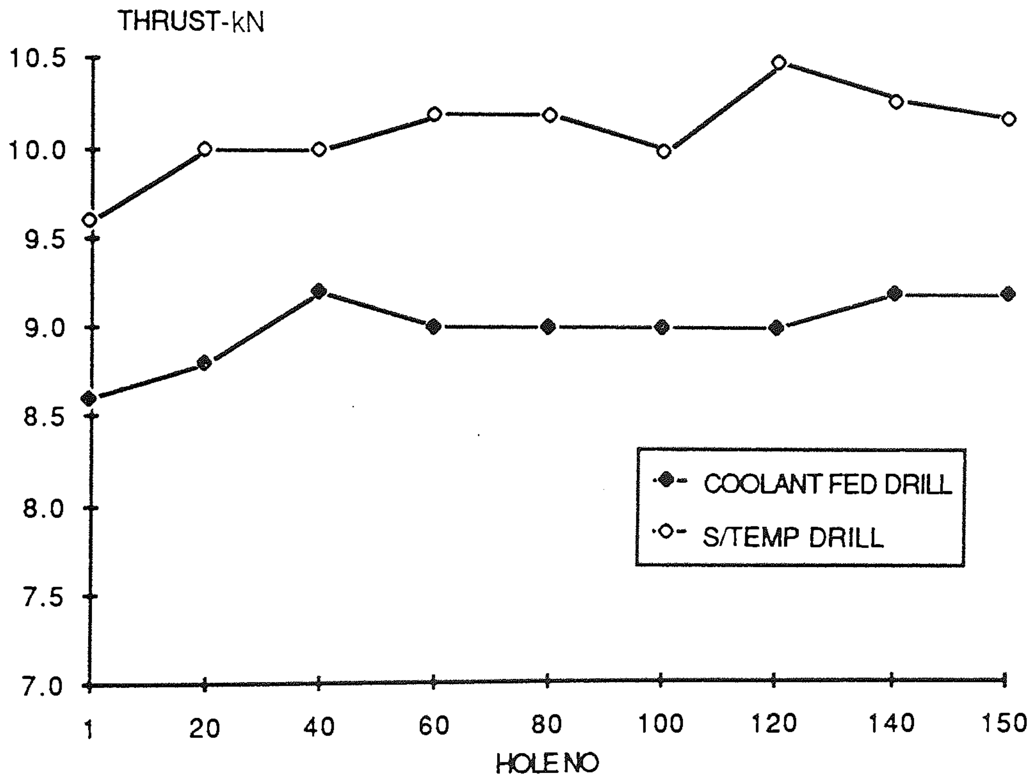



FIG 6.12 19.05 mm DIA TWIST DRILL - COMPARISON OF THRUST (kN) FOR COOLANT FED AND STEAM TEMPERED DRILL OVER 150 HOLES AT 600 rpm,0.6 mm/rev

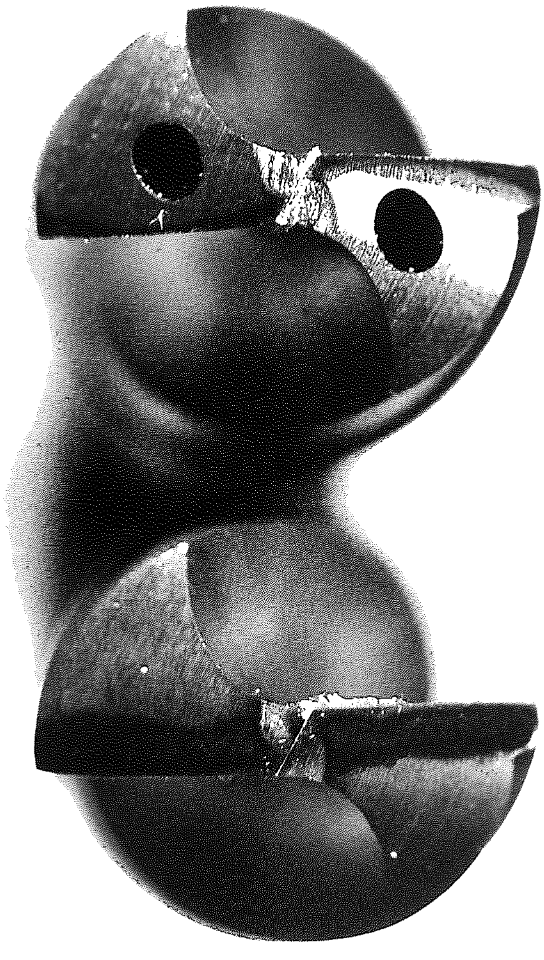


FIG 6.13 19.05 mm Dia TWIST DRILL
WEAR COMPARISON AFTER 150 HOLE TEST

TOP : COOLANT FED DRILL ( PRESSURE =6.5 bar)

BOTTOM : CONVENTIONAL DRILL

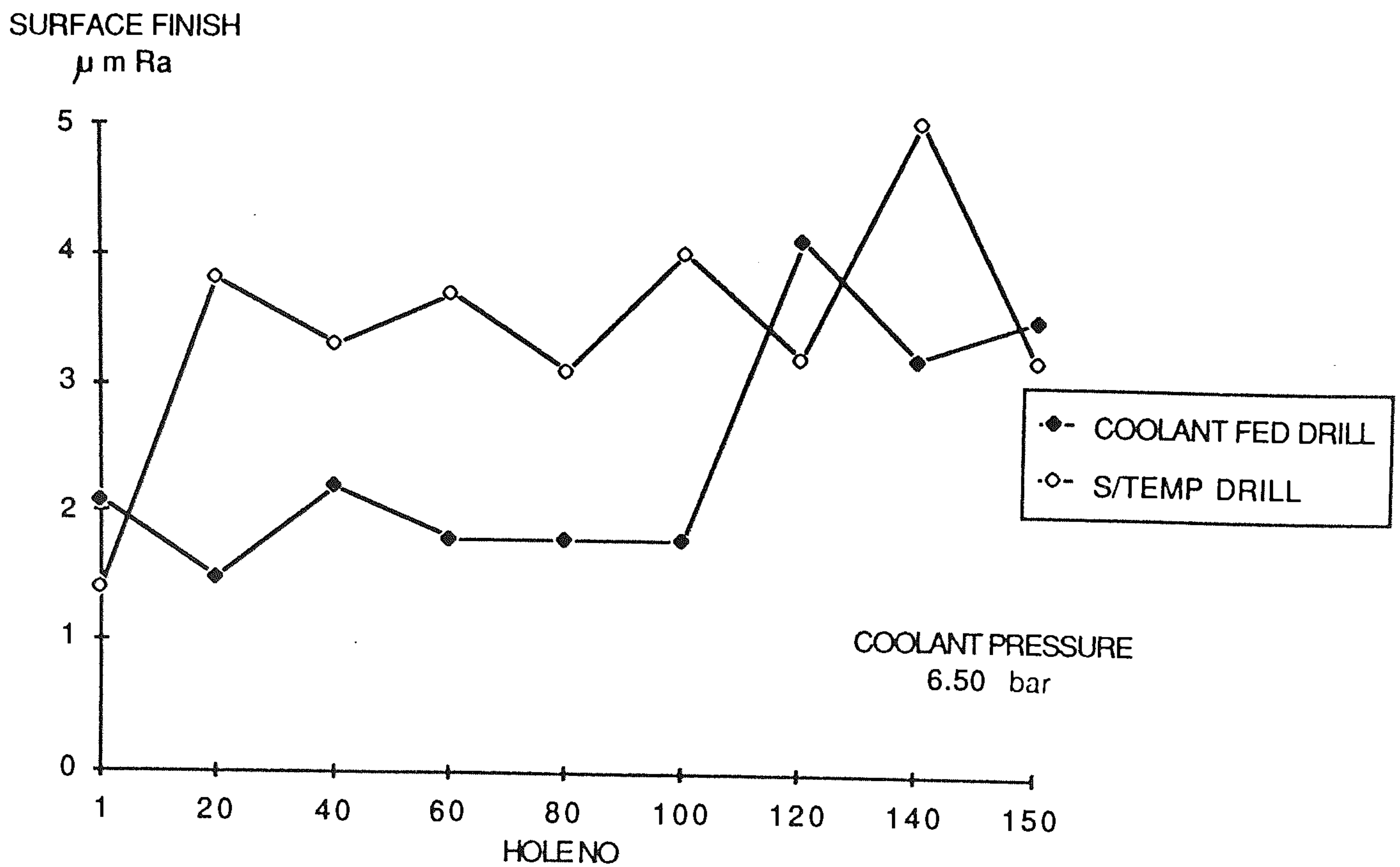



FIG 6.14 19.05 mm DIA TWIST DRILL - COMPARISON OF HOLE SURFACE FINISH (µ m Ra) FOR A COOLANT FED AND A STEAM TEMPERED DRILL OVER 150 HOLES ( 600 rpm ,0.6 mm/rev)

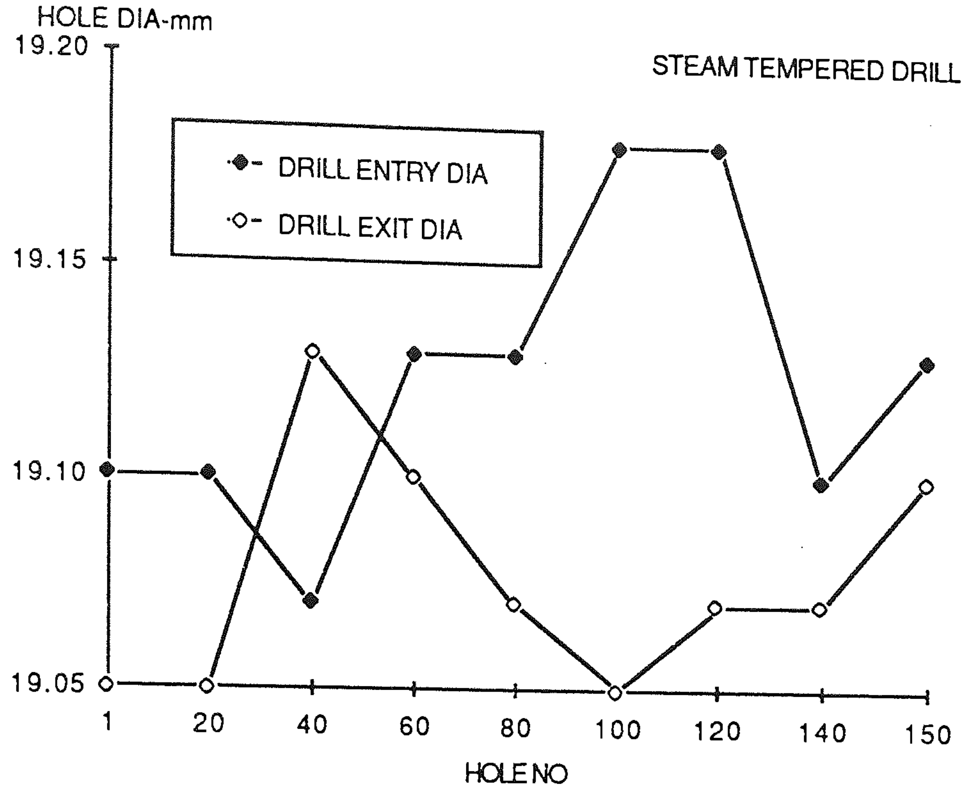



FIG 6.15 19.05 mm DIA STEAM TEMPERED TWIST DRILL
COMPARISON OF HOLE DIAMETER (mm) AT
DRILL ENTRY AND EXIT OVER 150 HOLES

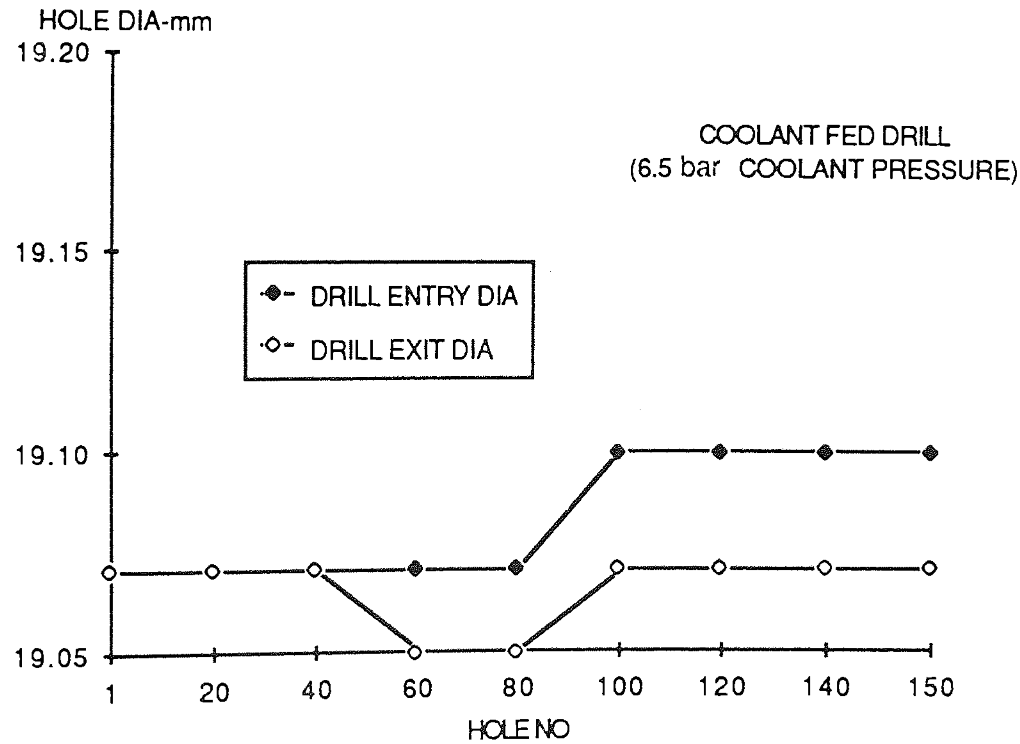



FIG 6.16 19.05 mm DIA COOLANT FED DRILL TWIST DRILL
COMPARISON OF HOLE DIAMETER (mm) AT
DRILL ENRTY AND EXIT OVER 150 HOLES

# CHAPTER SEVEN

# THE EFFECT OF TITANIUM NITRIDE COATINGS ON H.S.S. TWIST DRILLS

## 7.1 INTRODUCTION

Drills, like all metal cutting tools, wear with prolonged usage and the need for periodic regrinding of the drill point remains a constant problem particularly in organisations where precision grinding and point checking are not available.

Any feature that extends the life of the drill must therefore be regarded as potentially very useful, particularly if this will enable unmanned or automatic machines to run for longer periods without the need for tool changes.

The benefits of using coolant fed H.S.S. drills and the adoption of carbide tipped drills are included in this Research. Other changes in the drill point geometry may also enable extended periods of life to be obtained.

Another possibility is the coating of drills to extend the tool life and/or improve the overall performance. To a limited extent this has already been achieved with the oxide coating or steam tempered finish which may offer extended drill life compared with one in the bright finished condition.

## 7.2 TITANIUM NITRIDE COATINGS

Until recently, little research has been carried out into the possibilities of using drills with a conventional geometry but coated to improve the overall performance of the drill. The effort to find a suitable coating has centred around alloys of the element Titanium, particularly Titanium Carbide and Titanium Nitride.

### 7.2.1. Literature Review

As early as 1973, cutting inserts for turning and milling were commercially available with a surface layer of Titanium Nitride (TiN) on top of a Titanium Carbide coating. This offered a further increase in wear-resistance compared with the original Titanium Carbide coatings, which had been available since 1969.

The inherent brittleness of such hard material coatings could be largely overcome by reducing the thickness of the coating films, and coatings typically between 1 micron and 6 microns thick [60] hardly affect the dimensions of the cutting tool. The strength, toughness and high temperature stability of the substrate continue to be the principal criteria for the use of the tool.

Cutting inserts are discarded when wear becomes excessive (although cost savings can be made by using indexable inserts with several cutting surfaces presented in turn), but tools made from High Speed Steel are generally resharpened, which removes any coating from the reground surface.

It was formerly considered, therefore, that surface coating of H. S. S. drills would not be justifiable in view of the price premium involved, frequently about two and a half times the cost of uncoated drills.

Research [61],[62],[63],[64] has, however, established that twist drills coated with TiN can show improved wear-resistance compared with uncoated drills. Drills may also retain some of the improvement after resharpening [65].

The application of Titanium Nitride to High Speed Steel is not as simple as coating Carbides, for which the principal process is Chemical Vapour Deposition (CVD). The use of CVD for coating H.S.S.Tools involves heating the tool above the tempering temperature of 550°C which can cause distortion. The high temperature may also reduce substrate hardness and rehardening may cause unacceptable hardness in the tool. Special techniques, such as reheating under vacuum, are required to prevent or correct these problems [66].

To avoid the need for such post-coating operations, an alternative process of Physical Vapour Deposition (PVD) has been developed, in which the temperature of the High Speed Steel being coated remains well below the tempering range[67]. PVD was patented in the U.S.A. in 1969, and the patent lay dormant until 1974 when it was taken up by the U.S.S.R.

Their interest stemmed from the fact that tooling materials and alloys in use in the West were not then available in Russia, and the use of coatings was seen as a way around this difficulty. Work at the Kharkov Institute refined the process for production, and in 1979 an American company (Multi-Arc Vacuum Systems Inc)[68] purchased licences and a PVD machine from Russia. After further development in the U.S.A. the process entered commercial service in 1981.

An outline of the CVD and different types of PVD Process are described in Appendix VIII.

7.2.2. Properties of Titanium Nitride

A thin layer of Titanium Nitride imparts a golden colour to a substrate surface, so that TiN coated tools are readily distinguished visually. The benefits claimed are:-

(a) longer tool life.

(b) higher productivity

(c) reduced power consumption

These claims stem mainly from the following properties of Titanium Nitride.

7.2.2.1 Hardness

The Titanium Nitride coating is approximately three times harder than the High Speed Steel substrate, and even harder than Carbide. Measurements by the DPH (Vickers) and Rc (Rockwell)[69] are:-

| Material | DPH | Rc |
|---|---|---|
| TiN Coating | 3000 | 80-85 |
| Hardened H.S.S. | 850 | 65-70 |
| Sintered Carbide (C-2) | 1800 | 72-76 |

The coating is an extremely fine-grained, dense structure, with a high degree of purity.

7.2.2.2. Coefficient of Friction

Titanium nitride has an inherently low coefficient of friction. In drilling this should offer considerable advantages, both on the cutting edges of the tool and also in the flutes and on the lands. Reduced cutting resistance may also contribute to reductions in power consumption.

7.2.2.3. Refractory Nature

Titanium nitride is a ceramic material that possesses refractory properties which should help to protect a drill from the effects of overheating.

7.2.2.4. Chemical Stability

Titanium Nitride possesses high chemical stability, but its ability to provide corrosion resistance may depend upon the nature of the coating and number of pin hole defects present[70]. The behaviour of TiN coated drills with different types of cutting fluids may require further investigation.

#### 7.2.2.5. Coating Adherence

The titanium nitride coating can show excellent adhesion to High Speed Steel and may stand elastic and plastic deformation loads without cracking or lifting from the substrate. The preparation of the tool and, particularly, cleanliness prior to coating are very critical in obtaining good adherence.

## 7.3 WEAR CHARACTERISTICS OF CUTTING TOOLS

In order to study the behaviour of TiN coated H.S.S. twist drills it was necessary to understand the basic wear mechanisms that occur in metal cutting tools and the wear behaviour of drills in particular.

According to Hatschek[71] seven major wear mechanisms can affect the performance of metal cutting tools, i.e. abrasion, adhesion, fracture, wear by oxidation and subsequent adhesion, superficial plastic deformation, diffusion and solution wear and plastic collapse of the cutting edge.

The dominant mechanism will vary according to the workpiece/tool combination and the operating conditions. Wear will be determined by the local stresses in any particular part of the tool and heat distribution.

Abrasion is a major wear phenomenon which can be attributed to hard particles in the workpiece which are harder than the bulk hardness of the material[72]. These particles are also harder than the matrix in H.S.S. tools and they retain their hardness at elevated temperatures. Flank wear of tools can be directly attributed to abrasion.

Adhesion often occurs between the tool and workpiece, particularly where the lubrication or fluid film begins to break down. This tendency to weld together is reduced when the tool hardness is increased. Unfortunately, tools with very high hardness tend to become brittle and lose their ductility. Where adhesion occurs the deformation process becomes unstable and abrasive wear may ultimately occur.

Fracture of cutting tools is a common cause of failure which can be attributed to several factors including fatigue, overloading, the presence of stress raisers or defects in the tool material, and incorrect geometry either "as ground", or resulting from excessive tool wear.

Where oxidative wear occurs in metal cutting this takes place when the sliding surfaces are attacked by atmospheric oxygen and the layers of corrosion products are subsequently rubbed off. At elevated temperatures diffusion may also occur when atoms move from the tool material to the workpiece.

Plastic deformation of the cutting edge readily occurs when a

H.S.S. tool has been overheated and lost hardness. Under these conditions high cutting forces may result in a rapid loss of edge sharpness.

Built-up edge (BUE) is a common occurrence in metal cutting and it is usually evident as "welded on" particles of swarf along the cutting edge. The formation of BUE is partly due to the nature of the chip formation process and the friction conditions on the rake face of the tool. The nature of the shearing action is such that the passage of the chip over the rake face may result in some local welding or adhesive wear occurring. Crater wear on the rake face may be due to high local cutting forces exerted and diffusion wear simultaneously occurring.

In order to combat these different wear processes, cutting tools with increased hardness, particularly at high temperatures, offer potential advantages.

The abrasive wear properties of hard materials such asceramics tend to increase with decreasing ductility and the consequent increase in hardness. For this reason the application of thin ceramic well adhered coatings to a ductile H.S.S. substrate should be beneficial.

When thin coatings are used their minimum thickness should be sufficient to provide a uniform coating over the tool and cover the tips of any asperities. Some initial work has been reported on the optimum coating thickness on both turning and planing tools[73].

In observing the wear characteristics of H.S.S. TiN coated turning tools[74] a proposed wear mechanism was presented which suggested that reduced friction conditions on the rake face helped to minimise the contact length of the chip.

In the case of drills coated with TiN, Matthews[75] reported that there was wide variation in performance results due to differences in drill geometry, substrate hardness and surface finish.

In this chapter the wear characteristics of TiN coated and conventional H.S.S. Drills are discussed and possible reasons for scatter in the results of previous work are identified. The indications of wear on points of H.S.S. twist drills are shown in Fig.7.1.

## 7.4 TESTING OF TiN COATED DRILLS

In order to assess the performance of TiN coated twist drills a batch of bright finished 12.70 mm dia H.S.S. Twist Drills were obtained, inspected and 30 of these drills subsequently TiN coated by five diffrent coating companies, each using P.V.D. type coating processes.

An extensive testing programme was undertaken to determine the optimum tool operating conditions, speed, feed, improvements in tool life and quality of hole produced. Additional metallurgical trials enabled the coating thickness to be determined as well as drill substrate hardness and drill surface finish.

Detailed comparisons were made with bright finished and steam tempered drills (Fig.7.2) over 150 hole tool life tests. Wear characteristics were also compared and critically analysed.

Further trials were undertaken with 19.05 mm dia twist drills and the effects of point regrinding on TiN coated drill performance also established.

### 7.4.1. Drill Geometry and Condition

Twist drills have a complex geometry, and their performance is very sensitive to small errors and differences in point grinding and geometry. In this research both 12.70 and 19.05 mm dia. twist drills were considered.

In order to determine the exact drill geometry detailed measurements were undertaken with a micrometer microscope incorporating a goniometer. Aspects of point geometry, including chisel edge angle, clearance angle and differences in lip height, were determined (Table 7.1). It was important to ensure that in any batch of drills standard values were established. Where errors in point grinding lead to an asymmetric point configuration, such that the difference in lip height was .05 mm or greater, the drill was not included in the trials. In the limiting condition a drill with a large lip height difference may cut on only one lip, wear at a much faster rate and produce considerable hole oversize. Other aspects of the drill material condition and, in particular, hardness of the H.S.S. were also checked.

After inspection a batch of bright finish and steam tempered drills were set aside for testing. Other bright finish drills that were subsequently TiN coated were reinspected after coating to ensure that no major changes in substrate condition or drill geometry had occurred due to process heating effects. Sections were taken on sample drills and the coating thickness measured with a mircroscope. The drill surface finish and H.S.S. hardness were also measured.

### 7.4.2 Drill Test Design

Drilling tests without a centre or pilot hole were undertaken with both rotating drills on a Vertical Milling Machine and stationary drills, horizontal drilling on a Lathe. Through holes were produced in both cases.

#### 7.4.2.1. Vertical Milling Machine (see Appendix I)

The 12.70 mm dia twist drills were tested on an Olivetti Numerical Controlled (N.C.) Milling Machine (Fig.7.3) with high carbon EN8 Steel. N.C. programs were developed which enabled blocks of EN8 to be drilled and cutting force measurements taken at different speeds and feeds.

The forces were measured by a Kistler Drilling

Dynamometer (Appendix III), which was fixed to the bed of the machine and carried a small engineers vice for holding the workpiece. Hole depths of two diameters were drilled and a soluble oil in 10:1 dilution used for all cutting tests.

Initial tests were undertaken at 748 rpm (surface speed 30m/min) and a feed rate of 0.1-0.25 mm/rev. Further tests were then made at 1496 and 2120 rpm over the same feed range. Both the drill torque and thrust force were measured with the dynanometer and the output amplified and presented on a U.V. Recorder Trace.

In a second series of tests a further N.C. program was written to enable one hundred and fifty holes to be drilled in a tool life test at selected speeds and feeds. The cutting forces were measured on every tenth hole. TiN drills were tested at 2120 rpm x 0.2 mm/rev. For steam tempered and bright finish drills the test was made at 748 rpm x 0.2 mm/rev.

7.4.2.2. Computer Numerical Controlled (CNC) Lathe

All 19.05 mm dia. drills were tested on a Torshalla CNC Lathe (Fig 7.4). For these tests the dynamometer was mounted on to the turret of the machine and the drill located in the centre of the dynamometer with a Morse Taper Adaptor. The workpiece was held in the chuck of the lathe and holes of two diameters deep were made in mild steel EN1A material.

Both speed and feed and 150 hole tool life trials were undertaken and the torque and thrust established for both steam tempered and TiN coated drills. Further trials were undertaken with 19.05 mm dia TiN coated drills that had been reground so that the coating was removed from the flank faces of the drill. A speed range of 600-1200 rpm was used (36-72 m/min).

7.4.2.3. Hole Inspection

All drilled holes were inspected for hole diameter at drill entry and exit from the workpiece. Measurements were made with a digital readout bore gauge reading to .001 mm. Hole surface finishes (µm CLA) were measured with a Talysurf and the roundness of a sample of holes was obtained from a Talyrond machine.

7.4.2.4. Drill and Coating Quality

One drill from each TiN coating supplier was transversely sectioned so that a sample could be mounted in bakelite Care was taken not to burn the surface with the slitting wheel used. Polished samples were inspected on an Optical Microscope fitted with a camera. Photographs of the section at 500 times magnification then enabled the coating thicknesses and substrate quality to be compared on different parts of the drill section.

Substrate hardnesses were compared with a Vickers Hardness Testing Machine. Tests were performed at 1.5 mm below the coated surface to prevent edge defects and standardise the tests. Coating hardnesses could not easily be measured because the coating was of insufficient thickness to enable realistic readings to be obtained on transverse sections.

Drill Surface Finish values were obtained, however, for the bright finishes and for each TiN coating. The Talysurf Machine was used and readings were taken longitudinally on the outside diameter of the drill.

## 7.5 DRILL TEST RESUILTS

### 7.5.1 12.70 mm Dia Drills.

Typical swarf samples are shown in Fig.7.5.

The torque and thrust results from the drill cutting tests at speeds of 748 and 2120 rpm and selected feed rates are given in Table 7.2 and Figs.7.6 to 7.9. For the 150 hole tool life tests the torque and thrust results are shown in Table 7.3 and Figs.7.10 and 7.11. The drill wear data for the 150 hole test is shown in Figs.7.12 to 7.14. Comparison of the hole surface finishes are shown in Table 7. 4 and Figs.7.15 and 7.16, coating thicknesses are shown in Fig 7.17. Hole diameter measurements for a bright finished and TiN drill are presented in Table 7.5 and Figs.7.19 and 7.20. Typical hole roundess traces are given in Fig.7.21.

Table 7.6 summarises the results of coating thickness, substrate hardness and drill surface finish.

### 7.5.2. 19.05 mm dia. Drills - The Effect of Speed and Feed.

The torque and thrust comparisons for a 19.05 mm dia TiN coated and steam tempered drill at feeds of 0.3-0.7 mm/rev and speeds of up to 1200 rpm are presented in Table 7.7 and Figs 7.22 and 7.23.

### 7.5.3. 19.05 mm Dia Drills - The Effect of Regrinding

The results for the torque and thrust of reground TiN drill when compared with steam tempered and fully coated 19.05 mm dia drills are presented in Table 7.7 and Figs.7.24 and 7.25 for the performance at 600-1200 rpm. Fig.7.26 shows the comparison of the chisel built up edge formation on a reground steam tempered drill and a reground TiN coated drill.

## 7.6 DISCUSSION OF RESULTS

### 7.6.1. 12.70 mm Dia Twist Drills

The most important results to emerge from the speed and feed trials for the 12.7 mm dia twist drills was that in general TiN coated drills were capable of running at up to three times the surface speed of a conventional steam tempered drill without any dramatic increase in heat generation or built up edge on the lips or chisel edge of the drill.

The absence of built up edge and low friction for the TiN coated drill lead to a much smoother finish on the swarf (Fig.7.5). The swarf from a bright finish drill, by comparison, showed distinct longitudinal "tram lines" consistent with swarf adherence on the cutting lips.

The cutting forces were also consistently lower for TiN coated drills when compared to bright finish and steam tempered drills at 748 rpm, - see Torque and Thrust Graphs Figs.7.6 and 7.7. There was also evidence of built-up edge on the cutting lips of both the steam tempered and bright finished drills which did not occur with the TiN coated drills even where the speed was increased to 2120 rpm. Figs.7.8 and 7.9. The conventional drills were not run at this speed because the excessive heat generated may ultimately lead to tempering back of the H.S.S. and in rapid tool wear occurring.

Where the performance of steam tempered, bright finish and TiN coated 12.70 mm dia. drills were compared over 150 holes in EN8 material 25.4 mm thick, the benefits of TiN coating were clearly distinguishable. With the exception of one coating (TiN 70) the Torque (Nm) and Thrust (kN) over a 150 hole test were 10-20% lower for the TiN coated drills compared to the steam tempered and bright finish drills, Figs.7.10 and 7.11.

The use of high feed rates to achieve increased penetration rates with TiN coated drills was generally considered undesirable because increases in feed rate resulted in proportional increases in both drill torque and thrust. This trend did not occur at increased speeds of up to 2120 rpm and moderate feed rates (0.2 mm/rev) with the TiN coated drills.

### 7.6.1.1. Wear Characteristics of Coated 12.70 mm Dia Drills.

From the results of the 150 hole drill life trials at 2120 rpm x 0.2 mm/rev it was apparent that significant differences in the wear characteristics of TiN coated drills occurred according to the type of TiN process employed.

For both bright finished and steam tempered drills the wear rate was minimised by limiting the surface speed to that recommended for H.S.S.

Indications of wear on the point of a twist drill usually became apparent in the following ways,(Fig.7.1):

(i) chisel edge erosion and plastic deformation

(ii) wear on the cutting lips

(iii) rounding of the outer corner

(both along the lip and on the land)

(iv) cratering of the rake faces

(v) wear on the drill land

(vi) built up edge on lips, chisel and land, Fig.7.12.

Whilst some of this wear was temperature dependent, the predominant wear mechanism was associated with the outer corner of the drill. Rounding of the outer corner occurred because at the periphery of the drill the surface speed was highest and high heat generation occurs at this point. The wear mechanism was encouraged by the inherent weakness on the corner and the sharp included angle between the clearance face and the rake face. Any abrasive wear and loss of edge at this point also resulted in difficulty in maintaining the hole diameter.

A drill was adjudged to be fully worn and in need of a regrind if the wear extended across the whole width of the land.

For the TiN coated drills several different wear patterns and trends were observed compared to the conventional finishes, (Fig.7.13). For both the steam tempered and bright finished drill moderate wear on the land was observed after 150 holes.

Three coatings (TiN Nos. 46, 40 and 19) showed only very slight wear on the tip of the land. This wear was sometimes associated with a built up edge on the tip which may have protected the land from further wear. Evidence of some heat affected zone was present along the flank faces of these drills together with slight discolouration on the lands. No significant loss of coating was observed.

For TiN coated drill No.74 some of the coating was lost from the land of the drill after 150 holes, to reveal the bright finish of the substrate. Wear had also occurred across the complete land width,(Fig.7.14). The loss of coating was reflected in the poor hole surface finish obtained from this drill, (Figs.7.15 and 7.16), For the bright and steam tempered finish drills, the hole surface finish was consistently near or above 5μm Ra, but the other TiN coated drills achieved finishes generally better than 2μm Ra. Measurements taken of the coating thickness, Table 7.6 also confirmed that on drill No. TiN 74 only 1 micron of TiN was present, (Fig.7.17).

In order to cover the surface completely and hide any asperities a coating thickness of several times the surface finish should be used. Typical surface finishes on the bright drills were 0.4-0.5μm Ra and minimum thickness should therefore be in the range 2-3 microns. These coating thicknesses were achieved by other coating companies.

Three failures were recorded with one type of coating (TiN Nos.70,64,68), but the failure mechanism in each case was different.

For TiN 70 the test was stopped after 120 holes because the drill land had peeled away and the hole size reduced by up to 0.20 mm. The failure mechanism was associated with the loss of coating at the drill tip, wear across the complete land width and subsequent propagation of the wear backwards against the undersize lip of the hole being cut. Ultimate failure of the drill would occur through rubbing on the outside diameter of the body. Evidence of considerable overheating of the land accompanied this failure.

A repeat test, TiN 64, was undertaken and although this drill completed 150 holes, considerable "screech" was evident at the end of the test. Screech is usually indicative of failure although no excessive wear was observed.

A second repeat test, TiN 68, resulted in sudden catastrophic failure of the drill. Examination of the drill point showed that the failure was associated with rapid breaking down of the outer corner, consistent with overheating. This mode of failure usually occurred when the drill had run too fast and overheated. (Fig.7.18).

7.6.1.2. Hole Diameter and Roundness

Inspection of the hole diameters produced by the TiN coated drills confirmed that they were generally very "close tolerance", there being little variation between drill entry and exit diameter. Holes produced by TiN coated drills up to .05 mm oversize are generally parallel to within .03 mm.

The bright finished drill by comparison produced holes of up to 0.15 mm oversize with a variation 0.10 mm between drill entry and exit, (Figs.7.19 and 7.20). The reasons for this difference were attributed to the increased built-up edge formation on the chisel edge and lands of the bright finished drill.

Comparisons by the hole roundness, (Fig.7.21), also confirmed that the most consistent round holes were achieved with some of the TiN coated drills.

### 7.6.2. 19.05 mm dia. Drills

#### 7.6.2.1. 19.05 mm Dia Drills - The Effect of Speed and Feed

Tests undertaken to compare the performance of steam tempered and TiN coated drill with EN1A steel, confirmed that both the torque and thrust of the steam tempered drill were up to 20% higher than the TiN coated drill, (Figs.7.22 and 7.23). Tests with the steam tempered drill were curtailed at 900 rpm because there was a dramatic increase in cutting forces, particularly at higher feed rates due to built up edge of the cutting lips and chisel edge.

#### 7.6.2.2. 19.05 mm Dia Twist Drills - The Effect of Regrinding

The results of tests undertaken to determine the performance of reground TiN coated drills compared with fully coated and steam tempered drills are presented in Figs.7.24 and 7.25. From Fig.7.24 it was observed that there was very little difference between the torque of a fully TiN coated drill and a reground TiN coated drill. The reasons for this were that about 90% of the torque in drilling was required to overcome the cutting force on the drill lips. Providing that the TiN coating remained on the rake face and lands of the drill the torque would tend to remain constant (see Chapter 5).

The torque for a steam tempered drill, by comparison, tended to increase rapidly as the speed reached 900 rpm.

From the thrust results, (Fig.7.25), the reground TiN coated drill required about 20% greater thrust force than the fully TiN coated drill. The higher thrust force, which occurred across the range of speeds, was due to increased friction and BUE at the chisel edge region of the reground drill. The presence of TiN coating on the chisel edge, thus helped to protect the chisel edge from overheating and built up edge sheets and a reground TiN coated drill would have inferior tool life to a fully TiN coated drill.

The thrust force required by a steam tempered drill was about 30% greater than that of the TiN coated drill at 600 rpm and increases in speed lead to further dramatic increases in thrust force.

A reground TiN coated drill was therefore likely to have better tool life and higher cutting speed capacity than a conventional steam tempered drill. The hole quality achieved with the reground drill was also similar to that of the fully TiN coated drill.

An example of how the presence of TiN coating on the flutes of a reground TiN coated drill served to protect the chisel edge and cutting lips, compared with the BUE on a steam tempered drill is shown in Fig 7.26.

## 7.7 OVERALL CONCLUSIONS

(i) TiN coatings applied to twist drills helped to reduce built up edge and wear on the cutting lips. The low friction characteristics of the coating enabled the surface speeds to be increased by up to three times that of a conventional H.S.S. drill. Tool life was also increased.

(ii) TiN coated drills may be used with up to 20% increases in feed rate compared to conventional drills. At higher feed rates the additional torque and thrust taken may lead to drill failure.

Speed increases of up to three times those specified for H.S.S. drills were achieved without significant increases in drill torque and thrust.

(iii) Holes that were produced by TiN coated drills had a much closer tolerance compared to those produced by conventional drills. The surface finish of TiN coated drilled holes was also superior.

(iv) Even in the reground condition the performance of TiN coated drills gave improved hole quality providing that the coating remained in flutes and on the lands of the drill.

(v) Where precision holes were required, the use of TiN coated drills may eliminate the need for secondary reaming operations. Aspects of drill design and geometry for optimum performance with TiN coating were also studied.

(vi) TiN coated drills cost about 2½ times the price of a steam tempered drill. The economic benefit of these tools willonly realised if penetration rates can be increased, hole quality improved, and in some cases reaming operations avoided. All these benefits may be attained with TiN coatings.

(vii) Wear on the TiN coated and conventional drills was observed on the outside corner of the cutting lips. At the high surface speeds used for TiN coated drills this wear may rapidly extend to cover the whole land width and also propagate along the land by a "peeling" action on the edge of the hole.

(viii) Optimum coating thickness, quality and adherence to the substrate were required to ensure good drill life and precision holes, providing that the drill was accurately ground and running true in the chuck of the machine.

(ix) Coating thicknesses of 1 micron were unsatisfactory because they probably did not provide adequate cover for the surface asperities on the substrate and rapid loss of coating occurred.The loss of coating from the drill land may result in increased drill wear and a deterioration in hole quality.

(x) TiN coating thicknesses of 4-5 microns resulted in lower cutting forces and lead to reductions in drill thrust and torque in the order of 10-20%.

| POINT GEOMETRY | DRILL DIAMETER (mm) | |
|---|---|---|
| | 12.70 | 19.05 |
| Point Angle (Deg) | 118 | 118 |
| Helix Angle (Deg) | 31 | 32 |
| Clearance Angle (Deg) | 12 | 10 |
| Chisel Edge Angle (Deg) | 127 | 122 |
| Chisel Length (mm) | 1.8 | 2.0 |
| Lip Height Difference (mm) | nil | nil |
| Web Diameter (mm) | 1.8 | 2.5 |

**TABLE No. 7.1**

**TYPICAL TWIST DRILL GEOMETRY**
**(12.70 and 19.05 mm dia. Drill)**

| OPERATING CONDITIONS | | BRIGHT No.25 | | STEAM TEMPERED No.4 | | TiN No.45 | | TiN No.37 | | Tin No.18 | | TiN No.73 | | TiN No.71 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SPEED rpm | FEED RATE mm/rev | M | $F_Z$ | M | $F_Z$ | M | $F_Z$ | M | $F_Z$ | M | $F_Z$ | M | $F_Z$ | M | $F_Z$ |
| 748 | .1 | 5.5 | 1.4 | 5.6 | 1.3 | 5.4 | 1.35 | | | | | | | | |
| | .15 | 8.0 | 1.85 | 8.2 | 1.6 | 7.5 | 1.7 | | | | | | | | |
| | .2 | 10.0 | 2.2 | 10.4 | 2.2 | 9.0 | 2.0 | | | | | | | | |
| | .25 | 12.0 | 2.75 | 12.8 | 2.65 | 10.5 | 2.3 | | | | | | | | |
| 2120 | .1 | | | | | 5.0 | 1.2 | 5.2 | 1.15 | 6.0 | 1.2 | 5.6 | 1.25 | 4.6 | 1.25 |
| | .15 | | | | | 6.7 | 1.6 | 6.8 | 1.55 | 7.0 | 1.5 | 7.0 | 1.5 | 6.0 | 1.7 |
| | .2 | | | | | 8.6 | 2.0 | 8.6 | 1.85 | 8.6 | 1.8 | 8.8 | 1.9 | 7.4 | 2.15 |
| | .25 | | | | | 10.2 | 2.35 | 10.0 | 2.15 | 10.2 | 2.15 | 10.4 | 2.2 | 8.8 | 2.6 |

TABLE No. 7.2

**12.70 mm DIA TWIST DRILL: SPEED AND FEED TRIALS COMPARISON OF TORQUE 'M' (Nm) AND THRUST '$F_Z$'(kN) FOR CONVENTIONAL DRILLS AT 748 rpm AND TiN COATED DRILLS AT 2120 rpm.**

| No. OF HOLES DRILLED | STEAM TEMPERED No.10 | | BRIGHT No 55 | | TiN No.46 | | TiN No.40 | | Tin No.19 | | TiN No.74 | | TiN No.70 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $F_Z$ | M | $F_Z$ | M | $F_Z$ | M | $F_Z$ | M | $F_Z$ | M | $F_Z$ | M | $F_Z$ | M |
| 1 | 2.1 | 9.8 | 2.05 | 8.6 | 1.9 | 8.6 | 1.75 | 8.0 | 2.15 | 9.1 | 2.1 | 8.4 | 2.35 | 8.2 |
| 10 | 2.1 | 10.0 | 2.25 | 10.0 | 1.75 | 8.2 | 1.75 | 8.0 | 1.95 | 8.8 | 1.85 | 8.5 | 2.25 | 7.8 |
| 20 | 2.2 | 10.0 | 2.25 | 10.0 | 1.75 | 8.2 | 1.75 | 8.0 | 1.95 | 8.8 | 1.85 | 8.6 | 2.3 | 8.0 |
| 30 | 2.2 | 10.0 | 2.25 | 10.0 | 1.75 | 8.2 | 1.75 | 8.0 | 1.95 | 8.8 | 1.85 | 8.6 | 2.3 | 8.0 |
| 40 | 2.2 | 10.0 | 2.25 | 10.0 | 1.75 | 8.2 | 1.75 | 8.0 | 1.95 | 8.8 | 1.85 | 8.6 | 2.25 | 8.0 |
| 50 | 2.2 | 10.0 | 2.25 | 10.0 | 1.76 | 8.2 | 1.75 | 8.0 | 1.95 | 8.8 | 1.85 | 8.6 | 2.3 | 8.2 |
| 60 | 2.2 | 10.0 | 2.25 | 10.0 | 1.8 | 8.2 | 1.75 | 8.0 | 1.95 | 8.8 | 1.85 | 8.6 | 2.3 | 8.4 |
| 70 | 2.2 | 10.0 | 2.25 | 10.0 | 1.8 | 8.2 | 1.75 | 8.0 | 1.95 | 9.0 | 1.9 | 8.6 | 2.35 | 8.4 |
| 80 | 2.2 | 10.0 | 2.25 | 10.0 | 1.8 | 8.2 | 1.75 | 8.0 | 2.0 | 9.0 | 1.9 | 8.6 | 2.4 | 8.4 |
| 90 | 2.25 | 10.0 | 2.25 | 10.0 | 1.8 | 8.2 | 1.75 | 8.0 | 2.0 | 9.0 | 1.9 | 8.9 | 2.4 | 8.6 |
| 100 | 2.25 | 10.0 | 2.25 | 10.0 | 1.8 | 8.2 | 1.75 | 8.0 | 2.0 | 9.0 | 1.9 | 8.9 | 2.4 | 8.6 |
| 110 | 2.25 | 10.0 | 2.25 | 10.0 | 1.85 | 8.4 | 1.85 | 8.2 | 2.0 | 9.0 | 1.9 | 8.9 | 2.4 | 8.6 |
| 120 | 2.25 | 10.0 | 2.25 | 10.0 | 1.85 | 8.4 | 1.85 | 8.2 | 2.0 | 9.0 | 1.9 | 8.9 | 2.4 | 9.0 |
| 130 | 2.25 | 10.0 | 2.25 | 10.0 | 1.85 | 8.4 | 1.85 | 8.2 | 2.0 | 9.0 | 1.9 | 8.9 | Drill Failed on Land | |
| 140 | 2.25 | 10.0 | 2.25 | 10.0 | 1.85 | 8.4 | 1.85 | 8.2 | 2.0 | 9.0 | 1.95 | 8.9 | | |
| 150 | 2.25 | 10.0 | 2.25 | 10.0 | 1.85 | 8.4 | 1.85 | 8.4 | 2.0 | 9.0 | 1.95 | 8.9 | | |

TABLE No.7.3

12.70 mm DIA TWIST DRILL: COMPARISON OF THRUST '$F_Z$' (kN) AND TORQUE 'M' (Nm) OVER 150 HOLE TEST FOR CONVENTIONAL DRILLS AT 748 rpm x 0.2 mm/rev AND TiN COATED DRILLS AT 2120 rpm x 0.2mm/rev.

| HOLE No. | STEAM TEMP. No.10 | BRIGHT No.55 | TiN No.46 | TiN No.40 | TiN No.19 | TiN No.74 | TiN No.70 |
|---|---|---|---|---|---|---|---|
| 1 | 5+ | 4.7 | 1.75 | 2.18 | 1.78 | 1.78 | 3.02 |
| 10 | 5+ | 4.4 | 2.1 | 1.7 | 1.4 | 3.5 | 2.5 |
| 40 | 5+ | 4.5 | 1.8 | 1.4 | 1.1 | 3.1 | 1.75 |
| 60 | 5+ | 4.7 | 2.0 | 1.6 | 1.2 | 3.1 | 1.52 |
| 90 | 5+ | 4.7 | 2.1 | 1.6 | 1.2 | 3.3 | 1.58 |
| 110 | 5+ | 4.6 | 2.1 | 1.7 | 1.2 | 3.3 | 1.6 |
| 140 | 5+ | 5.0 | 1.9 | 2.0 | 2.0 | 3 | 3.7 |
| 150 | 5+ | 5.0 | 1.4 | 1.6 | 1.5 | 3.5 | - |

TABLE No. 7.4

MEAN SURFACE FINISHES (μmRa) OBTAINED WITH TiN COATED AND CONVENTIONAL DRILLS - 150 HOLE TEST.

| HOLE No. | TiN No.19 DRILL ENTRY Dia. | TiN No.19 DRILL EXIT Dia. | BRIGHT FINISH No.55 DRILL ENTRY Dia. | BRIGHT FINISH No.55 DRILL EXIT Dia. |
|---|---|---|---|---|
| 1 | 12.763 | 12.738 | 12.835 | 12.723 |
| 20 | 12.758 | 12.731 | 12.840 | 12.755 |
| 40 | 12.764 | 12.746 | 12.819 | 12.732 |
| 60 | 12.754 | 12.740 | 12.830 | 12.729 |
| 80 | 12.747 | 12.732 | 12.832 | 12.748 |
| 100 | 12.735 | 12.756 | 12.829 | 12.760 |
| 120 | 12.753 | 12.732 | 12.835 | 12.767 |
| 140 | 12.756 | 12.738 | 12.814 | 12.748 |
| 150 | 12.752 | 12.740 | 12.842 | 12.750 |

TABLE No. 7.5

COMPARISON OF HOLE DIAMETER (mm) AT DRILL ENTRY AND EXIT FOR TiN No.19 DRILL AND BRIGHT FINISH DRILL No.55.

| DRILL IDENTIFICATION NUMBER | COATING THICKNESS MICRONS | | SURFACE FINISH µm/Ra | HARDNESS DPH (30g LOAD) |
|---|---|---|---|---|
| | OD | FLUTE | | |
| S/Temp - 10 | - | - | .36 | 876-890 |
| Bright - 55 | - | - | .42 | 849-862 |
| TiN - 46 | 4 | 3 | .47 | 829-852 |
| TiN - 40 | 3 | 3 | .52 | 862-863 |
| TiN - 19 | 3 | 2 | .50 | 866-876 |
| TiN - 74 | 1 | 1 | .40 | 876 |
| TiN - 70 | 4 | 2 | .59 | 866-869 |

**TABLE No.7.6**

12.70 mm Dia. TWIST DRILLS: COMPARISON OF COATING THICKNESS, DRILL SURFACE FINISH AND SUBSTRATE HARDNESS.

| SPEED rpm | THRUST (kN) | | | TORQUE (Nm) | | |
|---|---|---|---|---|---|---|
| | S/TEMP | TiN | TiN REGROUND | S/Temp | TiN | TiN REGROUND |
| 600 | 4.75 | 3.6 | 4.3 | 46.5 | 40.0 | 40.5 |
| 700 | 4.75 | 3.6 | 4.3 | 46.5 | 39.5 | 40.5 |
| 800 | 5.0 | 3.6 | 4.4 | 46.5 | 40.0 | 41.0 |
| 900 | 5.75 | 3.65 | 4.4 | 50.0 | 40.0 | 41.0 |
| 1000 | - | 3.7 | 4.6 | - | 40.0 | 41.0 |
| 1100 | - | 3.7 | 4.65 | - | 39.0 | 40.0 |
| 1200 | - | 3.8 | 4.65 | - | 40.0 | 40.0 |

TABLE No. 7.7

19.05 mm Dia. TWIST DRILL HORIZONTAL DRILLING TRIALS: COMPARISON OF THRUST AND TORQUE WITH SPEED FOR A STEAM TEMPERED DRILL, TITANIUM NITRIDE COATED AND REGROUND TITANIUM NITRIDE COATED DRILL.
(Feed rate - 0.5 mm/rev.)

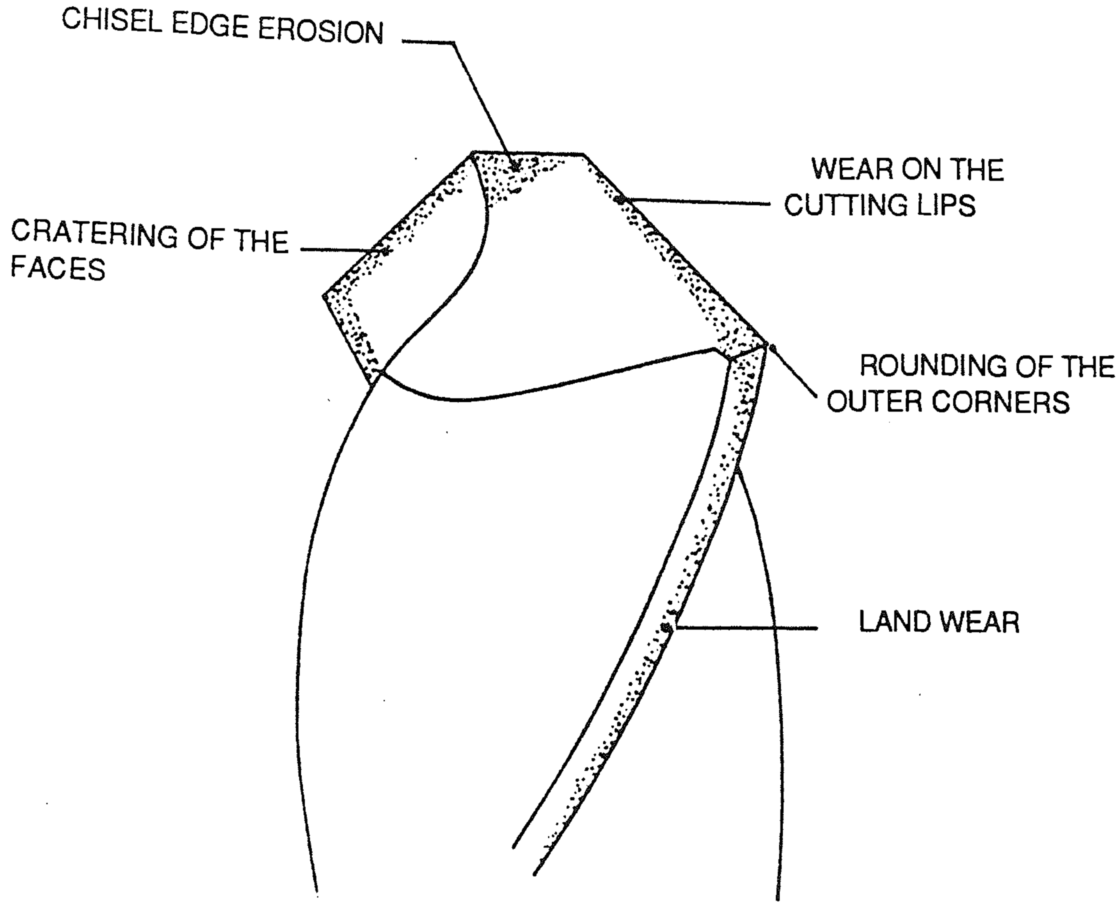



FIG 7.1 INDICATIONS OF WEAR ON THE POINT OF A TWIST DRILL

FIG 7.2 12.70 mm Dia TWIST DRILLS -THREE TYPES OF FINISH
LEFT TO RIGHT :
BRIGHT FINISH, STEAM TEMPERED,TiN COATED

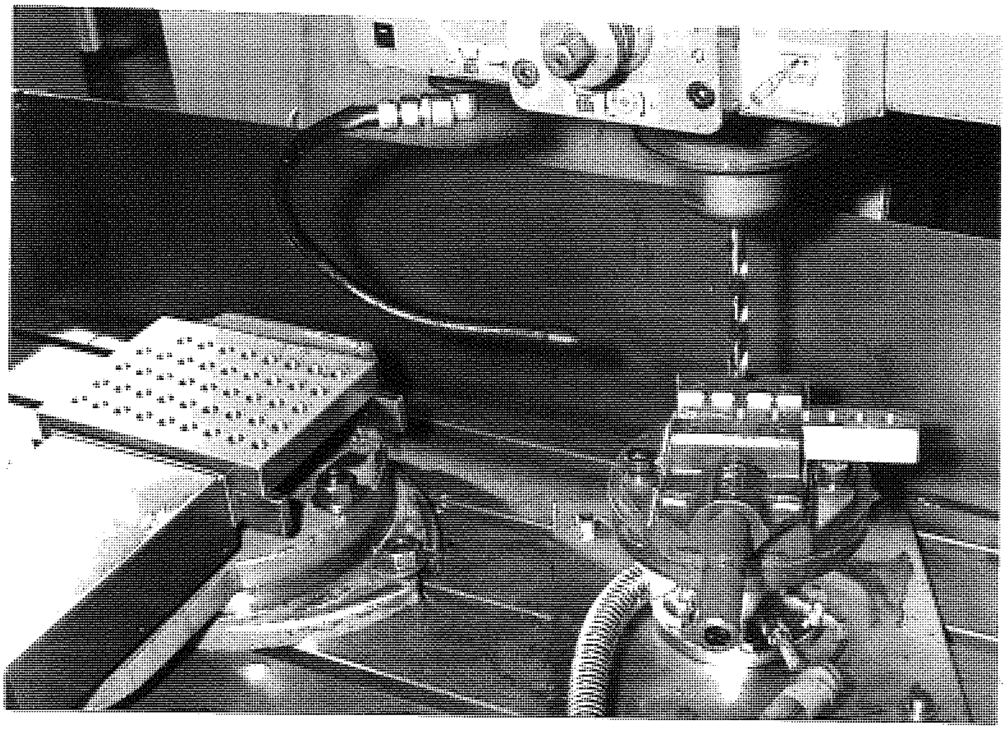


FIG 7.3 THE OLIVETTI " RIGID" NC MILLING MACHINE DRILLING TEST SET UP

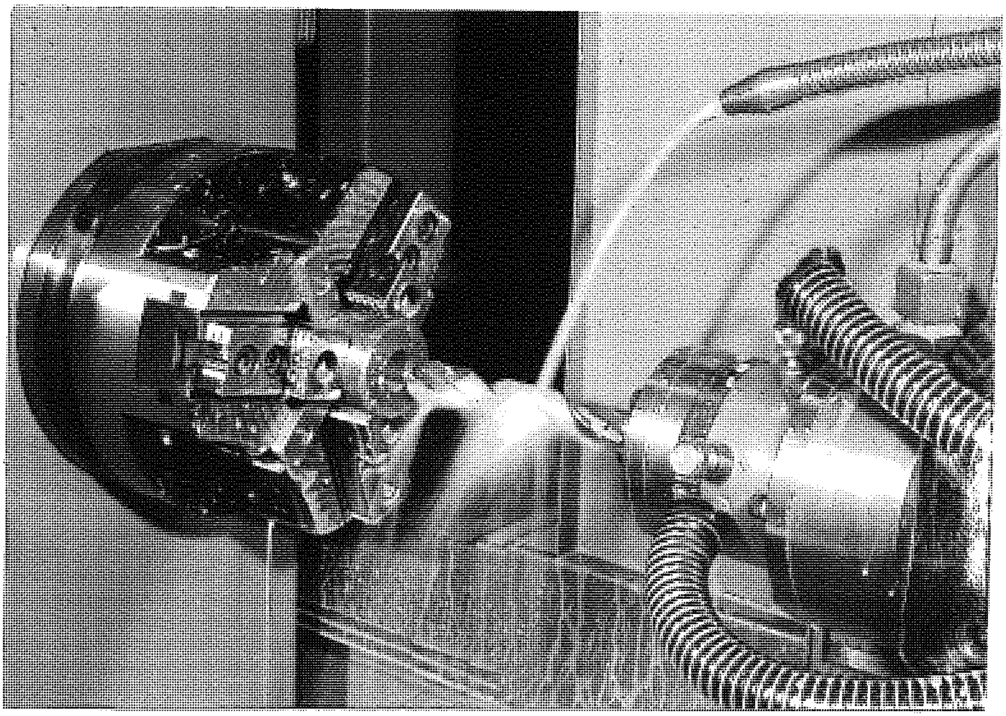


FIG 7.4 THE TORSHALLA CNC LATHE -DRILLING TEST SET UP

FIG 7.5 12.70 mm Dia TWIST DRILL - COMPARISON OF SWARF
LEFT: BRIGHT FINISH DRILL-748 rpm, 0.2 mm/rev
RIGHT : TiN COATED DRILL - 2120 rpm, 0.2 mm/rev

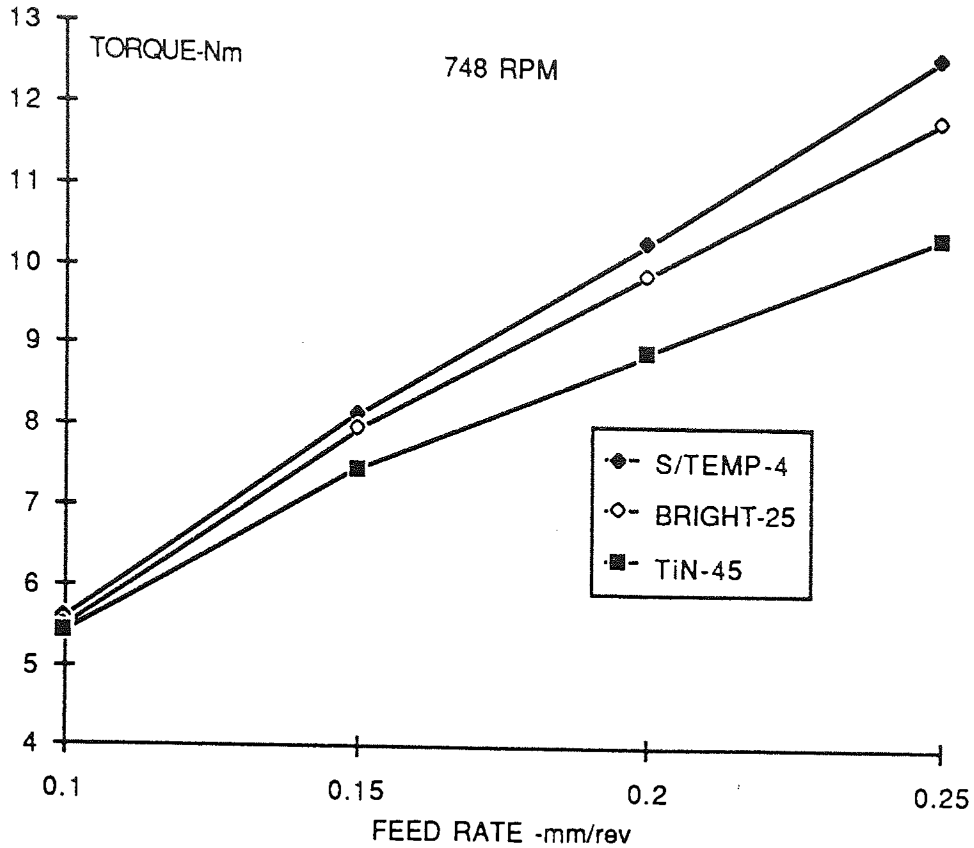



FIG 7.6 12.70 mm DIA TWIST DRILL- COMPARISON OF DRILL TORQUE (Nm) AT 748 RPM AND SELECTED FEED RATES

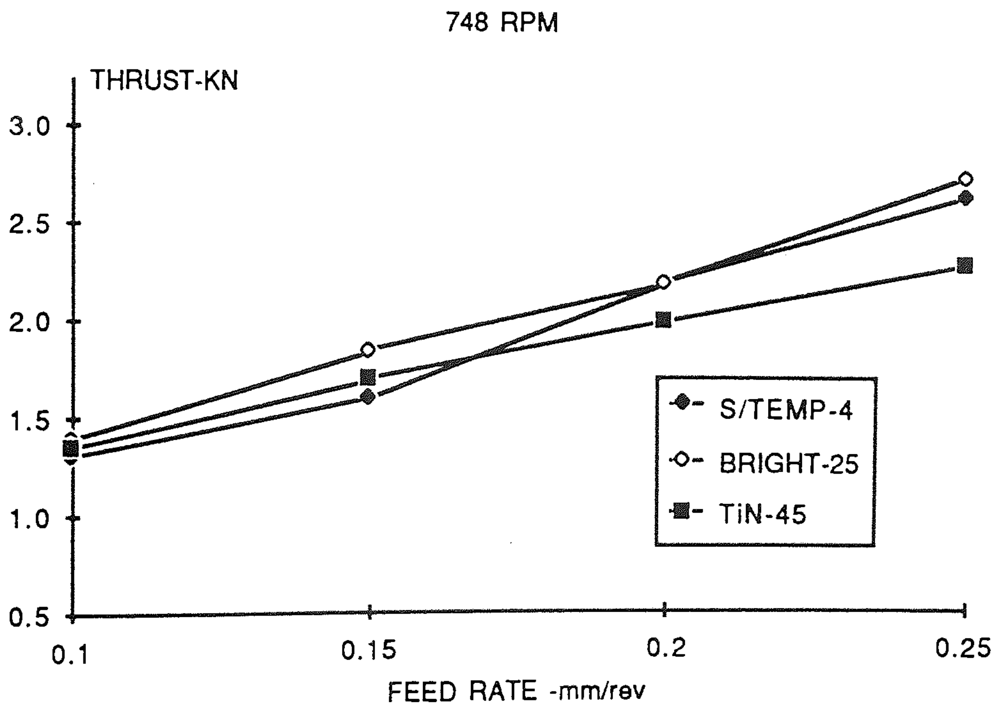



FIG 7.7 12.70 mm DIA TWIST DRILL-COMPARISON OF DRILL THRUST (KN) AT 748 RPM AND SELECTED FEED RATES

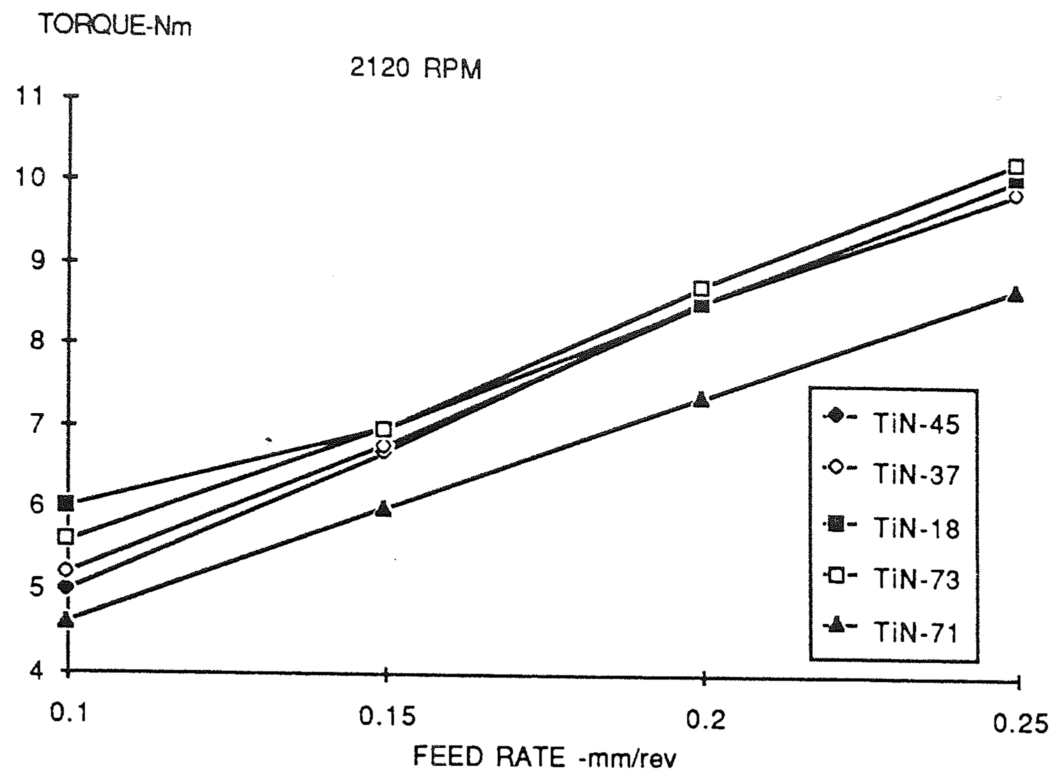



FIG 7.8 12.70 mm DIA TWIST DRILL -COMPARISON OF DRILL TORQUE ( Nm ) AT 2120 RPM AND SELECTED FEED RATES

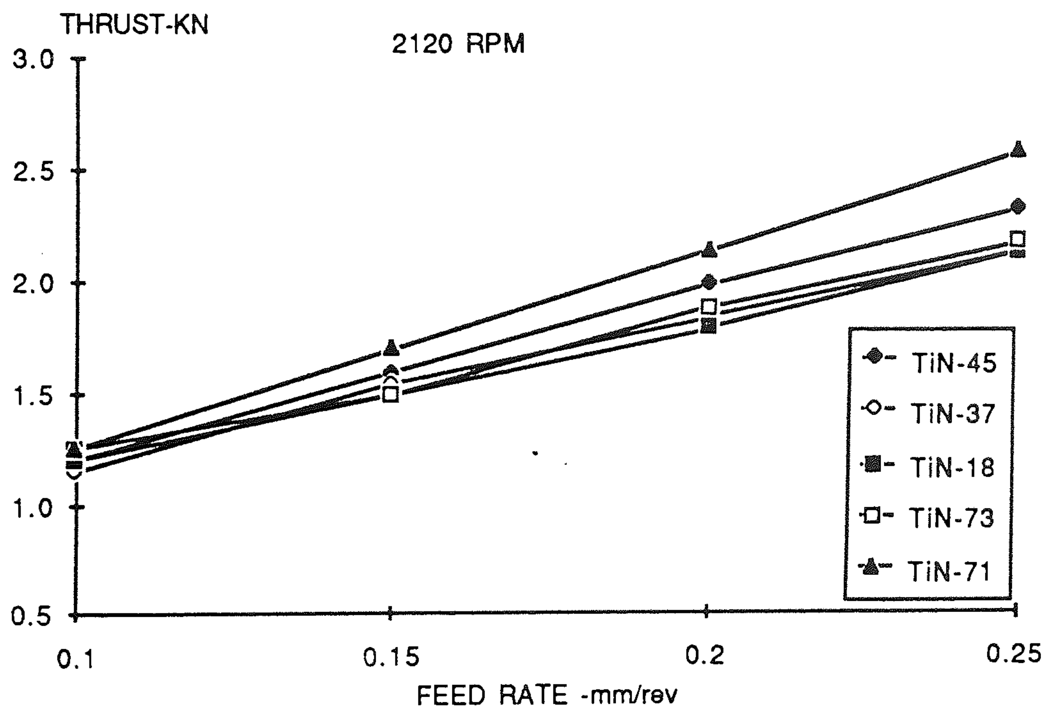



FIG 7.9 12.70 mm DIA TWIST DRILL -COMPARISON OF DRILL THRUST (KN) AT 2120 RPM AND SELECTED FEED RATES

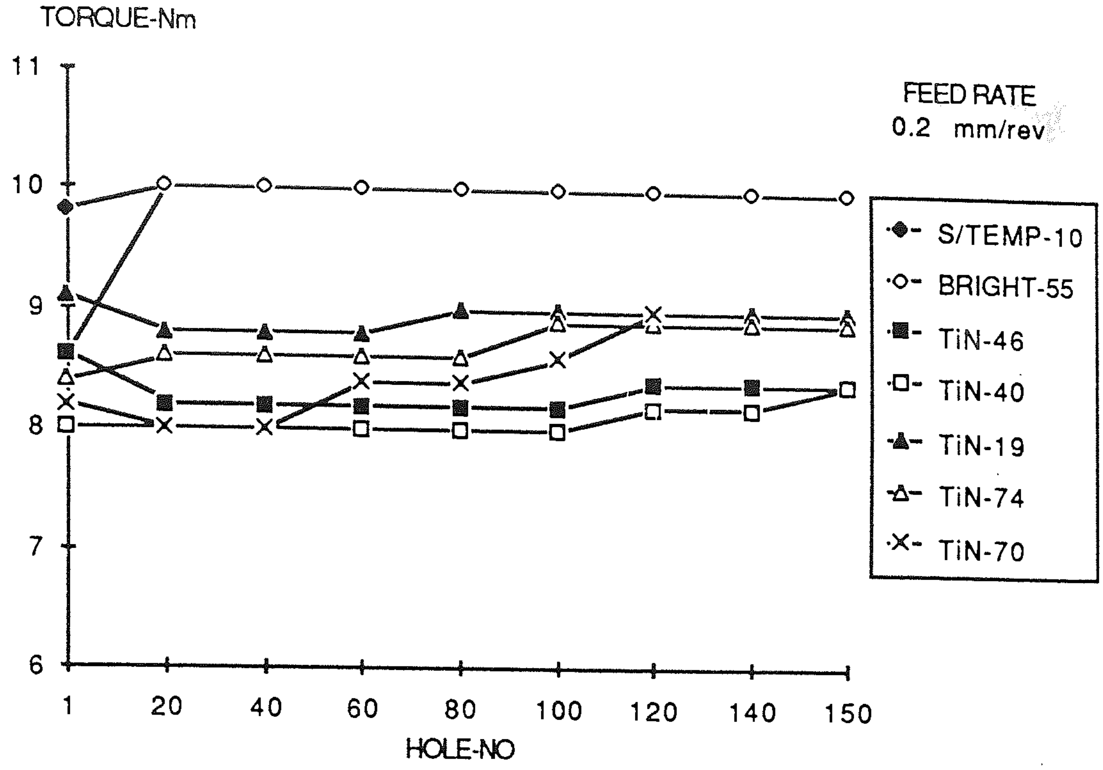



FIG 7.10 12.70 mm DIA TWIST DRILL
TORQUE COMPARISON OVER 150 HOLE TEST
(TiN DRILLS AT 2120 RPM OTHERS AT 748 RPM )

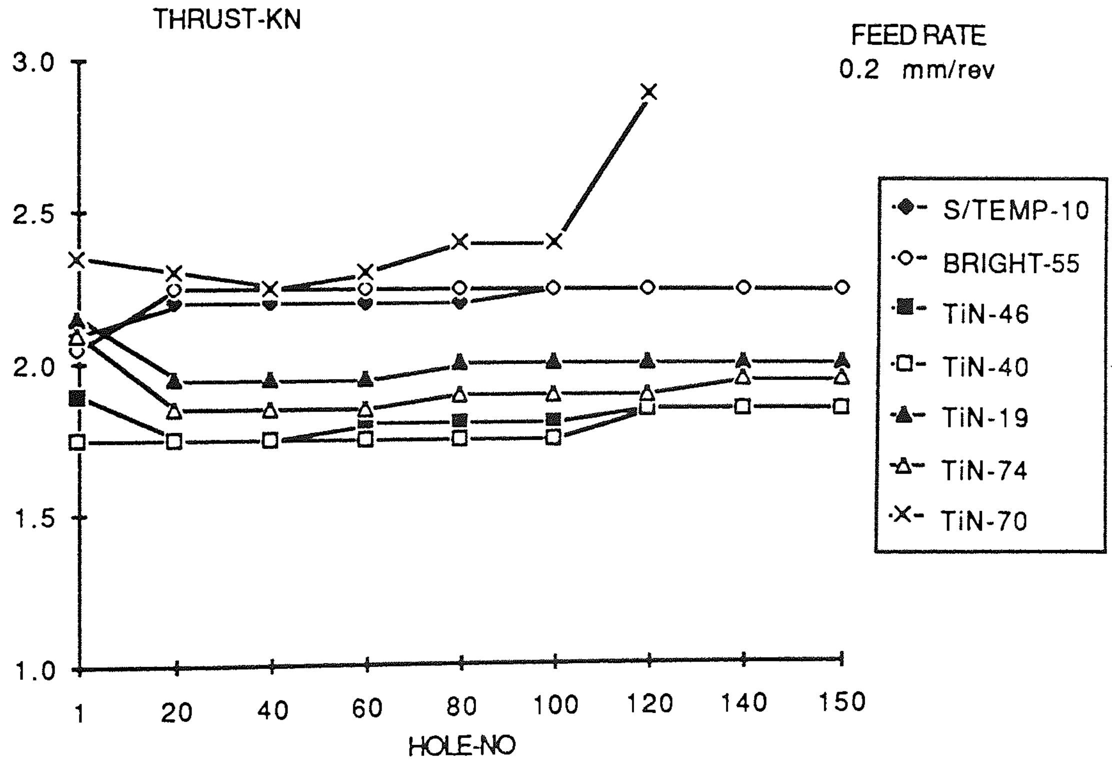



FIG 7.11 12.70 mm DIA TWIST DRILL
THRUST COMPARISON OVER150 HOLE TEST
( TiN DRILLS AT 2120 RPM ,OTHERS AT 748 RPM )

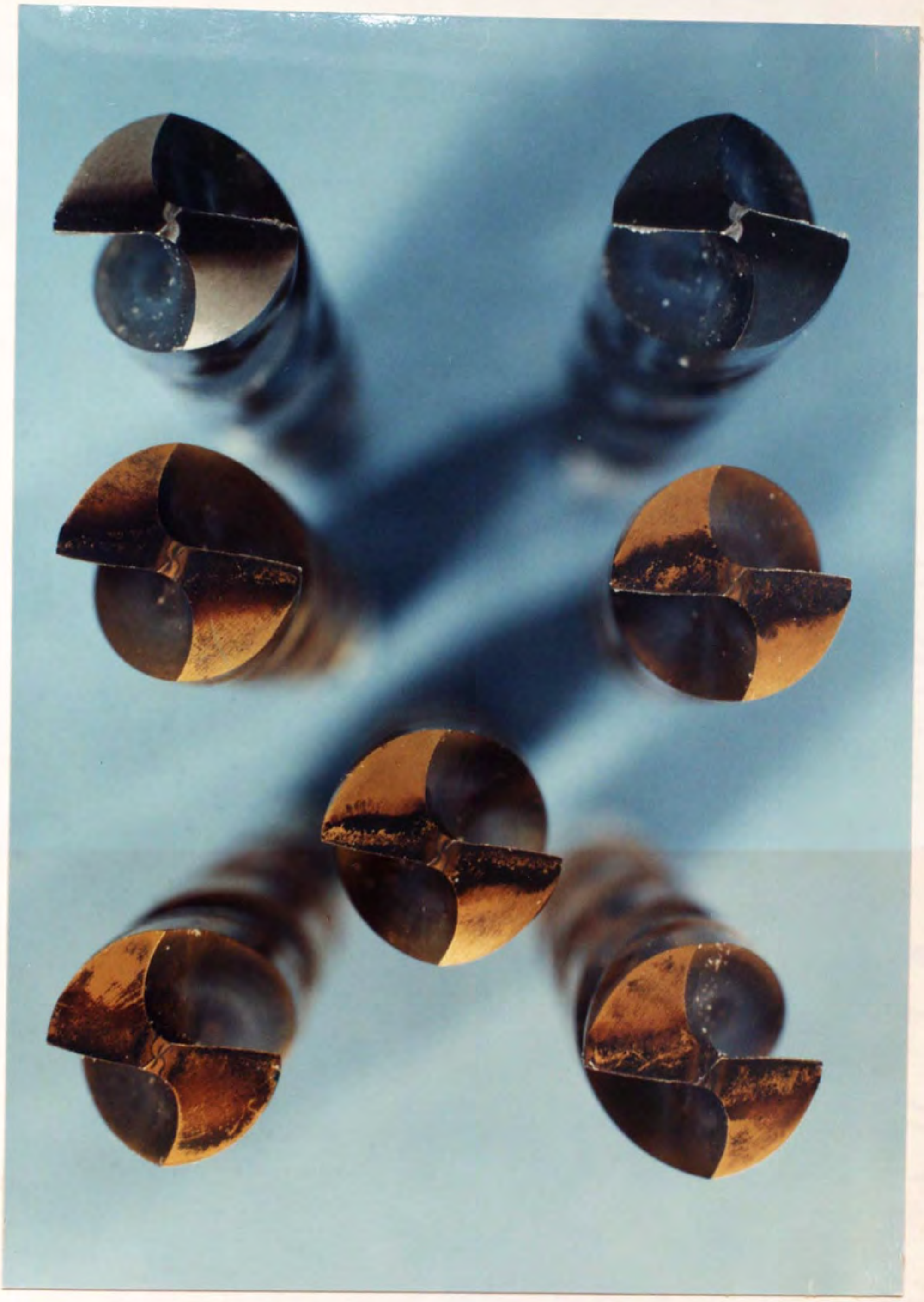


FIG 7.12 12.70 mm Dia TWIST DRILLS -150 HOLE TEST
COMPARISON OF WEAR AND HEAT AFFECTED ZONE ON CUTTING LIPS AND CHISEL EDGE

KEY : BRIGHT -55 S/TEMP -10

TiN -19 TiN -40

TiN -46

TiN -70 TiN -74

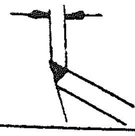
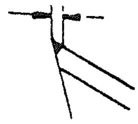
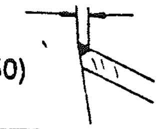
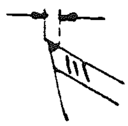
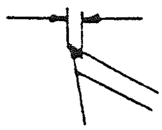
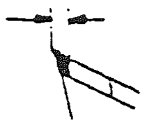
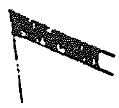
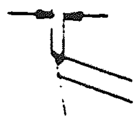
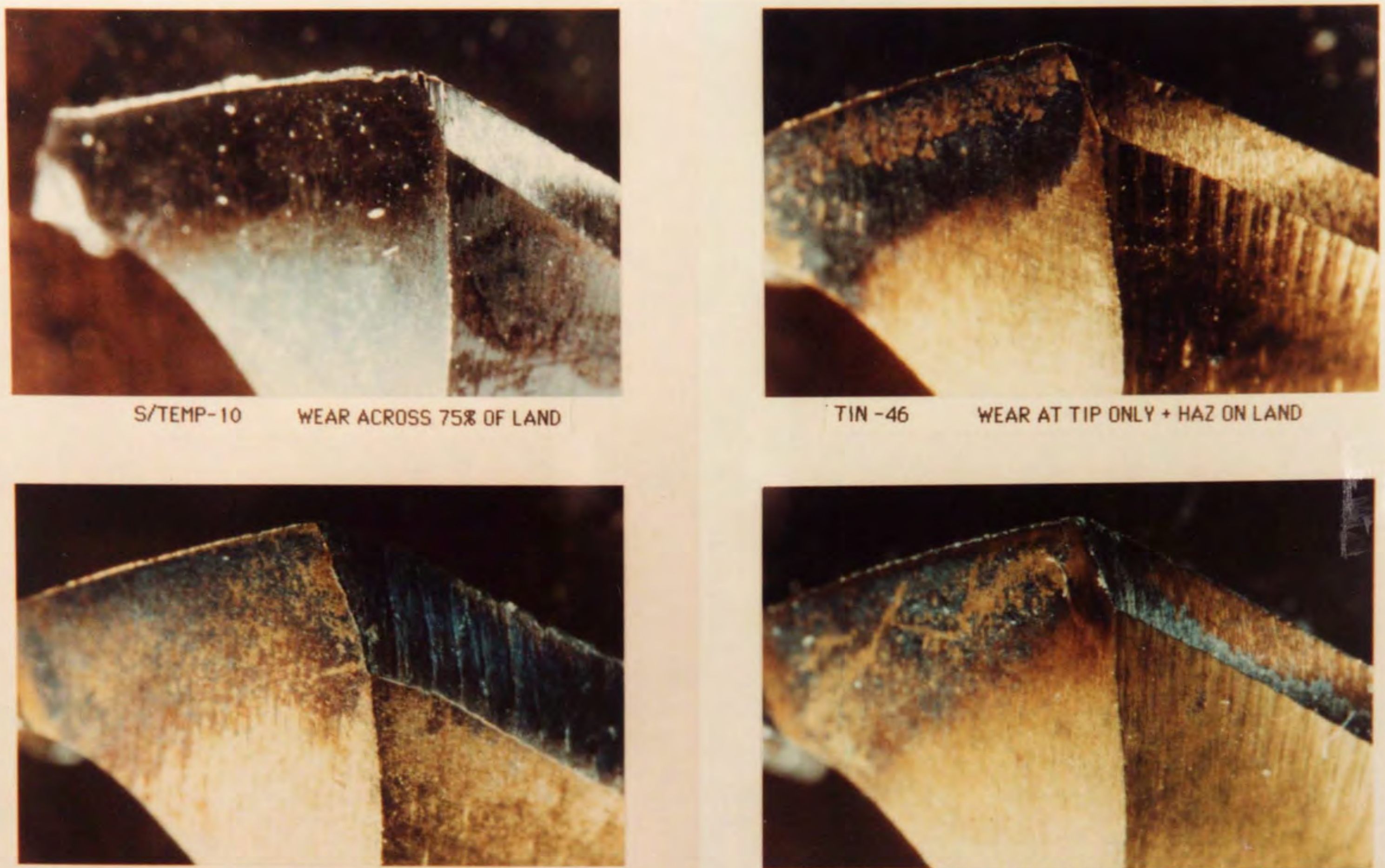
| DRILL NO | CORNER WEAR AFTER 150 HOLE TEST-(mm) |
|---|---|
| S/TEMP-10 | WEAR ACROSS 75% OF LAND (.236-.291)  |
| BRIGHT-55 | WEAR AT TIP ONLY +BUE (.234-.235)  |
| TIN -46 | WEAR AT TIP ONLY + HAZ ON LAND (.110-.250)  |
| TIN-40 | WEAR AT TIP ONLY +HAZ ON LAND (.330-.397)  |
| TIN -19 | WEAR AT TIP ONLY +BUE (.174-.211)  |
| TIN -74 | LOSS OF COATING +WEAR ACROSS COMPLETE LAND WIDTH (.390-.430)  |
| TIN -70 * | PEELING OFF AND OVERHEATING OF LAND (120 HOLES ONLY )  |
| TIN -64 * | WEAR AT TIP ONLY + BUE + HAZ (.194-.266)  |
| TIN -68 * | DRILL BROKE AFTER 14 HOLES - EXTENSIVE CORNER DAMAGE AND OVERHEATING  |

FIG 7.13 12.70 mm DIA TWIST DRILLS
COMPARISON OF LAND WEAR AFTER 150 HOLES

KEY : BUE = BUILT UP EDGE
HAZ = HEAT AFFECTED ZONE
* = ALL DRILLS COATED BY ONE COMPANY-(TIN 64 & TIN 68 NOT INCLUDED IN OTHER PERFORMANCE GRAPHS)



S/TEMP-10 WEAR ACROSS 75% OF LAND

TIN -46 WEAR AT TIP ONLY + HAZ ON LAND

TIN -70 PEELING OFF AND OVERHEATING OF LAND (120 HOLES ONLY )

TIN -74 LOSS OF COATING +WEAR ACROSS COMPLETE LAND WIDTH

FIG 7.14 12.70 mm Dia TWIST DRILLS -EXAMPLES OF LAND WEAR AFTER 150 HOLE TOOL LIFE TEST (MAGNIFICATION -14 TIMES)

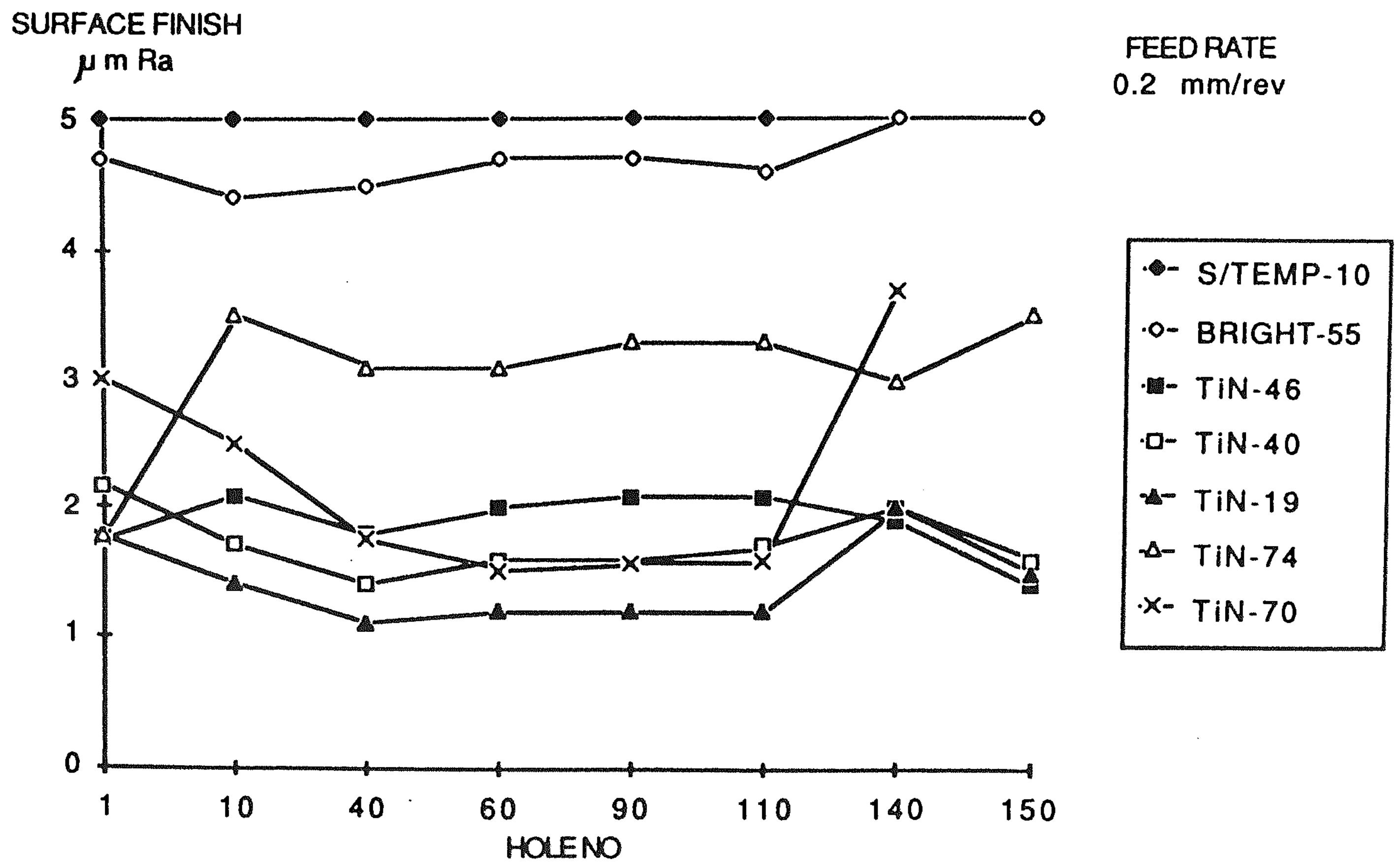



FIG7.15 12.70 mm DIA TWIST DRILL - COMPARISON OF HOLE SURFACE FINISH ( µ m Ra ) OVER 150 HOLE TEST (TiN DRILLS AT 2120 RPM OTHERS AT 748 RPM )

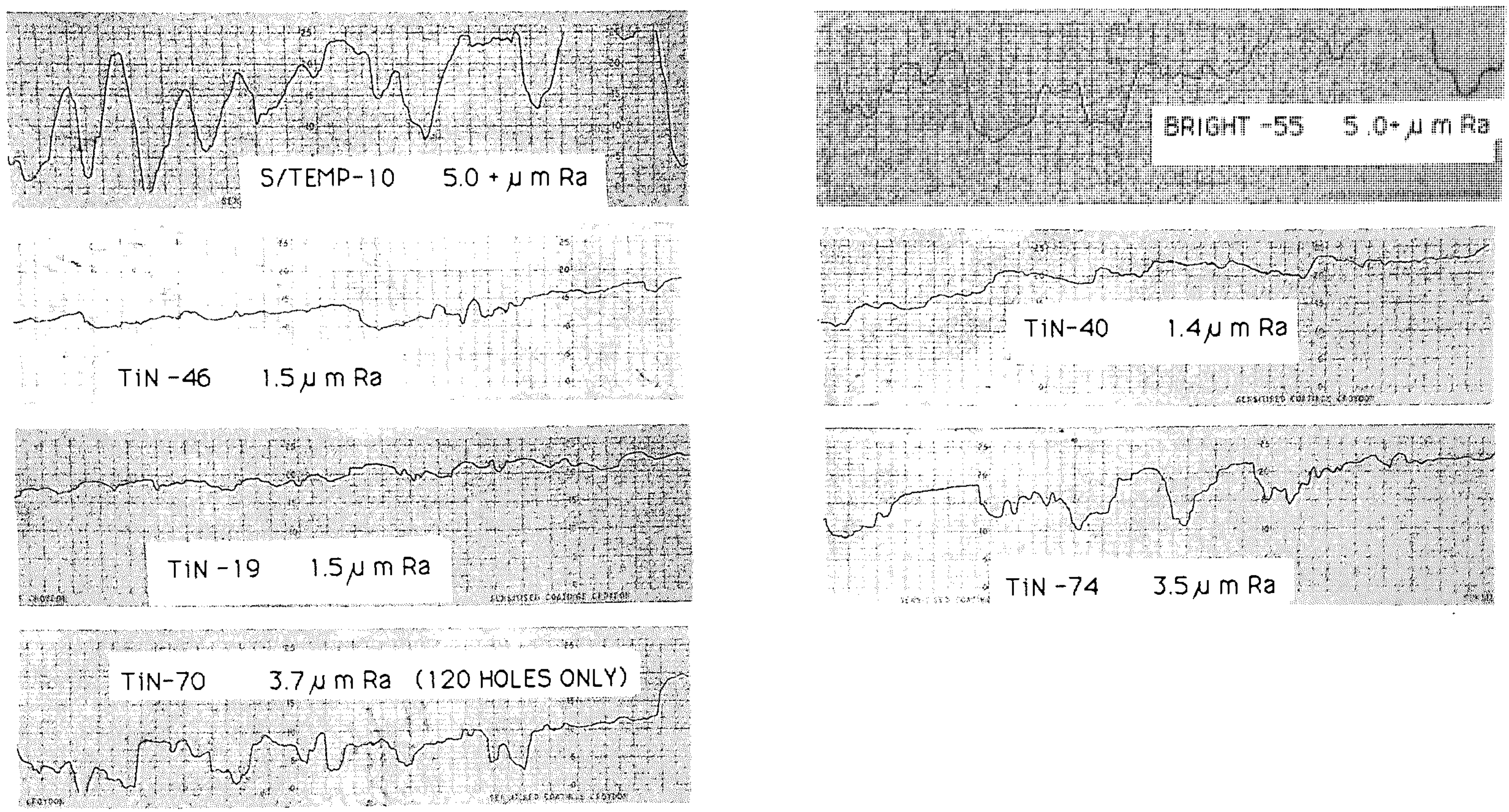
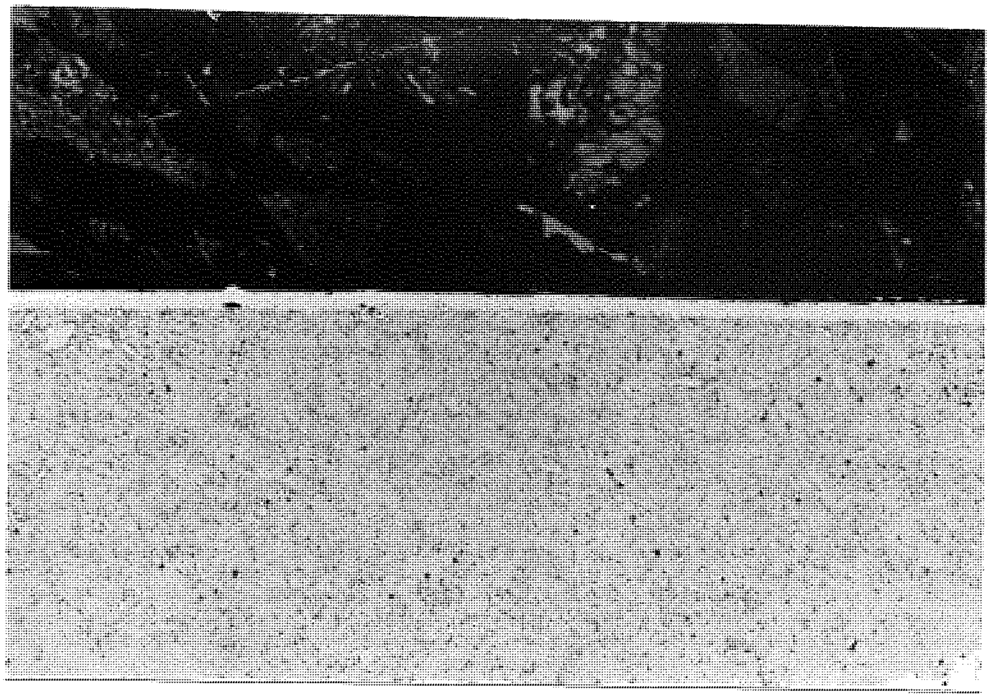



FIG 7.16 12.70 mm DIA TWIST DRILL-HOLE SURFACE FINISH ( um Ra) VALUES AND TRACES AFTER 150 HOLES

SCALE : X-AXIS 100 : 1

Y-AXIS 0-50 MICRONS



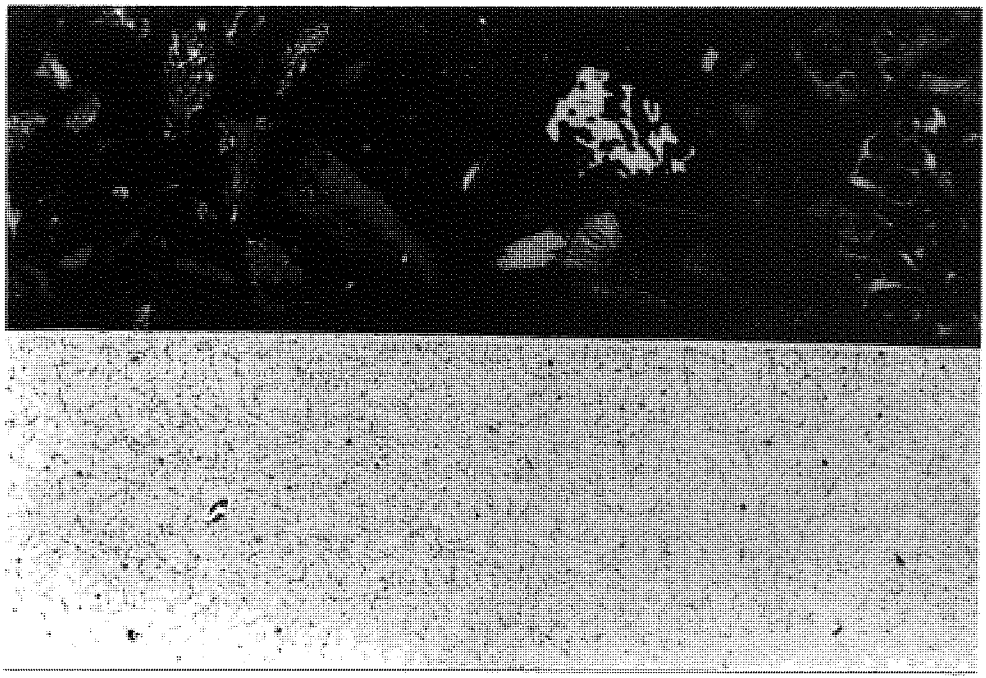


FIG 7.17 12.70 mm Dia TiN COATED TWIST DRILLS
COMPARISON OF COATING THICKNESS ON OUTSIDE OF DRILL BODY

KEY : TOP TiN -46 (5 MICRONS )
BOTTOM TiN -74 (1 MICRON )

FIG 7.18 TiN -68 WEAR AND DRILL BREAKAGE AFTER 14 HOLES AT 2120 rpm AND 0.2 mm/rev

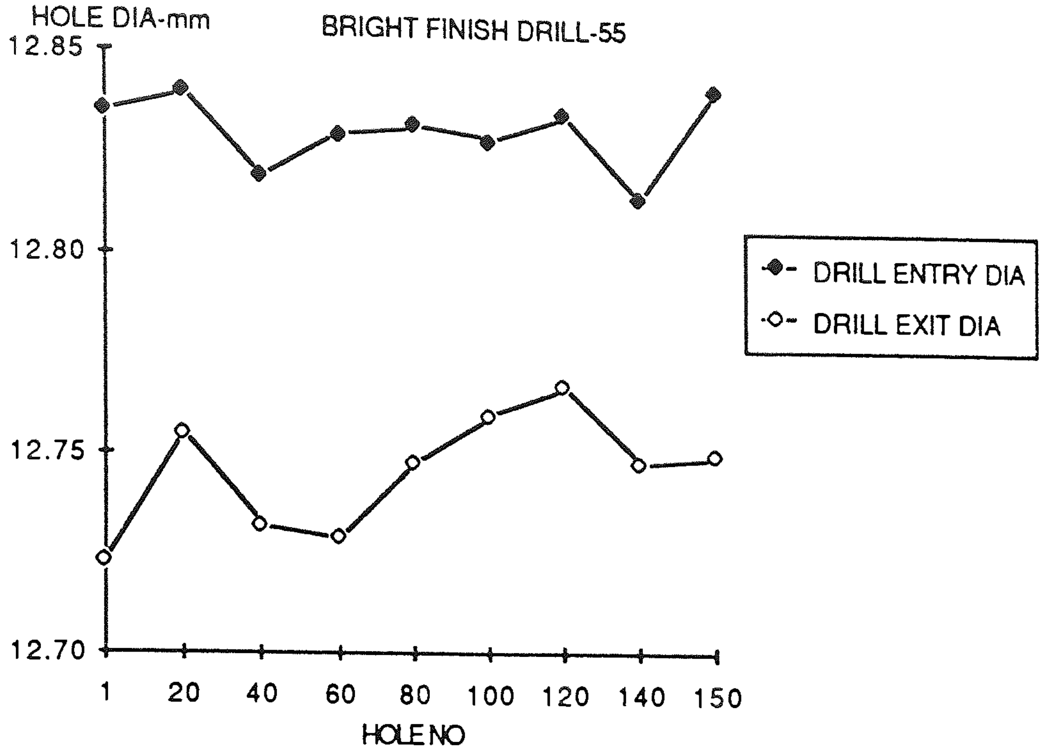



FIG 7.19 12.70 mm DIA TWIST DRILL BRIGHT-55 -COMPARISON OF HOLE DIAMETER (mm) AT DRILL ENTRY AND EXIT OVER 150 HOLES

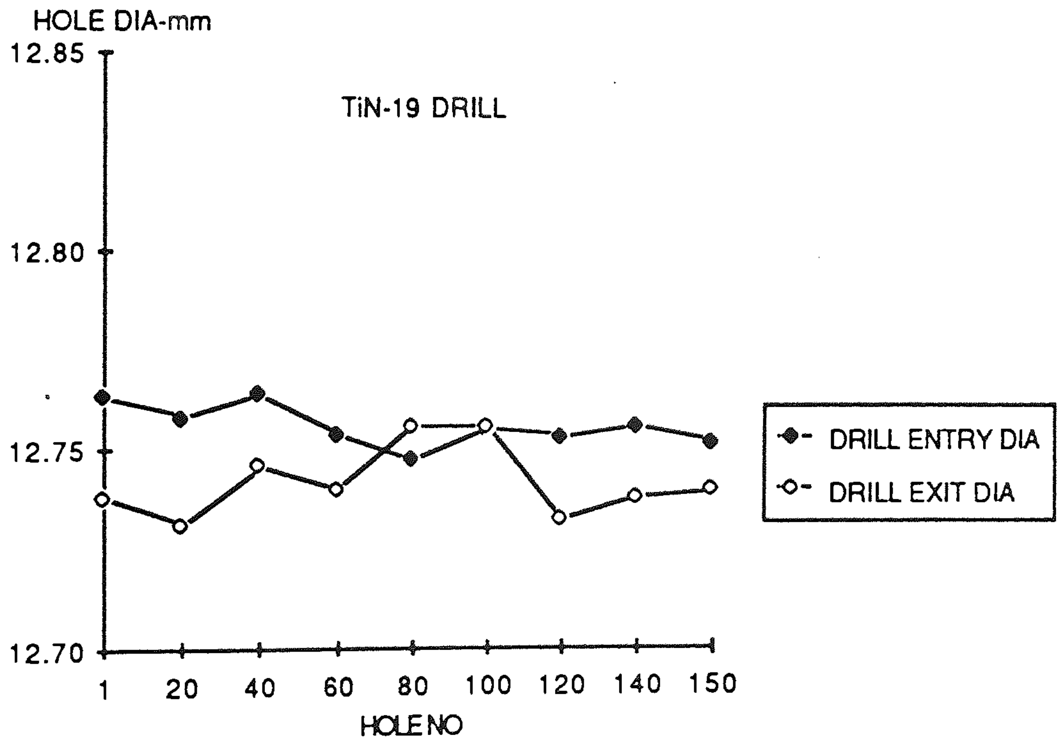



FIG 7.20 12.70 mm DIA TWIST DRILL TiN 19-COMPARISON OF HOLE DIAMETER (mm) AT DRILL ENTRY AND EXIT OVER 150 HOLES

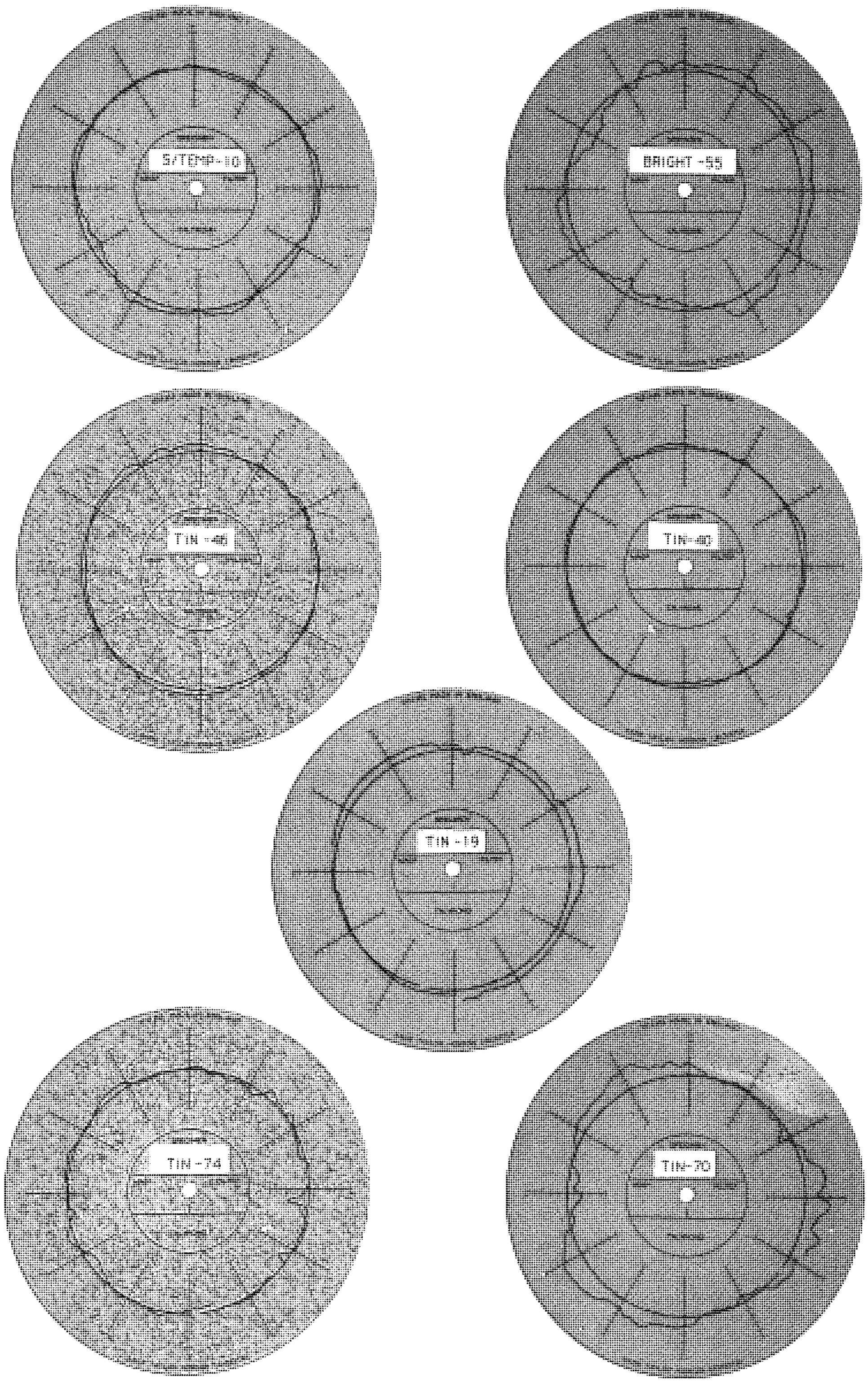
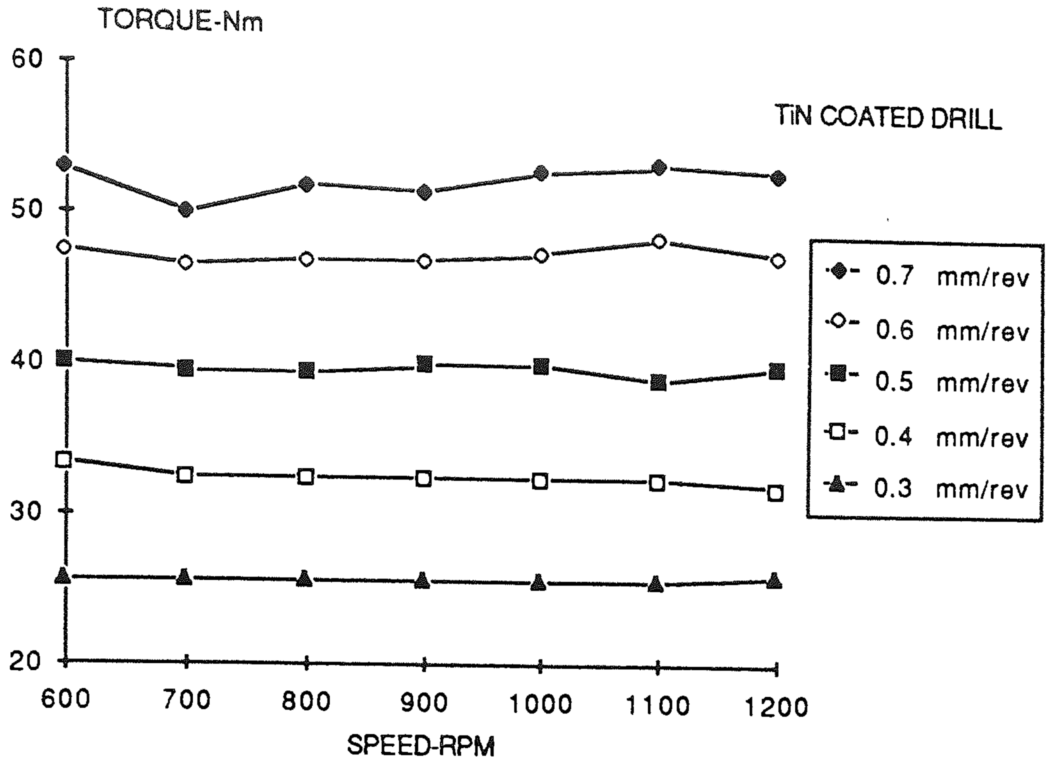



FIG 7.21 12.70 mm Dia TWIST DRILLS
COMPARISON OF HOLE ROUNDNESS, STEAM TEMPERED, BRIGHT FINISHED AND 5 TYPES OF TiN COATED DRILL AFTER 150 HOLES (1 DIVISION =6.35 MICRONS )



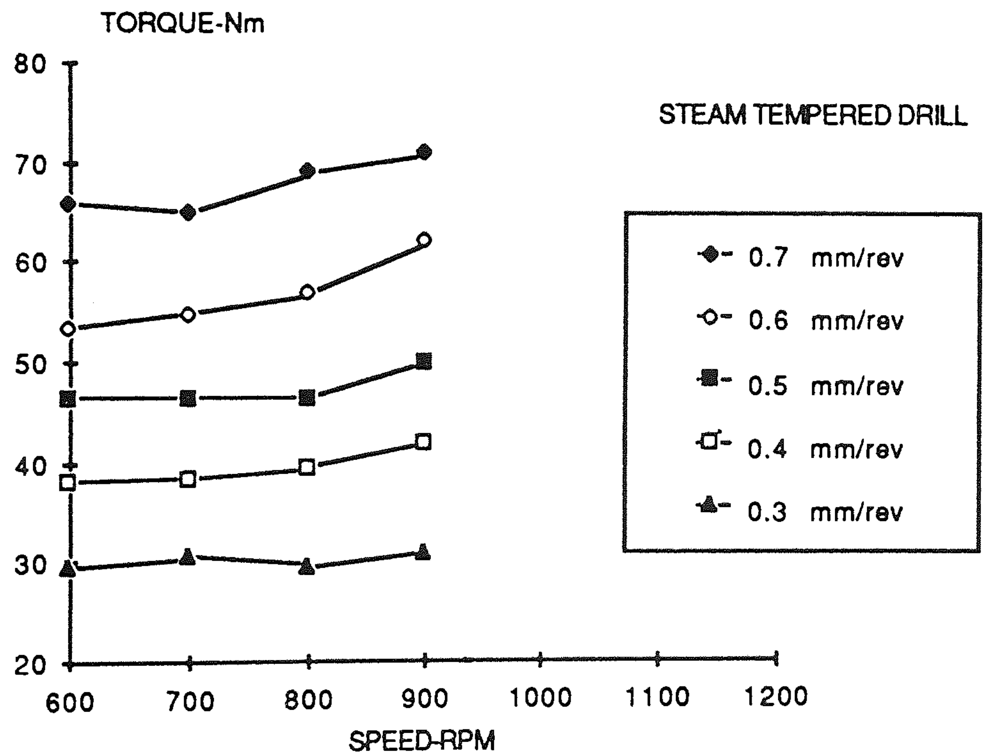
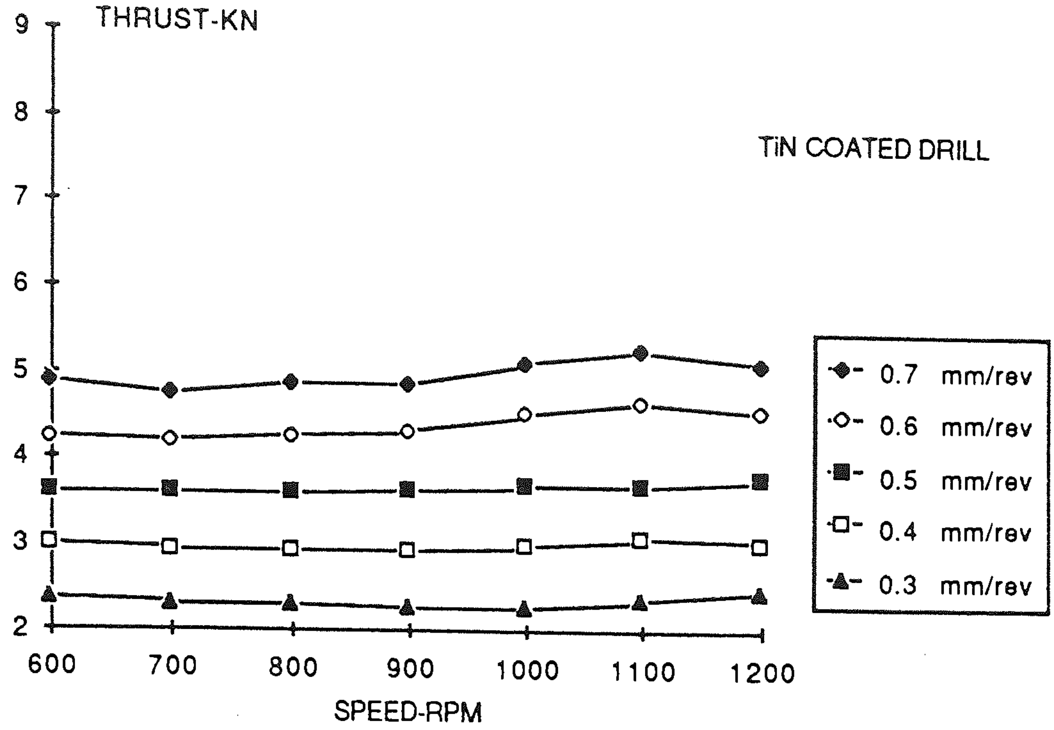




FIG 7.22 19.05 mm DIA TWIST DRILL -COMPARISON OF TORQUE (Nm) FOR A TiN COATED DRILL AND STEAM TEMPERED DRILL AT SELECTED SPEEDS AND FEED RATES, DRILLING EN-1A STEEL



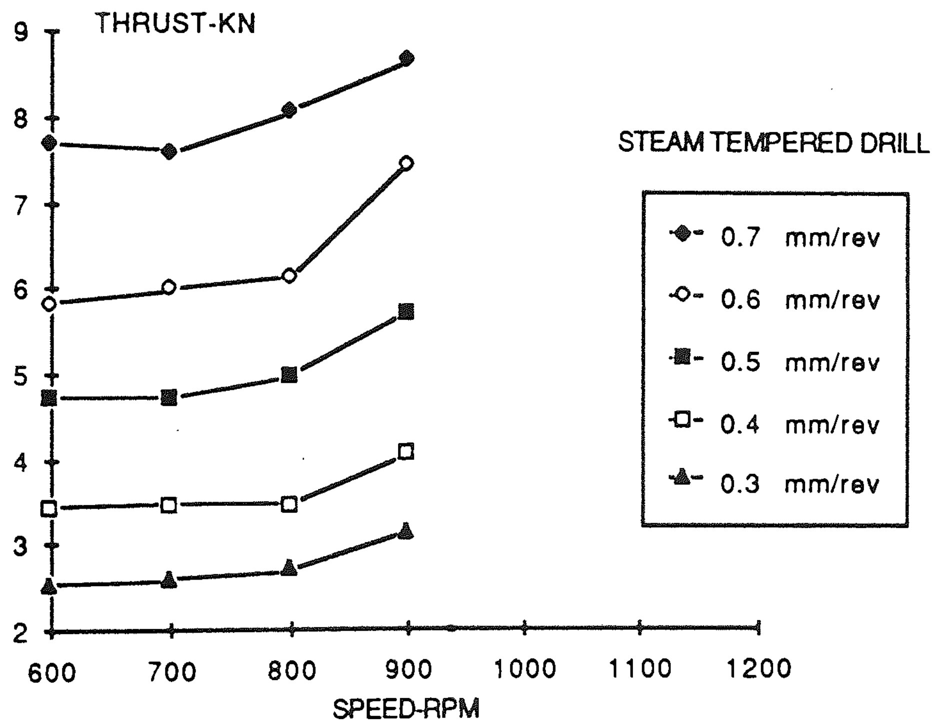




FIG 7.23 19.05 mm DIA TWIST DRILL- COMPARISON OF THRUST FORCE (KN) FOR A TiN COATED DRILL AND A STEAM TEMPERED DRILL AT SELECTED SPEEDS AND FEED RATES, DRILLING EN-1A STEEL

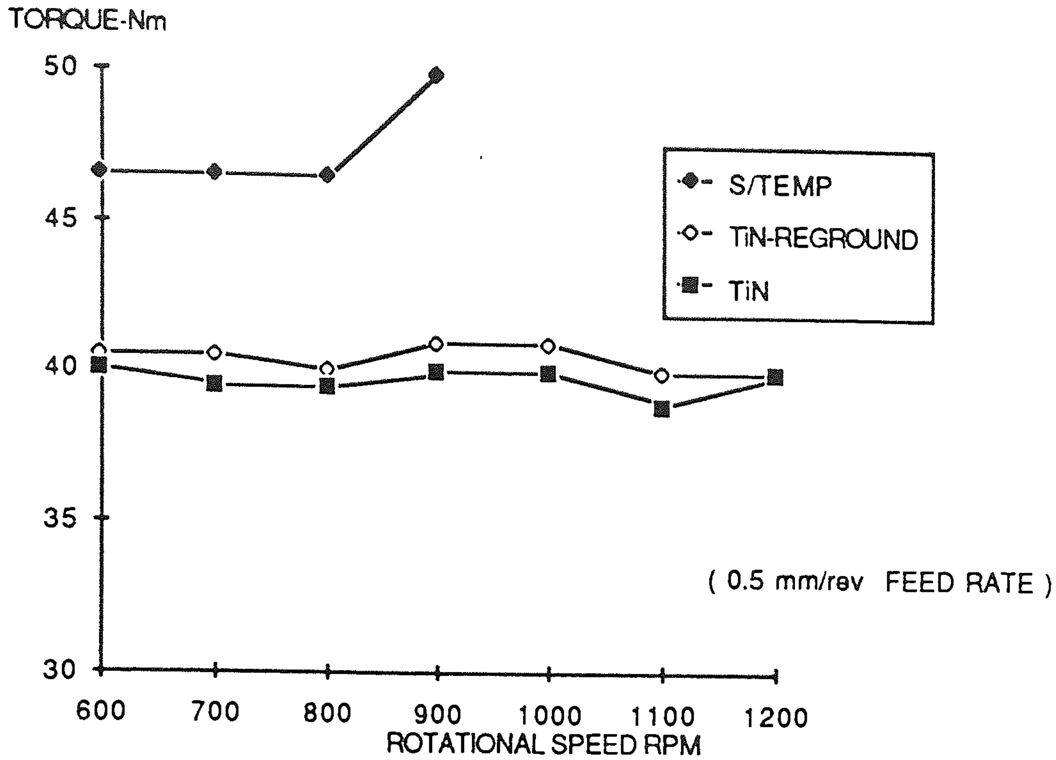



FIG 7.24 19.05 mm DIA TWIST DRILL- COMPARISON OF TORQUE (Nm) FOR A STEAM TEMPERED, TiN AND REGROUND TiN DRILL

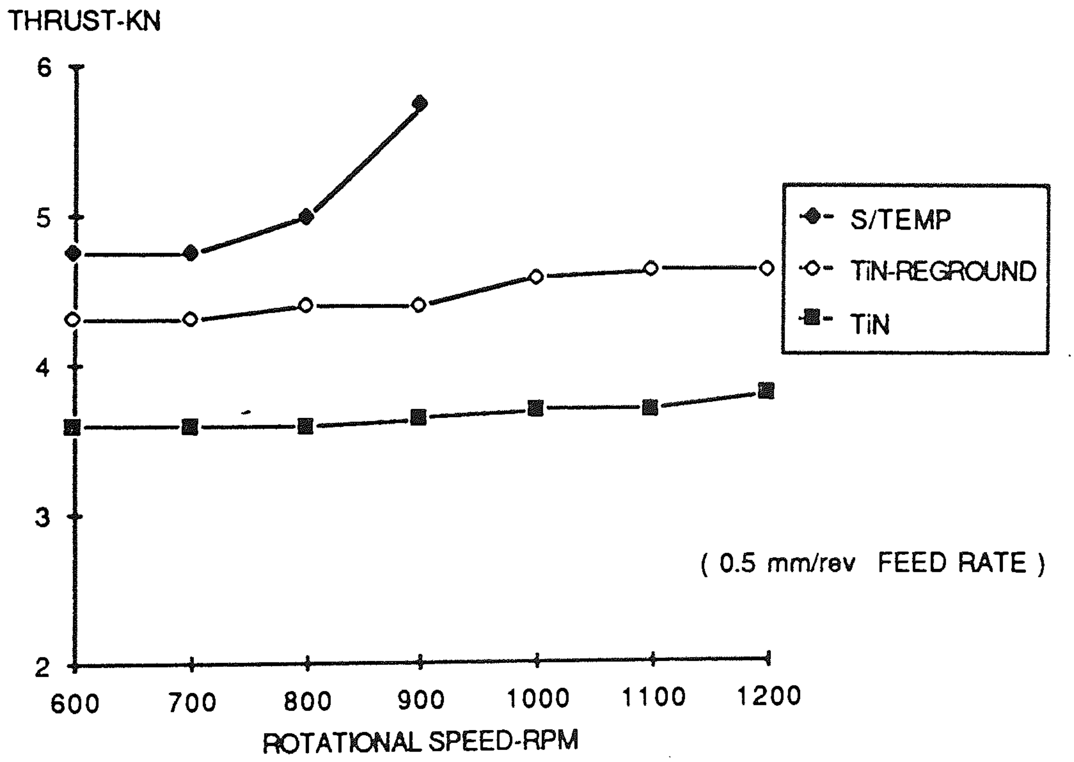



FIG 7.25 19.05 mm DIA TWIST DRILL- COMPARISON OF THRUST (KN) FOR A STEAM TEMPERED, TiN AND REGROUND TiN DRILL

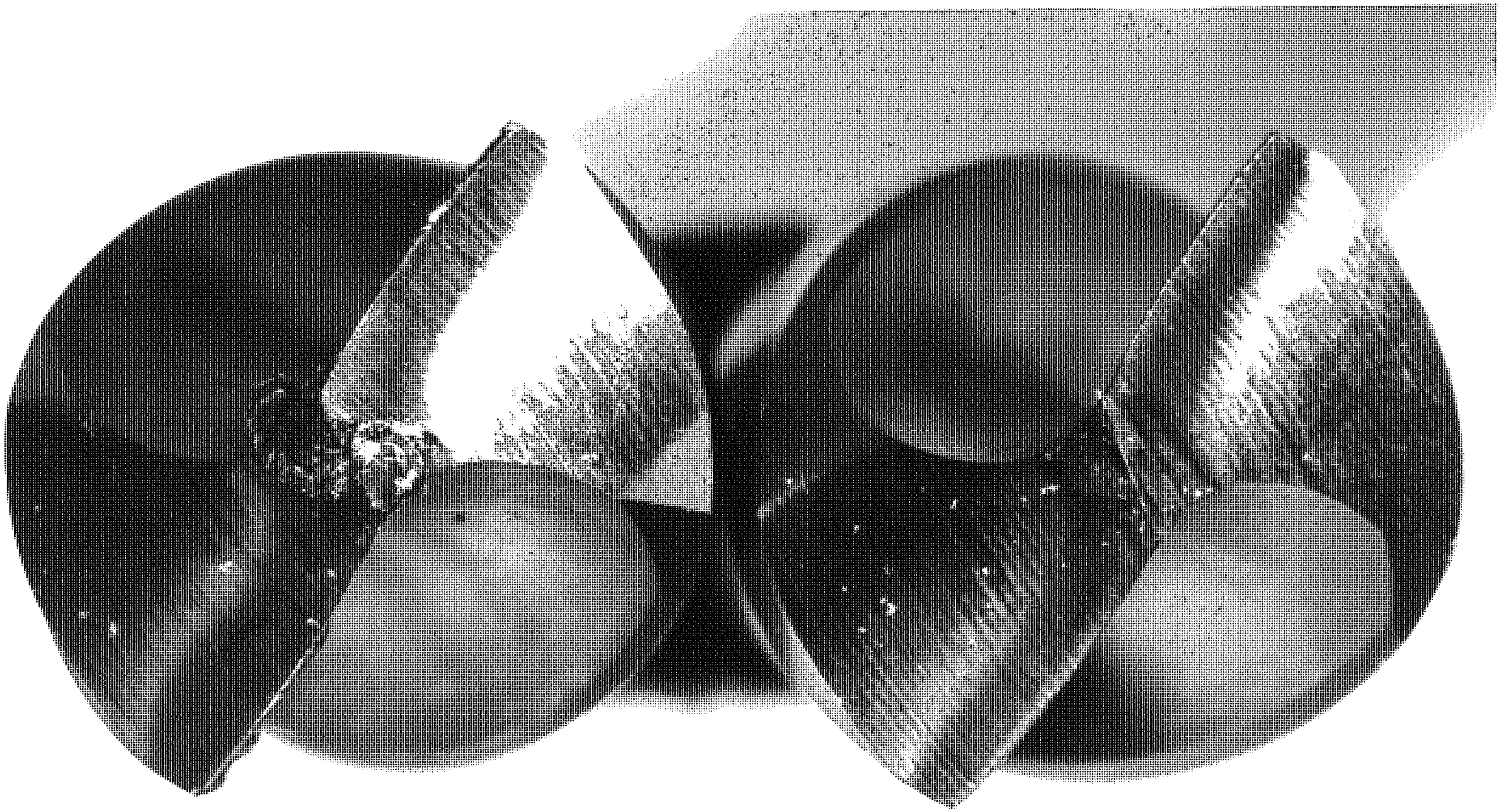


FIG 7.26 19.05 mm DIA REGROUND TWIST DRILLS
COMPARISON OF CHISEL BUILT UP EDGE

LEFT : STEAM TEMPERED DRILL - 600 RPM,0.6 mm/rev
RIGHT: TiN COATED DRILL -1000 RPM, 0.6 mm/rev

# CHAPTER EIGHT

## DRILLING WITH NEW DRILL DESIGNS INCOPORATING HELICAL CARBIDE INSERTS : PROTOTYPE Nos. 2 and 3

### 8.1 INTRODUCTION

The use of carbide tipped drills for drilling steel and other high tensile materials has, until recently been very limited. The reasons for this are that the drill design using carbide with conventional drill geometries has been unable to withstand the arduous conditions imposed by drilling.

The high thrust force, particularly at the chisel edge of the drill may cause high local point stresses. Tungsten carbide is inherently weak in tension and its brittle nature inhibits its use where vibration or excessive deflection of the machine spindle occurs. Carbide is also susceptible to failure at low cutting speeds which will be experienced near the centre of a drill.

The major advantage of tungsten carbide however is in its ability to cut at higher surface speeds (eg 100 m/min) compared to conventional H.S.S. rates of about 30 m/min.

An entirely new type of carbide tipped drill geometry was considered. The new design incorporated helically twisted tungsten carbide cutting edges with the cutting lips set radially across the centre line of the drill. The carbide extended down the flutes on each cutting lip and eliminated the need for precision grinding on the rake face. The need for a web separating the two inserts resulted in a design that used one large insert which extended radially from the drill centre to the periphery and one smaller width of carbide set diametrically opposite (Fig.8.1). A feature of the new design was the elimination of the chisel edge and the associated negative rake cutting angles. On the new drill the axial rake angle varied from about 0° at the drill centre to the value of the helix angle at the drill periphery.

Trials to optimise the point configuration of the new design using Prototypes 2 and 3 are considered, the objectives being:-

1. To evaluate the performance of the radial cutting lips and tool geometry.
2. To develop the new drill geometry for hole depths of two diameters.
3. To produce high quality holes at higher penetration rates to those currently achieved with H.S.S. twist drills.

## 8.2 EXPERIMENTAL EQUIPMENT

### 8.2.1 Tooling - Prototype No.2 - Drill Design

Initial work was undertaken by Dr A B El Wahab [76] with a 19.05 mm dia ball ended die sinking tool (designated Prototype No.1). This work established that the new tool when used as a conventional drill on a vertical milling machine rapidly failed due to tool breakage.

Modifications were undertaken to increase the swarf space near the tip of the drill by milling additional flute clearance and ten Prototype No.2 tools were supplied for testing. All drills were nominally 19.05 mm diameter.

8.2.2. CNC Lathe

The initial research with the Protype Drill No.2 was undertaken on a Torshalla CNC Lathe (see Appendix II).

Horizontal drilling tests were made with the stationary tool clamped inside a flanged adaptor that was made to be fixed to a Kistler Drilling Dynamometer. The Dynamometer was secured to a second adaptor which was locked into a Turret Tool holder on the Lathe Turret.

A CNC drilling program was written for the lathe which enabled individual holes to be drilled automatically. Different speeds and feeds were selected and entered in the program via the lathe computer keyboard to suit the desired test conditions.

In order to ensure that the drill and lathe centres were on the same centre line, concentric measurements were undertaken before drilling commenced. The measurements were made with a dial gauge mounted in the chuck of the lathe and rotated so that equal radial readings were obtained off the two drill lands.

The workpiece was gripped in the jaws of the lathe chuck.

Actuation of the chuck jaws was by means of a foot pedal control to a hydraulic servo system.

On Prototype Drills No.2 the existing lathe coolant pump was programmed to provide an external jet of suds coolant to the tool/workpiece interface at 52 litres/min, 3 bar pressure.

The coolant used was an emulsion type with extreme pressure (E.P) additives. The specification was Edgar Vaughan Hocut type 3210A which was diluted one part fluid to ten parts of water.

### 8.2.3 Instrumentation

The instrumentation used for these and all subsequent tests, consisted of a Kistler Type 9273 four component Drilling Dynamometer. This was coupled to a Kistler Charge Amplifier unit comprising of three Type 5006 Amplifiers. The Amplifiers in turn were connected to a Gould-Bryans U.V. Recorder for the presentation of the signal.

Three Dynometer terminals were used, i.e. Torque 'M' (Nm), Thrust '$F_Z$' (kN) and Radial (out of balance) Force $F_X$ or $F_Y$.

The specification of the instrumentation is given in Appendix III.

### 8.2.4. Test Material - Carbide Tipped Drills

The material used for all tests with carbide tipped drills was free cutting mild steel Grade EN 1A. This was supplied in bright finished bars, 50 mm dia and parted off into 38 mm (2d) lengths on a bar feed Capstan Lathe.

## 8.3 TEST PROCEDURE

All Prototype tools were measured and inspected before testing in order to determine the relative positions of the carbide tips and their respective heights to the centre line.

Initially some inspection was undertaken with an eyepiece attachment of a Jig Boring Machine using the x - y readouts for measurement. Later work included the use of both the Shadow Graph and Universal Measuring Machine and included profiles as well as end views and measurements.

The target operating conditions set for the new Protype Drill were up to three times the surface speed and half the feed rate of that specified for a conventional H.S.S. drill of the same diameter (ie 1800 rpm x 0.2 mm/rev).

The actual speeds and feeds used were limited by the drill life that could be obtained without tool breakage.

8.4 RESULTS - Prototype No.2

Examples of the drill dimensions for Prototype 2 are given in Table 8.1. Some of the grinding modifications made in an attempt to improve drill performance are shown in Fig.8.2, with detailed shadow graph traces of two tools shown in Figs.8.3 and 8.4.

The performance of the tools at 1400 rpm x .08 mm/rev is presented in Table 8.2 and Fig.8.5 for the modifications carried out.

8.5 DISCUSSIONS OF RESULTS - Prototype No.2.

Due to the inaccuracies in the brazing and the prototype nature of the manufacturing process only six of the original batch of ten tools were tested. Two tools were rejected because there was excessive braze thickness and the cutting lips were therefore not radial. One tool was damaged in handling. On another tool (No.7) the large carbide insert did not extend to the centre of the drill and this would result in an 'uncut' core remaining in the centre of the hole (see Table 8.1).

The initial tests with Tool No.4 as supplied resulted in taper or bell mouthed holes being produced. The U.V. trace confirmed that out of balance forces of up to 0.6 kN resulted in hole oversizes of up to 0.55 mm at drill entry (see Table 8.1). The fundamental problem with the new drill was that there was a large lip height difference between the two carbide inserts, the large carbide taking almost all of the initial part of the cut. This was apparent from the built up edge and breakage that occurred on the large insert during the early trials. Modifications were then made to reduce the lip height of the large insert (see Fig.8.2). Although some improvement in out of balance was achieved, the use of low feed rates (0.08 mm/rev) tended to exacerbate the problem. Higher feed rates were not possible without excessive vibration or tool breakage.

The performance trials confirmed that the modifications did generally improve the hole size and although the torque remained nearly constant, the thrust force was extremely sensitive to drill point geometry (see Fig.8.5).

## 8.6 CONCLUSIONS - Prototype No.2.

(i) The Tool as supplied was not capable of drilling parallel holes. A tapered hole, typically 0.5 mm oversize at the drill entry, was produced by the unbalanced cutting action and large lip height difference.

(ii) Modifications to reduce the lead on the large carbide were successful in improving the hole quality and reducing the out of balance forces.

(iii) A built-up edge that formed at the centre of the drill resulted in tool failure. The BUE was due to a combination of zero surface speed at the centre, high thrust leading to high point stress, insufficient cooling and poor chip flow.

(iv) Experiments to remove the built-up edge by grinding were successful providing that a blend radius was developed to match the Ball End profile.

(v) A built-up edge was also formed on the small carbide and the weak nature of the point together with the restricted flute space lead to tool breakage.

(vi) For a given speed and feed, changes in point geometry had the greatest effect on thrust as would be expected. The torque remained fairly constant.

## 8.7 DRILL DESIGN - Prototype Drill No.3

The experience gained with Prototype No.2 enabled two major modifications to be made for Prototype No.3, these were:-

(i) The width of the small carbide was increased from 5 to 6.5 mm leaving a minimum web thickness of about 2 mm between the inserts. The existing tool bodies were milled to take the increased width of carbide. It was hoped that this modification would overcome some of the problems of out of balance and weakness on the small cutting edge point.

(ii) The ball nosed end form was changed to an 'M' shape. Each side of the 'M' was ground so that a blend radius was produced on either side of the centre. This modification was intended to overcome the difficulty of BUE at the tool centre.

Photographs of Prototypes 1, 2, and 3 are shown in Fig.8.6. The same testing set up used for Prototype No.2 was used for Prototype Drill No.3.

8.8 RESULTS - Prototype Drill No.3

Two tools (Nos. 11 and 12) were tested. The basic dimensions are given in Fig.8.7. Selected results are presented in Table 8.3, and Fig.8.8.

The type of blind hole end form generated with Prototype No.3 is shown in Fig.8.9. A shadow graph projection of tool No.11 is shown in Fig.8.10. Sample hole roundness traces are shown in Fig.8.11.

8.9 DISCUSSION OF RESULTS - Prototype Drill No. 3.

Prototype No.3 gave very much improved hole quality and reduction in out of balance force compared with No.2.

A lip height difference of .075 mm on the large carbide was found to adversely affect the out of balance at drill entry. When the lead was removed to bring the cutters into line there was a reduction in thrust, torque, out of balance force and hole oversize (see Fig.8.8). Typical out of balance forces were reduced to below 0.2 kN and the hole diameter tolerance to below 0.1 mm with the lip modification.

Problems of BUE at the tool centre were eliminated with the 'M' point. Difficulty was experienced with the small carbide which broke on tool No.11. Tool No.12 produced long continuous swarf from the small cutting lip and attempts to incorporate a chip breaker were only successful over a limited range of speeds and feeds. Continuous swarf was found to contribute to poor hole finish and increased oversize.

The quality of drilled holes varied according to the depth. Surface finishes to 2-5 µm Ra were recorded, with the worst values at the start of the hole. Probable reasons for this were the restricted flute space on the small carbide which probably caused swarf choking and rubbing on the sides of the already drilled hole.

Isolated "rings" in the drilled finish also indicated BUE and swarf removal problems.

A shadow graph trace (Fig.8.10) of the drill tip (No.11) taken before and after drilling confirmed that some erosion of the web occurred due to the abrasive chip flow at the drill point. This may have ultimately led to tool failure at the brazed joint.

The range of speeds and feeds over which the tool was successfully operated without vibration was limited to betweenm 1200 rpm x 0.08 mm/rev and 1600 rpm x 0.13 mm/rev.

Some aspects of the drill design and geometry may have contributed to the operating limitations.

A negative rake angle (-20°) ground along the cutting lips for 0.1 mm reduced the "running in" time of the drill, helped to reduce the chatter and generally strengthened the cutting lip.

Talyrond measurements taken on sample holes confirmed that the roundness was within 0.015 mm over the entire hole length (see Fig.8.11).

These results were very encouraging, particularly as low feed rates are generally associated with tool wander, hole oversize and out of roundness at entry on a conventional chisel point twist drill.

## 8.10 CONCLUSIONS - Prototype Drill No.3.

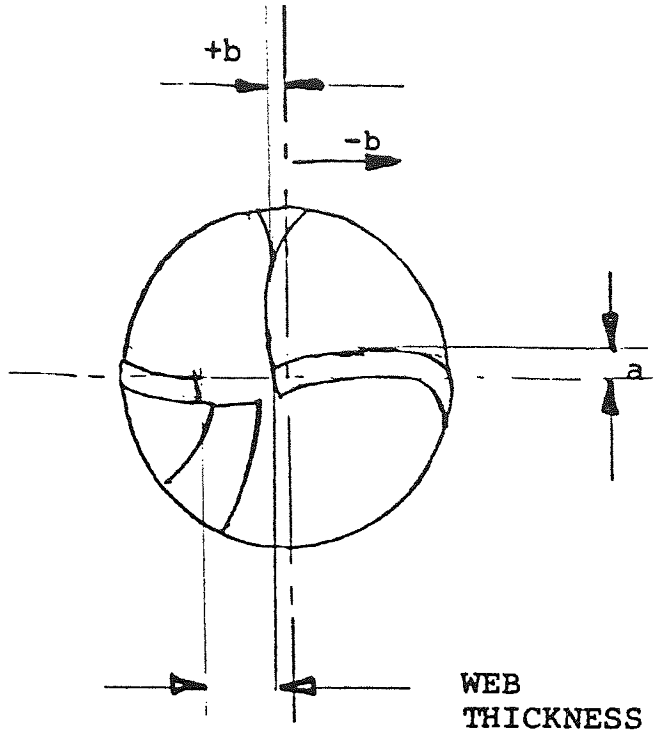
(i) A dramatic improvement in hole quality and reduction in out of balance force was achieved with Prototype No.3 when compared with No.2.

(ii) The use of helically twisted tungsten carbide was successfully demonstrated on a two flute ball ended drill for short holes in horizontal drilling at surface speeds of 70 - 100 m/min and feeds of 0.08 - 0.13 mm/rev.

(iii) The high negative rake cutting conditions normally experienced at the centre of a conventional drill were eliminated with the new radial lip ball ended profile, in which the centre axial rake angle was near to zero degrees.

(iv) Problems of built-up edge at the drill centre were overcome by adoption of an 'M' shaped tool end form but this new form was difficult to reproduce exactly on each cutting lip by grinding.

(v) Tool vibration at feed rates greater than 0.13 mm/rev was attributed to the lip profile and asymmetric geometry.




| TOOL | a (mm) | ±b (mm) | COMMENTS FOR TOOLS NOT USED |
|---|---|---|---|
| 1 | 0.84 | + 0.23 | [ MAJOR LIP |
| | | | [ TOO MUCH ABOVE |
| 2 | 0.96 | + 0.13 | [ CENTRE (+a) |
| 3 | 0.30 | - 0.13 | |
| 4 | 0.63 | 0 | |
| 5 | 0.38 | + 0.38 | |
| 6 | 0.48 | + 0.17 | TOOL CHIPPED |
| 7 | 0.25 | - 0.56 | BELOW CENTRE (-b) |
| 8 | 0.25 | + 0.13 | |
| 9 | 0.30 | + 0.38 | |
| 10 | 0.07 | + 0.15 | |

TABLE No. 8.1

PROTOTYPE No.2 : THE EFFECT OF MANUFACTURING TOLERANCES ON MAJOR CUTTING LIP POSITION ABOUT CENTRE LINE.

| TOOL No. | THRUST $'F_Z'$ (kN) | TORQUE 'M' (Nm) | OUT OF BALANCE $'F_X'$ (kN) | HOLE OVERSIZE (mm) ENTRY | EXIT |
|---|---|---|---|---|---|
| 4 | 0.63 | 9.4 | 0.39 | 0.55 | 0.28 |
| 8 | 0.4 - 0.8 | 8.0 - 13.0 | 0.60 | 0.30 | 0.08 |
| 8 | 0.84 | 9.0 | 0.24 | 0.20 | 0.05 |
| 5 | 0.6 - 1.3 | 12.0 | 0.24 | 0.20 | 0.05 |
| 9 | 1.0 - 1.4 | 8.8 | 0.30 | 0.33 | 0.05 |
| 10 | 0.64 | 8.8 | 0.31 | 0.08 | 0.05 |
| 10 | 0.76 | 9.0 | 0.60 | 0.20 | 0.08 |

**TABLE No.8.2**

**PROTOTYPE DRILL No.2 : EXAMPLES OF DIFFERENT PERFORMANCE TEST RESULTS AT 1400 rpm x .08 mm/rev. FOR TOOLS EVALUATED.**

| TOOL No. | THRUST 'F$_Z$' (kN) | TORQUE 'M' (Nm) | OUT OF BALANCE 'F$_X$' (kN) | HOLE OVERSIZE (mm) ENTRY | EXIT |
|---|---|---|---|---|---|
| 11 | 1.00 | 12.8 | .22 | .15 | .10 |
| 11 | 0.86 | 9.2 | .16 | .10 | .08 |
| 12 | 1.20 | 12.0 | .18 | .08 | 0 |
| 12 | 0.80 | 12.4 | .24 | .06 | .02 |
| 12 | 0.94 | 12.4 | .12 | .04 | .03 |
| 12 | 0.76 | 9.8 | .14 | .04 | .04 |

**TABLE No. 8.3**

**PROTOTYPE DRILL No.3 : EXAMPLES OF DIFFERENT PERFORMANCE TEST RESULTS AT 1400 rpm x .08 mm/rev. FOR TOOLS EVALUATED.**

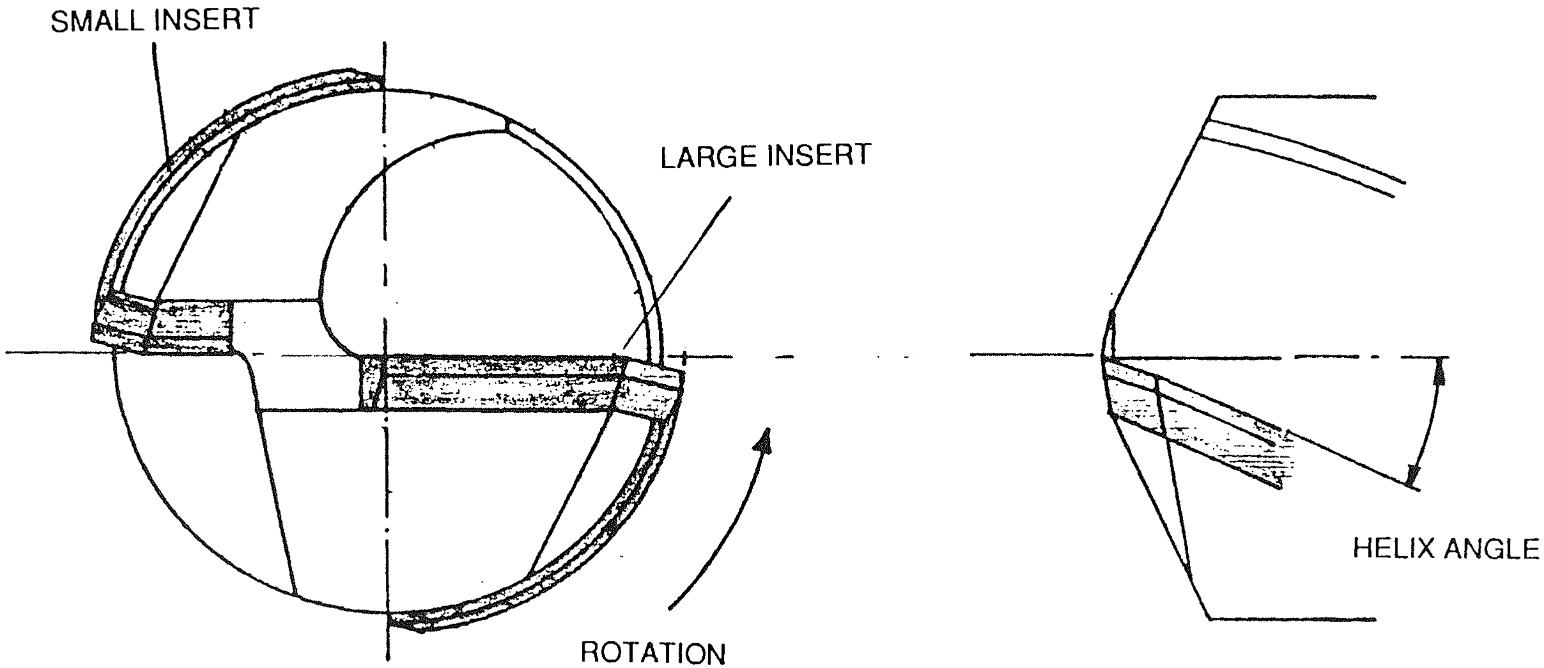



FIG 8.1 THE NEW PROTOTYPE DRILL - EARLY DESIGN SHOWING BRAZED IN HELLICALLY TWISTED TUNGSTEN CARBIDE INSERTS

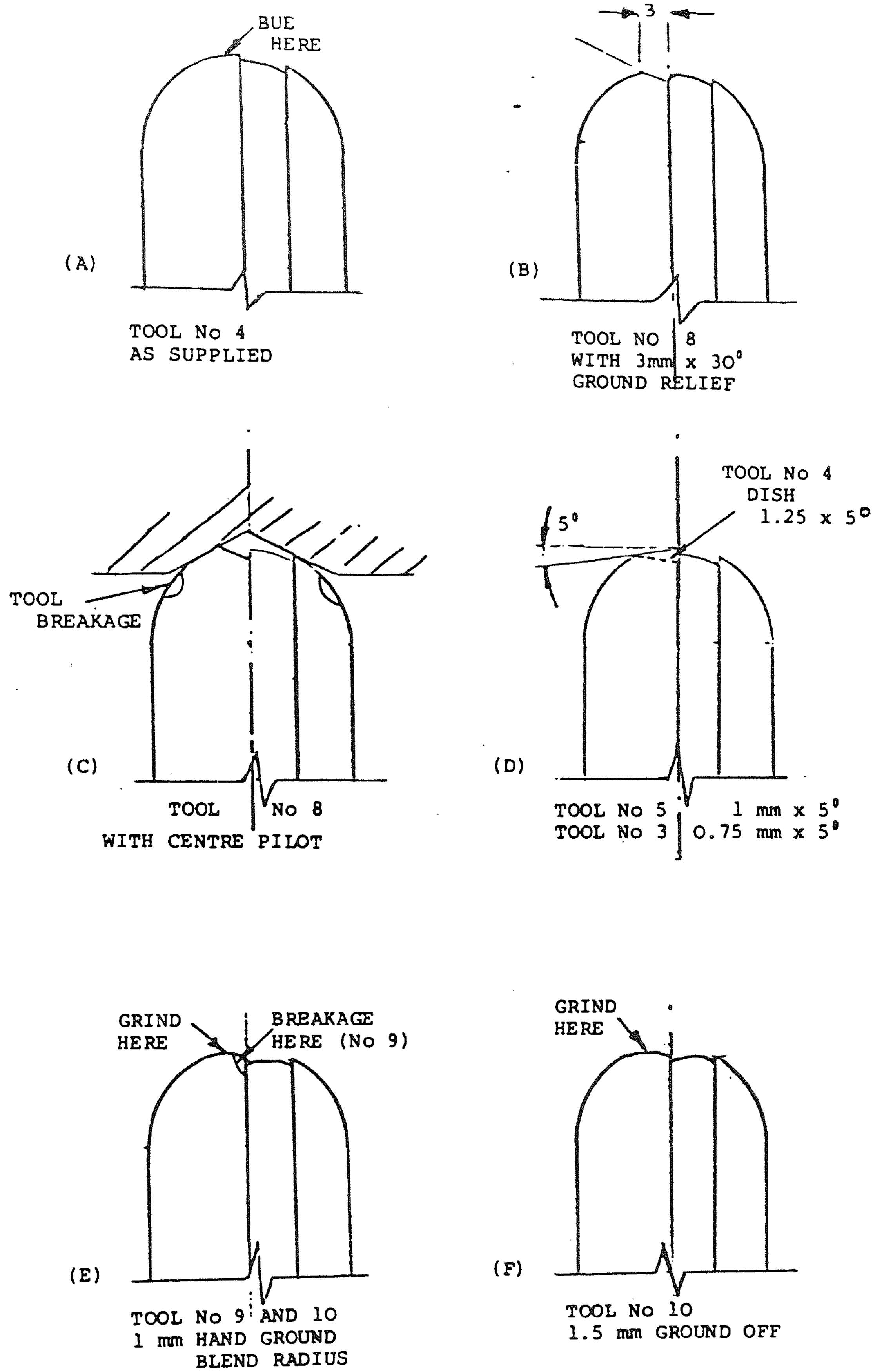



FIG 8.2 TOOL POINT GEOMETRIES -PROTOTYPE NO 2

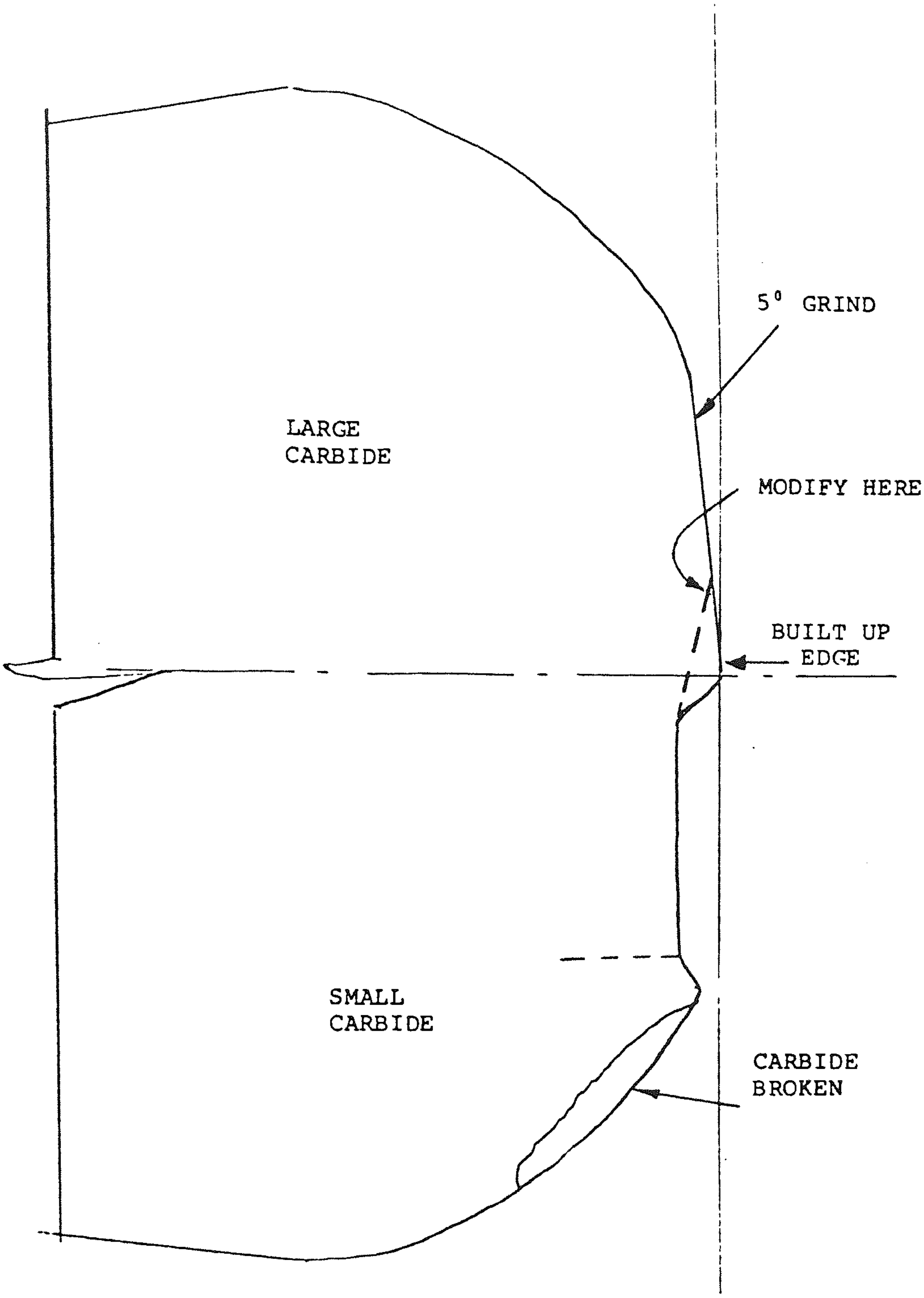



FIG 8.3 SHADOW GRAPH TRACE - PROTOTYPE NO 2
TOOL NO 5 (MAGNIFICATION - 8 TIMES)

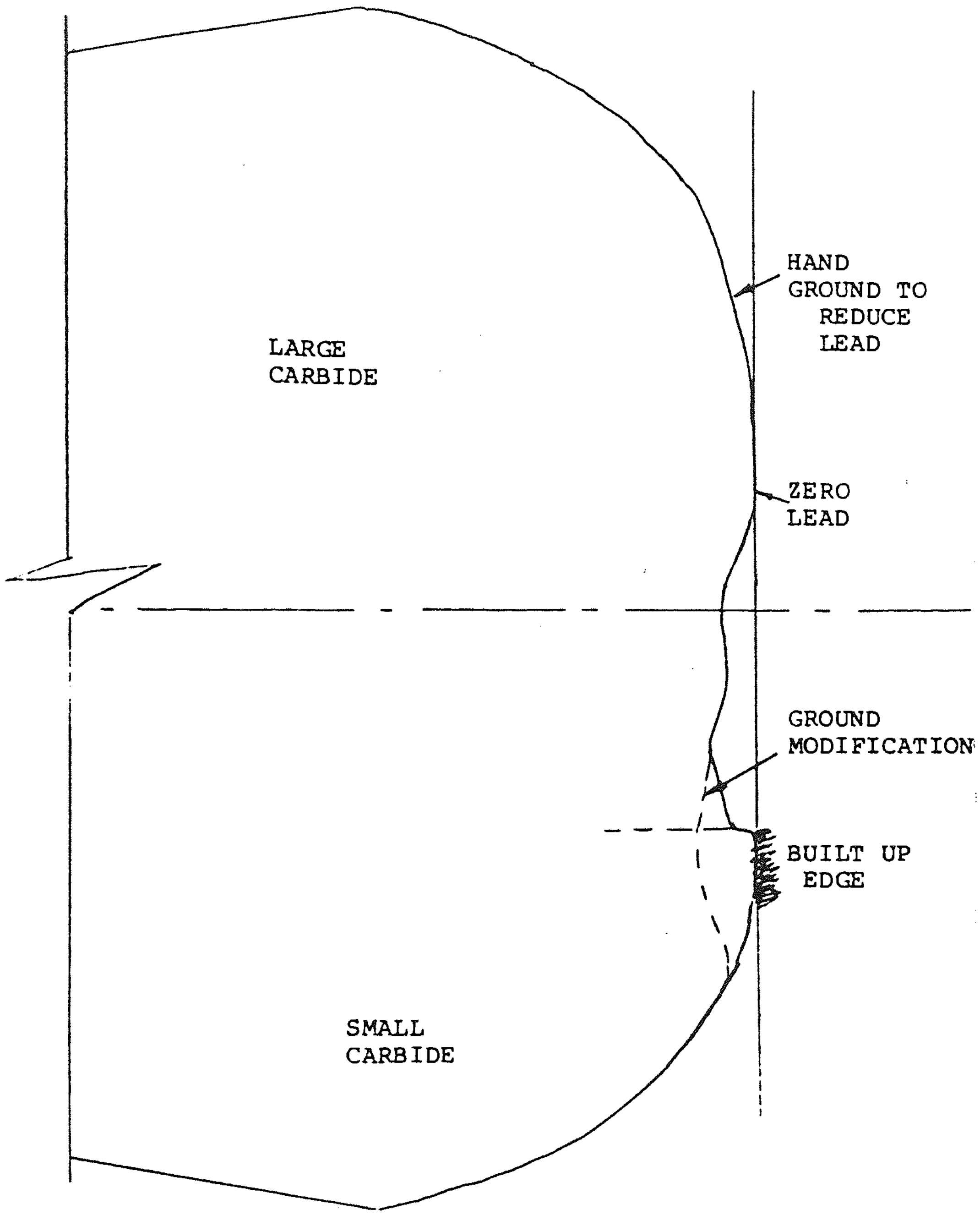



FIG 8.4 SHADOW GRAPH TRACE - PROTOTYPE NO 2
TOOL NO 10 (MAGNIFICATION 8 TIMES)

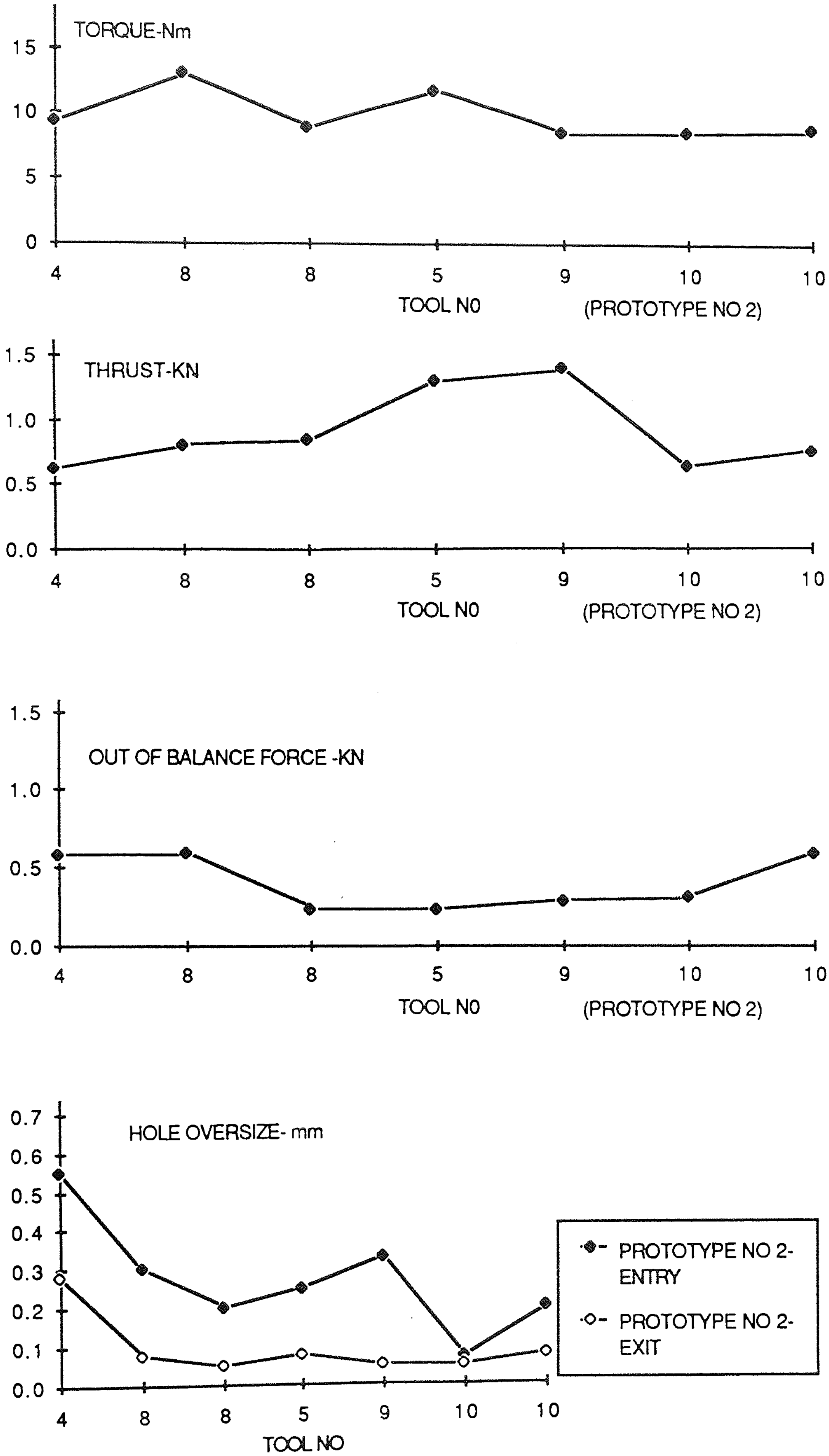



FIG 8.5 PROTYOTYPE DRILL NO 2- SUMMARY OF PERFORMANCE TEST RESULTS AT1400 rpm,0.08 mm/rev

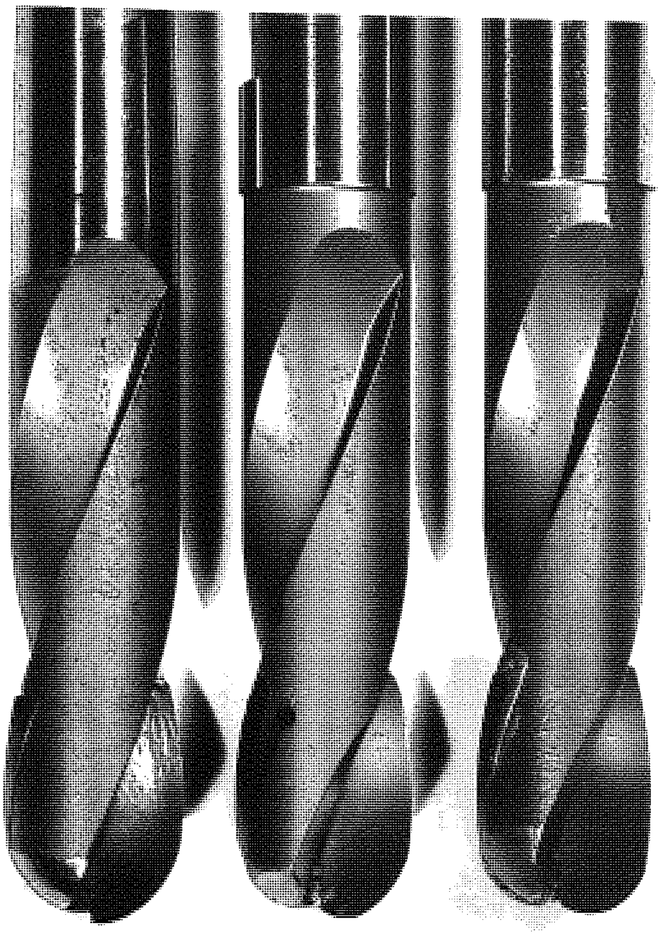
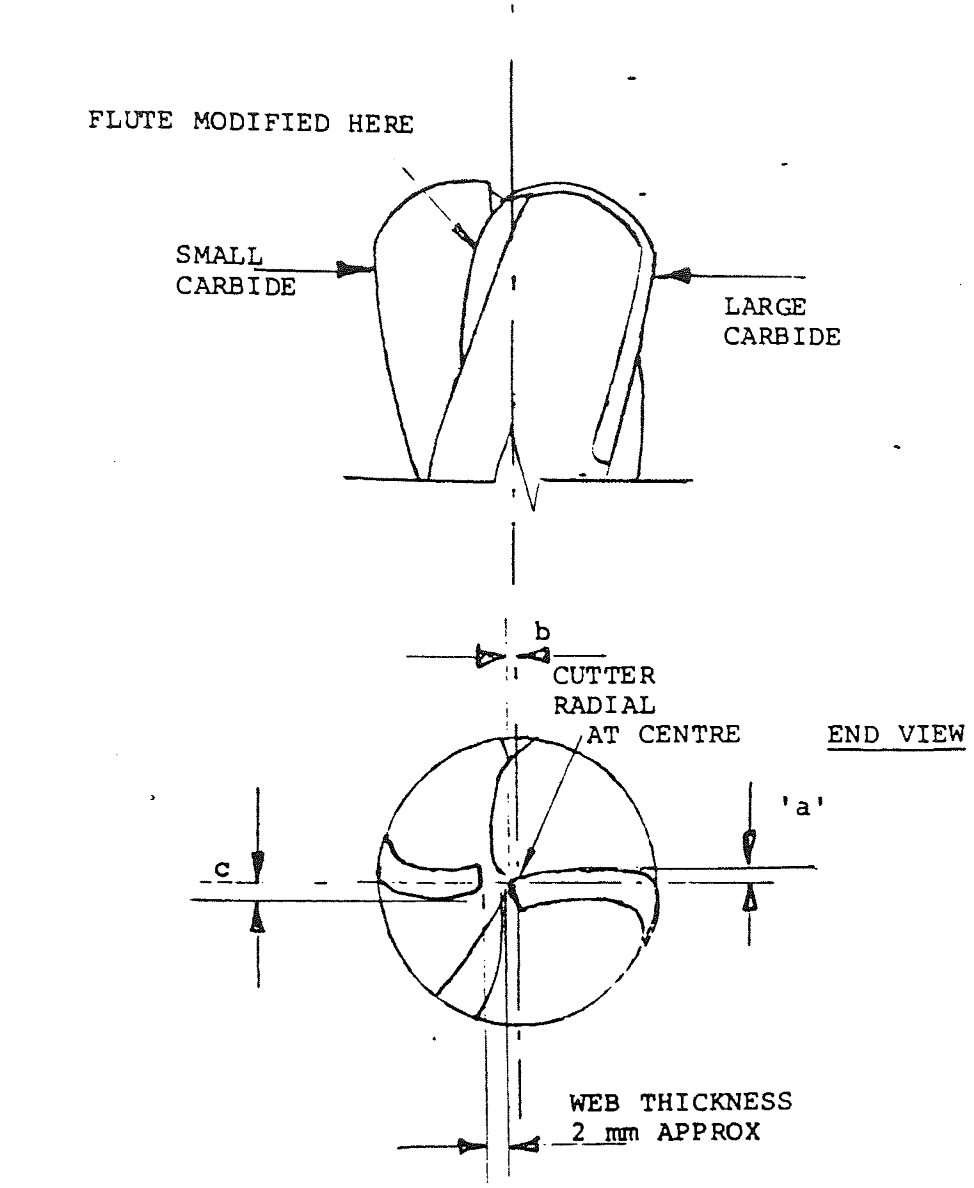


FIG 8.6 PROTOTYPE DRILLS NOS 1, 2 AND 3




| TOOL No | a (mm) | b (mm) | c (mm) |
|---|---|---|---|
| 11 | 0.5 | 1.27 | 0.38 |
| 12 | 0.4 | 1.25 | 0.35 |

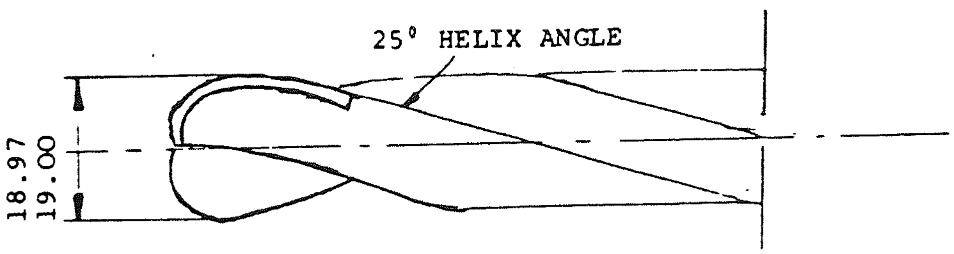



FIG 8.7 MODIFIED BALL ENDED CUTTER -PROTOTYPE DRILL N03

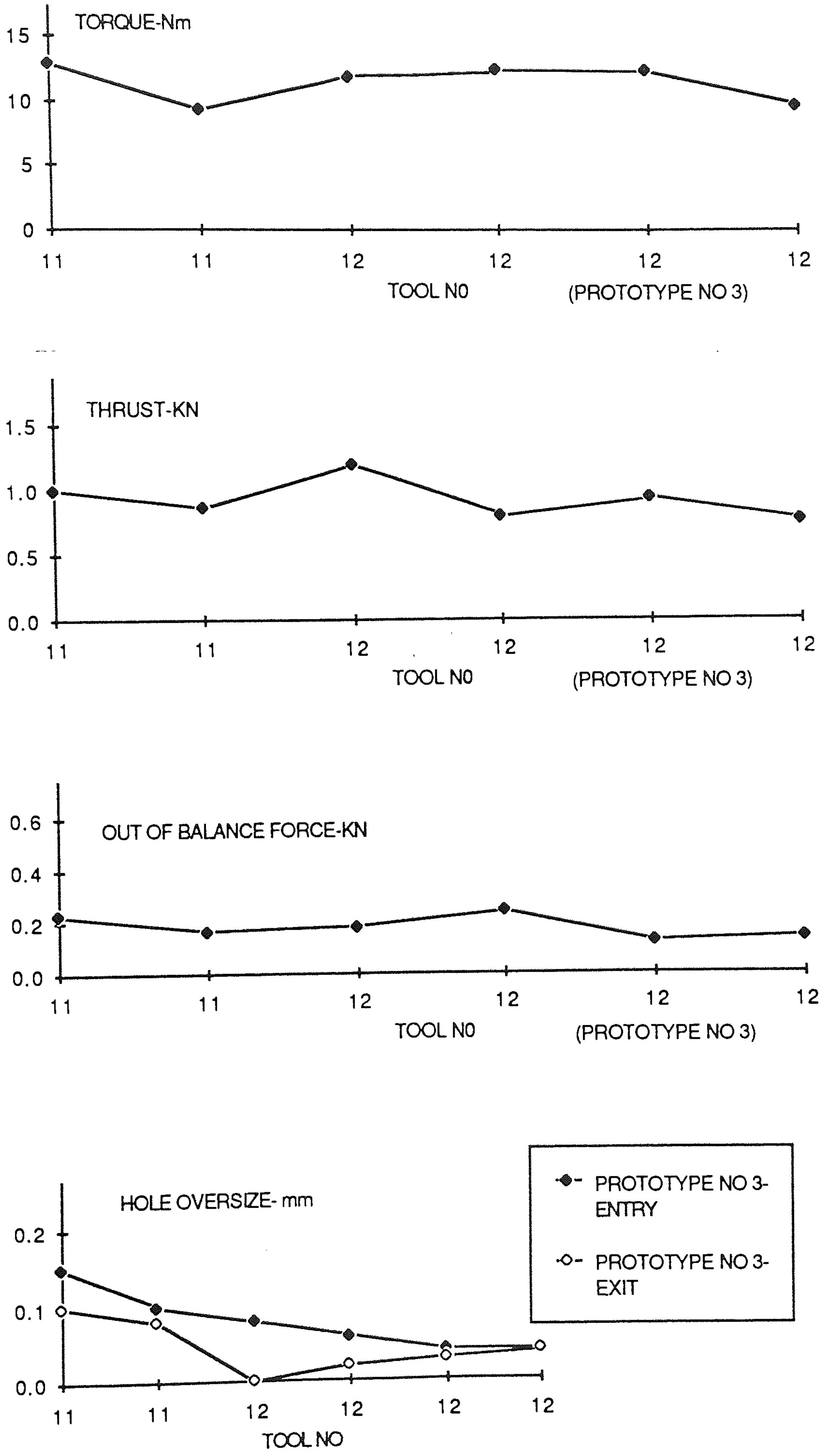



FIG 8.8 PROTYOTYPE DRILL NO 3- SUMMARY OF PERFORMANCE TEST RESULTS AT1400 rpm,0.08 mm/rev

FIG 8.9 PROTOTYPE DRILL NO 3
WITH BOTTOM OF HOLE FORM PRODUCED

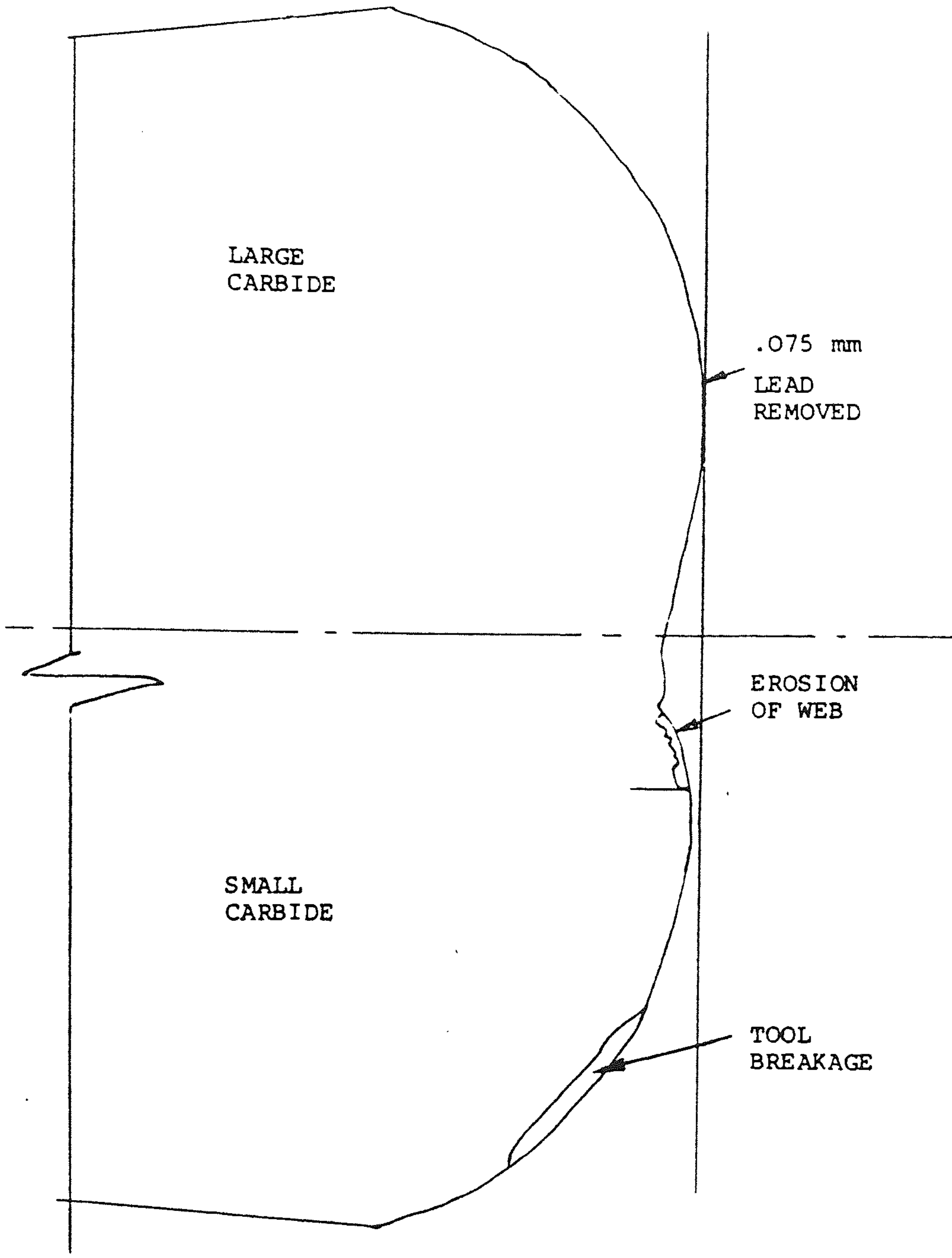



FIG 8.10 PROTOTYPE DRILL NO 3
SHADOW GRAPH TRACE -TOOL NO 11
(MAGNIFICATION 8 TIMES)

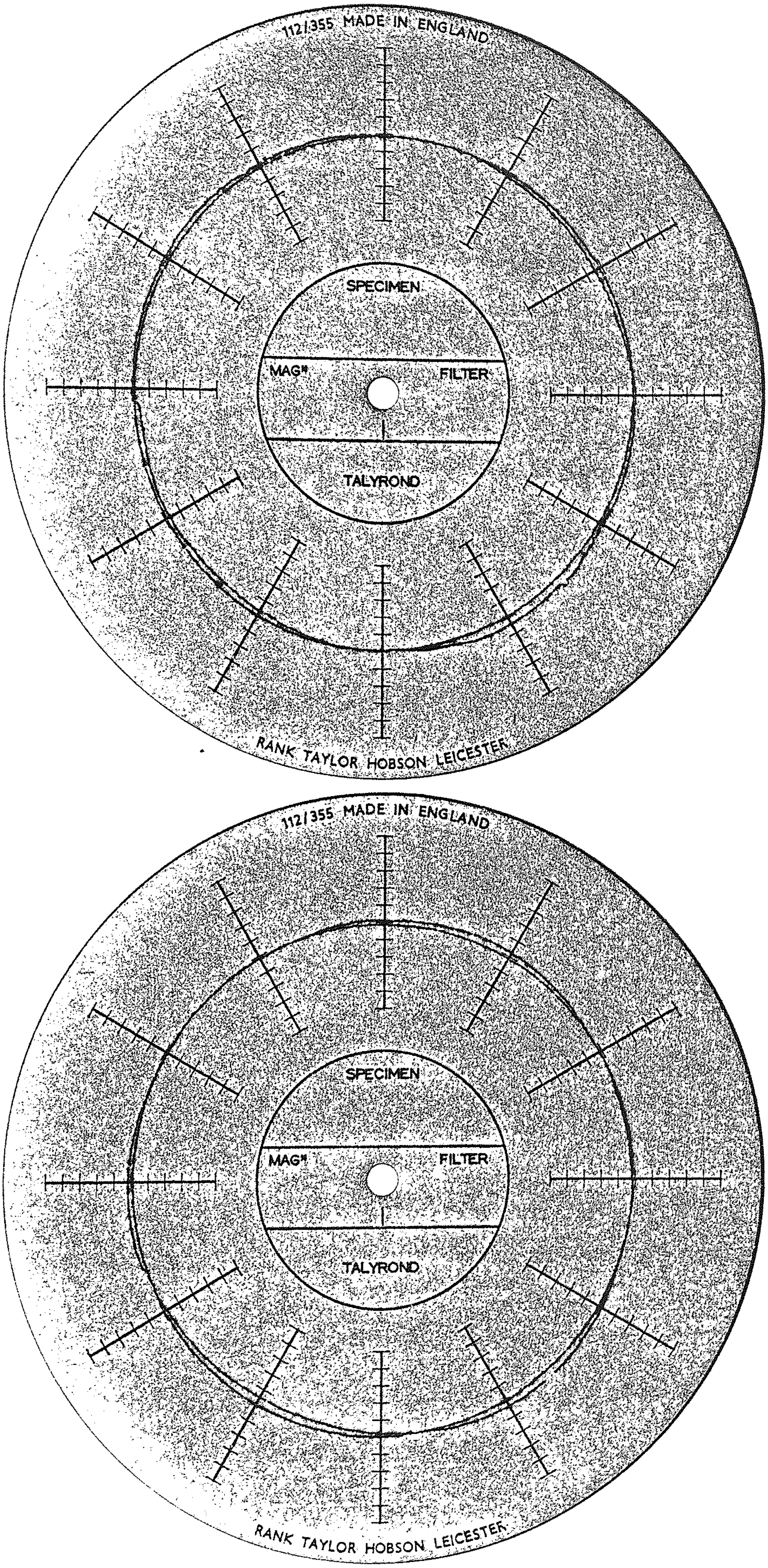



FIG 8.11 "TALYROND" TRACE - PROTOTYPE DRILL NO 3
(I DIVISION = .0127 mm)
TOP - DRILL ENTRY BOTTOM DRILL EXIT

# CHAPTER NINE

## HELICAL INSERT DRILLS WITH COOLANT FEEDING HOLES

## PROTOTYPE Nos. 4, 5 and 6.

## 9.1 INTRODUCTION

In later trials with the new Prototype drill, coolant feeding holes were incorporated into the design to assist the swarf ejection and improve hole quality. A coolant hole was drilled in each of the flutes for Prototype Nos. 4 and 5. On Prototype No. 6 the coolant holes were positioned in the flank faces of the drill. Initial trials with Prototype Nos.4, 5, and 6, were undertaken on the CNC Lathe (Appendix II) with a stationary drill. Later research with Prototype No. 6 included trials with the tool rotating, as well as stationary.

## 9.2 ADDITIONAL TEST EQUIPMENT

### 9.2.1. Coolant System

A new coolant system was installed on to lathe for use with Prototype Nos. 4 - 6. The new system consisted of a Grundfoss Type CP2-200K Multistage Centrifugal Pump and the interconnecting pipework, valves and pressure gauge. Coolant pressures of up to 16 bars, with flow rates of 14 litres were used.

An outline of the performance characteristics of the new system are given in Chapter 6. For the stationary drill the coolant was fed axially through the drill via a connection on the Dynamometer housing.

### 9.2.2. CNC Lathe Set-Up for a Rotating Drill

In order to compare the performance of the new drill, both stationary and rotating, later horizontal drilling trials included both modes of operation for Prototype No. 6.

In the rotating mode, a new tool and workpiece holding arrangement was designed so that the existing high pressure coolant system was retained, together with a rigid drilling set up. The new rotating drill tool design included:-

(i) A drill coolant feeding adaptor, which was designed for use with a Morse Taper Adaptor on a drilling machine spindle. This was gripped and accurately centred in the lathe chuck in a parallel Morse Taper Adaptor (see Fig.9.1).

(ii) A redirected coolant supply securely clamped to prevent any relative movement of the pipework where it was connected to the coolant adaptor.

(iii) A new special workpiece mounting block, fitted on to the front face of the dynamometer, which incorporated a locking screw to grip the workpiece on a specially milled flat.

(iv) A new CNC drilling program was developed so that the stationary workpiece was advanced against the rotating drill to produce a through hole in the 38 mm deep blank.

This test set up was used for the rotating drill and a force measurement trace produced for every hole drilled using the Kistler Drilling Dynamometer (Appendix III).

### 9.2.3. Tooling - Prototype Nos 4 & 5 Drill Design with Flute Coolant Holes

Several changes were made to the design of Prototype No.3 in order to enhance the performance of the new drill for Prototype Nos. 4 and 5, i.e.:-

(i) Equal flute forms for each cutting lip to improve the swarf evacuation (Fig.9.2). A 12.70 mm dia ball ended milling cutter was used to produce the new flute.

(ii) A range of 15°, 20° and 25° helix angles were tested on Prototype No.4, but a 15° helix angle was adopted on Prototype No.5 to assist in swarf breakage and strengthen the cutting edge.

(iii) The width of the carbide insert was increased on the smaller tip so that the web thickness between the cutters was reduced to about 1 mm.

(iv) Two coolant holes were drilled in the flutes near to the drill tip to assist in the chip ejection. These holes were fed from a central axial hole drilled in the drill shank. The angle of the flute holes was such that coolant could be directed onto the cutting lips.

(v) A new 'V' gash with a 90° included angle was used between the two inserts (Fig.9.3). This feature was designed to provide a self guiding pilot cone at the bottom of the hole being drilled. A tip radius of 0.4d was used on the carbide.

## 9.3 RESULTS - Prototype Nos. 4 & 5

The flute form for Prototype No.4 is shown in Fig.9.2 and a shadow graph trace of the new design is shown in Fig.9.3. The performance results of Prototype Nos. 4 & 5 with a 15° helix angle are shown in Table 9.1 and Fig.9.4.

An example of the hole roundness profile with and without the use of pressurised through fed coolant is shown in Fig.9.5.

## 9.4 DISCUSSION OF RESULTS - Prototype Nos. 4 & 5

Although 15°, 20° and 25° helix angle drills were evaluated in this series of tests, tool breakage occurred with both the 20° and 25° helix tools and these tests were discontinued. The reasons for the breakage were attributed to the prototype nature of the tools rather than the particular helix angles used.

Tests with the 15° helix angle drill stationary were undertaken with Prototype Nos. 4 & 5. The 15° helix provided a stronger cutting edge with improved swarf breaking. The performance test results are shown in Table 9.1 and Fig 9.4 for tests at 1400 rpm x 0.14-0.20 mm/rev and coolant pressures of 6.5 bar.

The use of high pressure coolant did enhance the hole quality and reduce built up edge, but the major problem in directing the coolant from holes in the flutes, was that the jets tended to block with swarf. Increases in the coolant back pressures of up to 3 bar were observed when blockage occurred in the coolant holes.

The drilled holes produced were very close to nominal size (i.e. +.075 mm max) with good roundness, Fig 9.5. The surface finishes were generally in the order of 2μm Ra, although some isolated tool marks were left in the drilled surface.

Whilst an important step towards design symmetry was made with the equal flutes, the asymmetric cutting geometry and lip height differences lead to high out of balance forces being recorded at drill entry. The swarf also tended to wrap itself around the body of the drill in the annular clearance space between the 17.5 mm body dia and the wall of the 19.05 mm dia hole.

Only very limited trials were performed with Prototype No.5

when it became apparent that swarf blockage would affect the coolant holes.

## 9.5 CONCLUSIONS - Prototype Nos. 4 & 5

1. Coolant holes in the drill flutes were generally unsuccessful because they tended to block with swarf.

2. High pressure coolant did help to improve hole quality, assist chip ejection and reduce built up edge on the drill.

3. The use of a symmetrical flute form enabled improved chip flow to be obtained.

4. The ball end profile was difficult to accurately grind in order to maintain a precision point. Large differences in lip height were likely to occur.

## 9.6 PROTOTYPE DRILL NO 6. DRILL DESIGN WITH FLANK COOLANT HOLES

A number of improvements were made in the design of Prototype No 5 to enhance the performance of the drill for Prototype No 6, they included:

(i) The use of coolant holes, one in each of the drill flank faces rather than in the flutes as previously. It was hoped that this modification would overcome the tendency of swarf to choke in the coolant holes (Fig.9.6).

(ii) The use of a new grinding fixture for producing the cutting lip radius on the drill tip. Better control of the grinding operation was achieved and the lip radius was reduced to 0.3d to reduce the overall length of the lip.

(iii) Additional flute clearance was created at the drill tip by milling off some additional body material, but maintaining the 15° helix angle in the flute.

(iv) The body diameter was increased from 17.5 to 18 mm dia to improve the torsional stiffness and reduce the tendency for swarf to wrap around the drill in the annular space between the drill and the wall of the hole.

## 9.7 RESULTS - Prototype No 6

Initial tests and trials to optimise the design of Prototype No 6 were undertaken with the drill stationary as previously. In later trials the drill was used rotating on the special lathe set up. Comparison results for Torque, Thrust and Out of Balance Force are presented in Tables Nos. 9.2 and 9.3 and Fig. 9.7.

## 9.8 DISCUSSION OF RESULTS - Prototype No 6

### 9.8.1. Drill Stationary

Two major difficulties were encountered when drilling with Prototype No 6,

(i) There was a large difference in lip height and high out of balance force of up to 600N.

(ii) Swarf choking occurred, which was observed as a steady increase in cutting forces as the hole was drilled.

Regrinding was undertaken to reduce the lip height error. To eliminate the choking problem, the web thickness at drill tip was reduced from 7.5 mm to 5 mm. The effect of reducing the web thickness was to create more swarf clearance and also reduce the friction in the flutes by the hand polishing technique adopted.

Consistent cutting conditions were achieved at 1500 rpm at feed rates of up to 0.3 mm/rev but the hole quality was generally poor.

High out of balance forces, typically over 400N were recorded at drill entry but this reduced to about 100N once the drill had penetrated to the depth of the ball end radius (i.e. 0.3d). (see Trace Fig.9.8).

### 9.8.2 Drill Rotating

With the drill rotating there was increased noise and vibration generated, particularly at drill entry. This could be overcome by programming a fine feed at drill entry and then increasing the feed rate once the tool had begun to cut.

The torque and thrust measured for the rotating drill were both higher than when the drill was stationary and the workpiece rotating. Typical increases were about 10% on Torque and up to 25% on Thrust force. (see Fig.9.7). The differences were probably due to loss of coolant pressure from the inducer housing and centrifugal effects in the inducer.

There were also differences in chip formation which resulted in a greater tendency for swarf clogging to occur particularly in the centre 'V' of the rotating tool.

A completely different trend in the radial out of balance force was recorded for the rotating drill. The magnitude of the out of balance was much lower than for the stationary drill.

The rotating drill out of balance increased with feed rate to a maximum of 50N at 1500 rpm 0.3 mm/rev and it was cyclic in nature.

Improved hole tolerances of .038 mm were achieved with the rotating drill but the higher out of balance on the stationary drill led to oversizes of up to 0.17 mmn.

In both cases the hole surface finish was generally poor with some deep tool marks remaining in the surface. The poor finish was attributed to the ineffectiveness of the radial land on the carbide. The use of back taper on the land prevented any effective burnishing action on the drilled surface.

An advantage of the ball ended Prototype drill design was that entirely "burr free" holes were produced. Previous research [77][78] has shown that the formation and control of drilling burrs depends upon many factors including the hardness of the material, the drill feed rate and the drill geometry.

In initial trials with Prototype Drill Nos. 2 & 3 (Chapter 8), feed rates of up to 0.13 mm/rev were used without burr formation.

In Prototype No.6 the feed rate was increased to 0.3 mm/rev without any significant burr being produced at drill exit from the workpiece. The absence of burr was attributed to the corner radius of the drill which provided greater surface area of support around the cutting edge. This enabled the drill to remain cutting at "break through", rather than form a burr by a shearing action on the last part of the cut around the hole circumference.

## 9.9 CONCLUSIONS - Prototype No 6

The variability in drill performance and particularly out of balance force were attributed to the asymmetric nature of the cutting lips, i.e.

(i) Potential differences in both radial and axial rake angles. These varied according to the accuracy of producing the milled cutter pocket or the difference in braze thickness for each insert.

(ii) Difficulty in setting up the cutters each exactly radially on the centre line.

(iii) Grinding accuracy was very critical to drill performance, particularly lip height errors.

(iv) Aspects of tool design particularly the centre 'V'( may have contributed to swarf choking and imbalance.

(v) Since the imbalance occurred on initial contact with the workpiece, this corresponded to two segments on each of the radiussed tips which took the first part of the cut. The symmetry and the radial position of these segments was therefore critical for balance.

(vi) The ball end profile produced completely "burr free" holes. This was a distinct advantage over a more conventional drill geometry which may result in a carry over burr on break through.

| FEED RATE (mm/rev) | TORQUE (Nm) | THRUST (kN) | OUT OF BALANCE FORCE (N) | |
|---|---|---|---|---|
| | | | DRILL ENTRY | STEADY STATE |
| .14 | 15.0 | 1.32 | 630 | 160 |
| .16 | 17.5 | 1.55 | 630 | 190 |
| .18 | 19.5 | 1.70 | 730 | 200 |
| .20 | 24.0 | 1.75 | 760 | 200 |

**TABLE No. 9.1**

PROTOTYPE DRILLS Nos. 4/5 : PERFORMANCE TEST RESULTS AT 1400 rpm WITH 15° HELIX ANGLE. (Horizontal Drilling with a Stationary Drill)

| FEED RATE (mm/rev) | TORQUE (Nm) | THRUST (KN) | OUT OF BALANCE FORCE (N) | |
|---|---|---|---|---|
| | | | DRILL ENTRY | STEADY STATE |
| 0.1 | 12 | 0.85 | 360 | 60 |
| 0.2 | 22 | 1.75 | 520 | 50 |
| 0.3 | 33 | 2.75 | 560 | 50 |

**TABLE No. 9.2**

PROTOTYPE No. 6.
DRILL PERFORMANCE TEST RESULTS : DRILL STATIONARY

| FEED RATE (mm/rev) | TORQUE (Nm) | THRUST (KN) | OUT OF BALANCE MAXIMUM (N) |
|---|---|---|---|
| 0.1 | 13 | 1.25 | 0 |
| 0.2 | 25 | 2.25 | 90 |
| 0.3 | 35 | 2.90 | 150 |

**TABLE No. 9.3**

PROTOTYPE No. 6.
DRILL PERFORMANCE TEST RESULTS : DRILL ROTATING

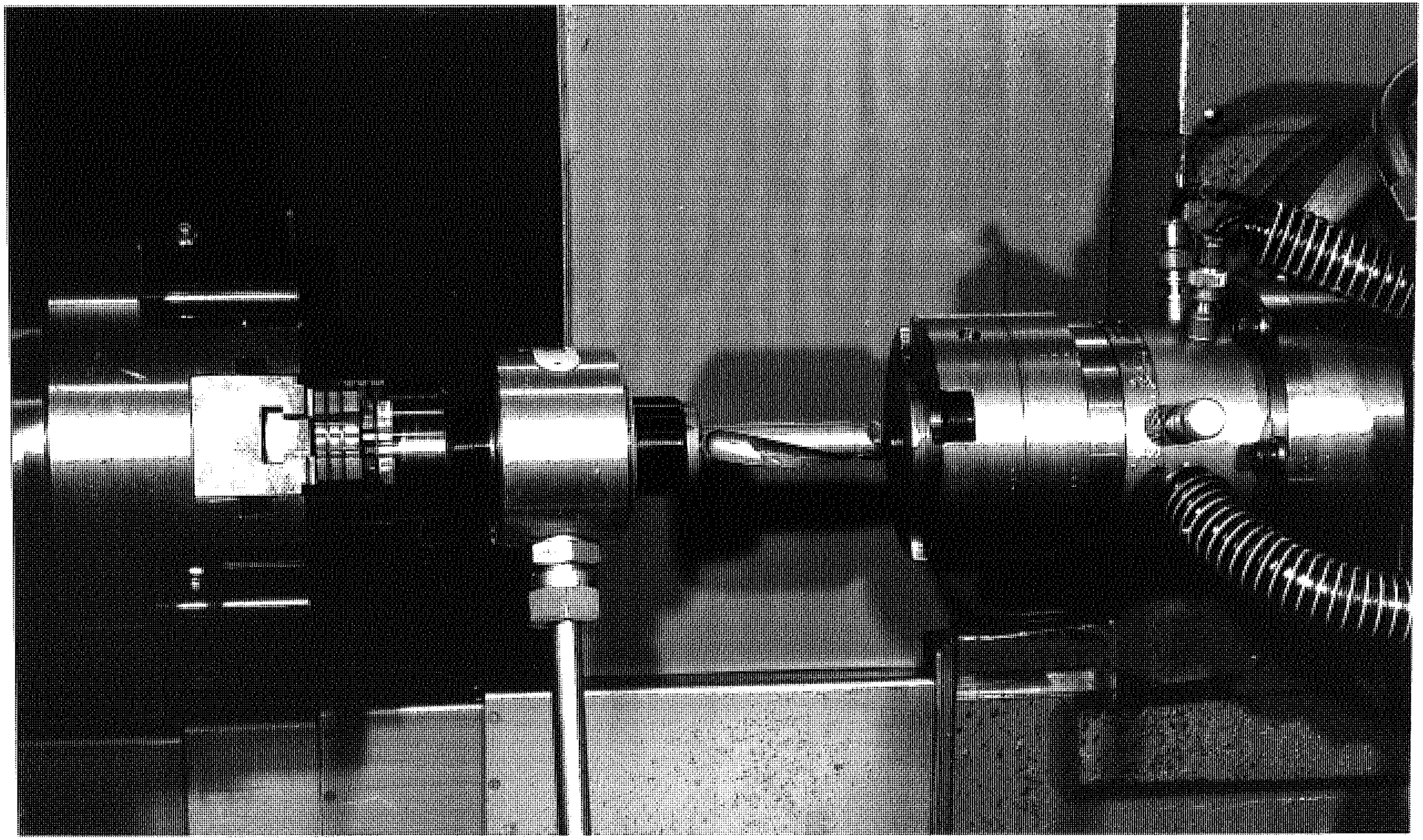


FIG 9.1 CNC LATHE - SPECIAL TEST SET UP DESIGNED FOR TESTING ROTATING CARBIDE TIPPED DRILLS

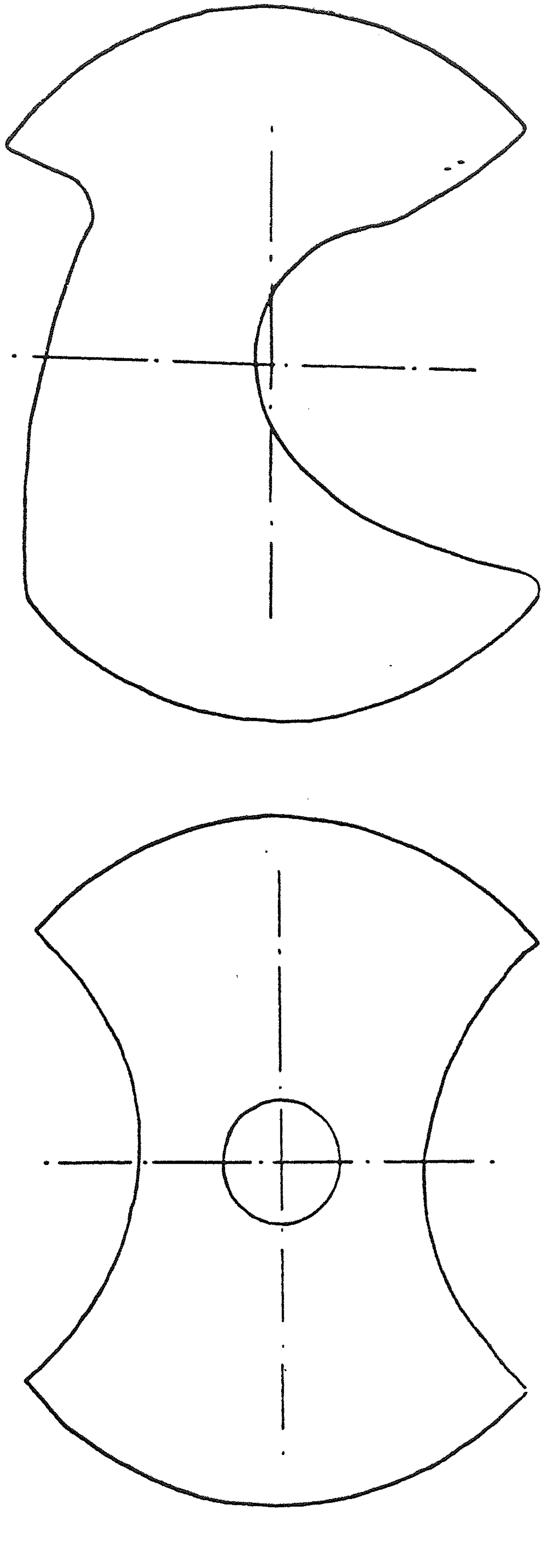


FIG 9.2 19.05 mm DIA CARBIDE TIPPED HELICAL INSERT DRILL FLUTE CROSS SECTIONS (5 TIMES MAGNIFICATION)

TOP : PROTOTYPE NOS 1-3
BOTTOM : PROTOTYPE NO 4 (WITH COOLANT HOLE)

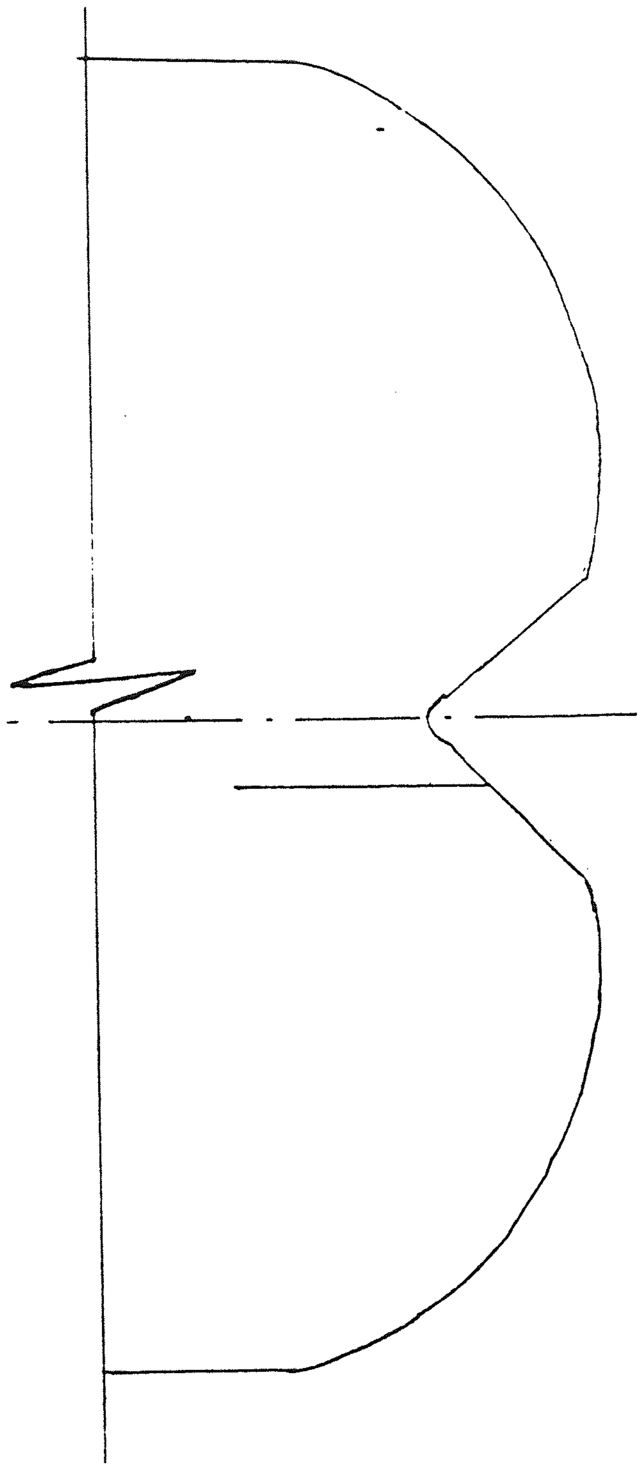


FIG 9.3 PROTOTYPE DRILL NO 4 - SHADOW GRAPH TRACE- NEW DESIGN SHOWING 90 INCLUDED ANGLE AT DRILL CENTRE TO GENERATE A SELF GUIDING PILOT CONE AT THE BOTTOM OF THE HOLE
( MAGNIFICATION 8 TIMES )

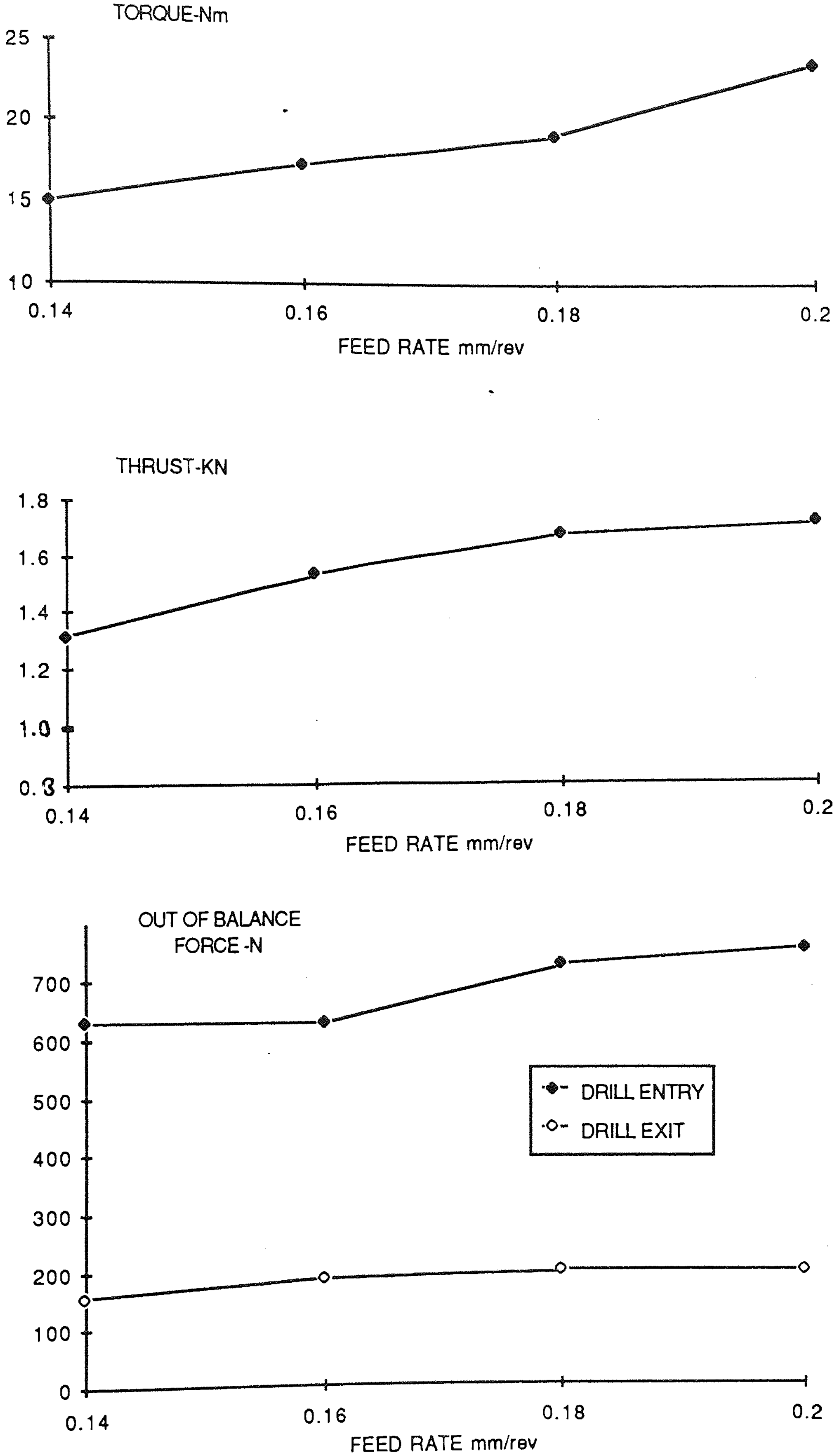
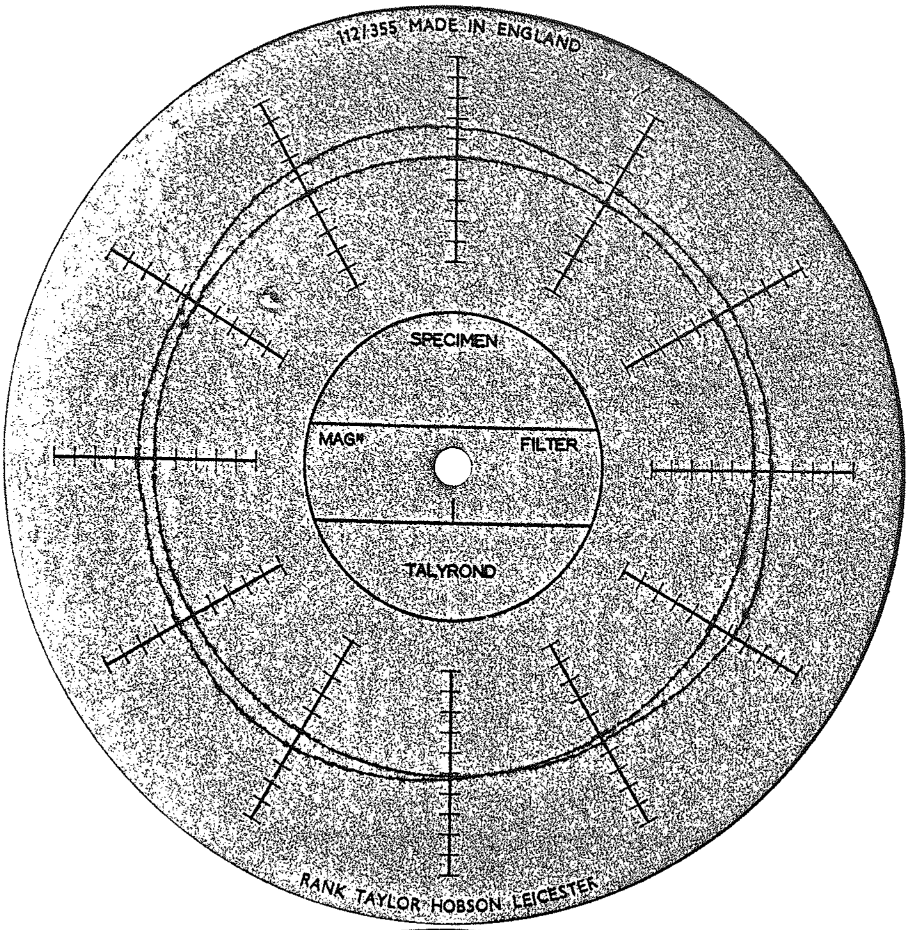



FIG 9.4 PROTOTYPE NO 4 (15° HELIX) WITH FLUTE COOLANT HOLES
THE EFFECT OF FEED RATE ON TORQUE (Nm), THRUST AND OUT OF BALANCE FORCE AT 6.5 bar COOLANT PRESSURE AND 1400 rpm



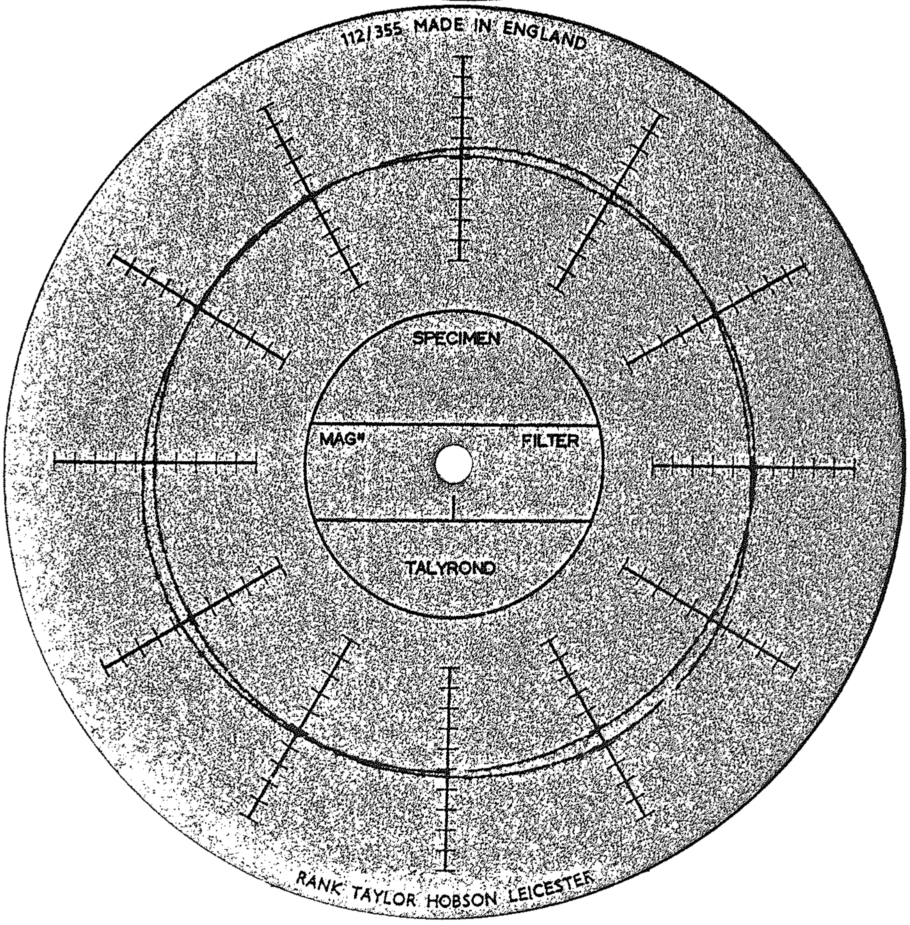
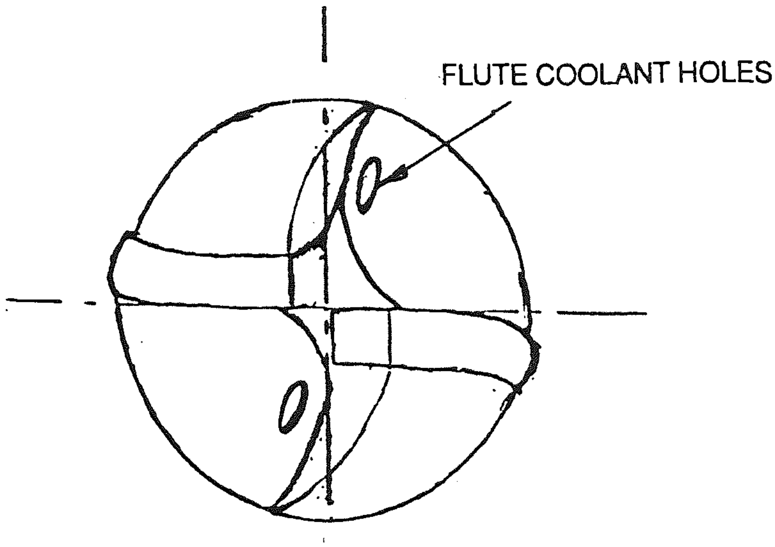



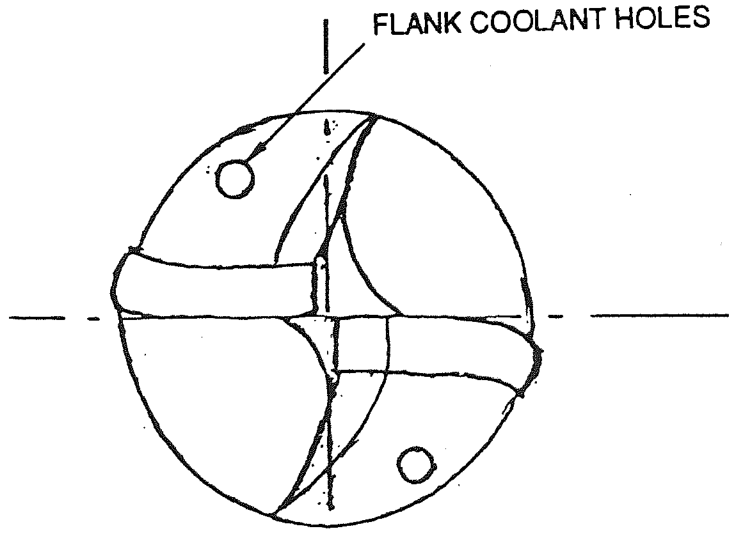

FIG 9.5 PROTOTYPE NO 4 -HOLE ROUNDNESS COMPARISON FOR CONSEQUTIVE HOLES(1400 rpm ,0.14 mm/rev)

TOP : EXTERNAL SUPPLY OF COOLANT ONLY
BOTTOM : PRESSURISED COOLANT 6.5 bar

(SCALE 1 DIVISION =0.0127 mm)




PROTOYPE DRILL NO 4




PROTOTYPE DRILL NO 6

FIG 9.6 CARBIDE TIPPED PROTOYPE COOLANT FED DRILLS
DIFFERENT METHODS OF COOLANT APPLICATION

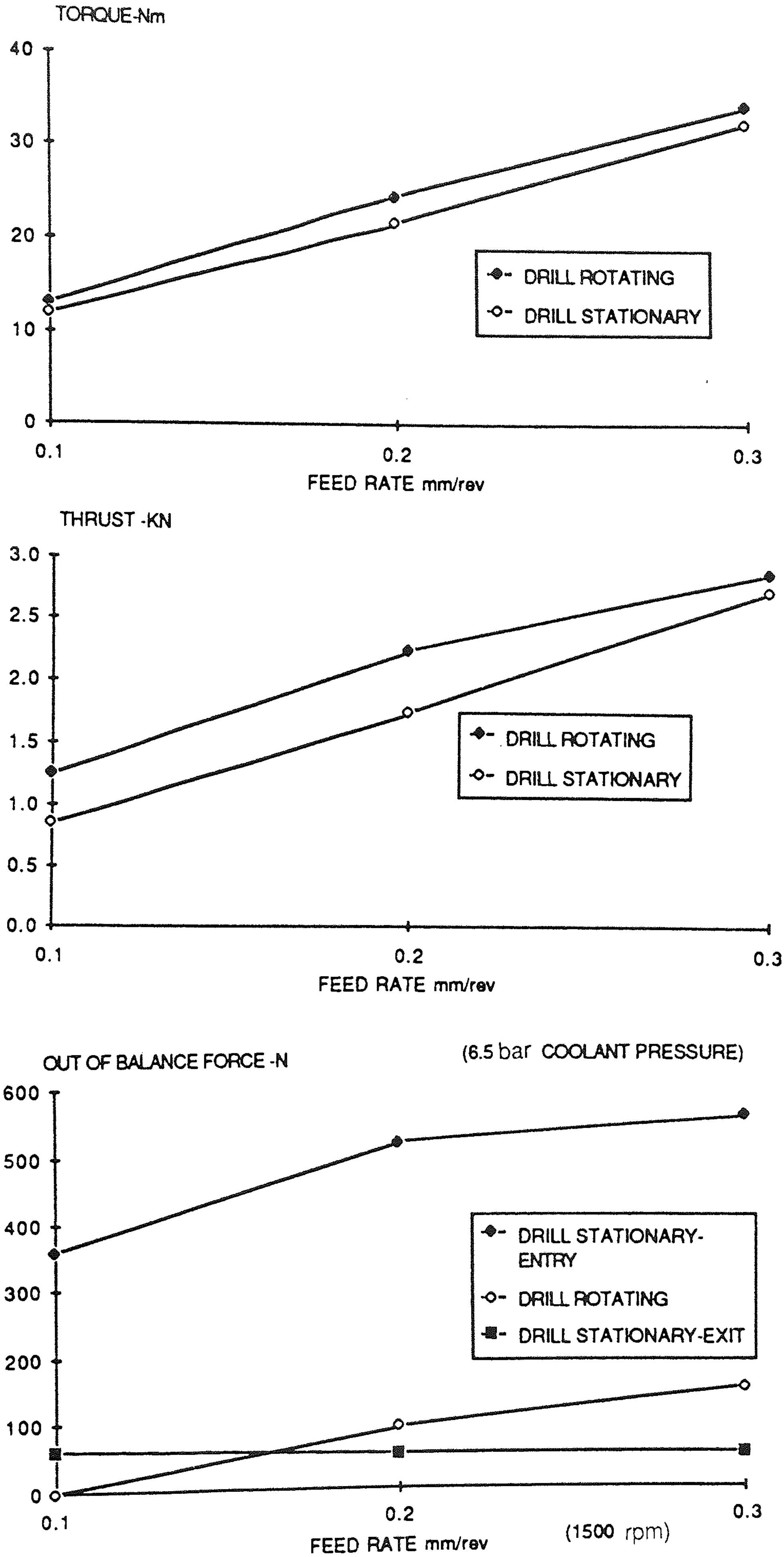



FIG 9.7 PROTOTYPE NO 6 -COMPARISON OF TORQUE (Nm), THRUST (KN) AND OUT OF BALANCE FORCE (N) FOR DRILL ROTATING AND STATIONARY

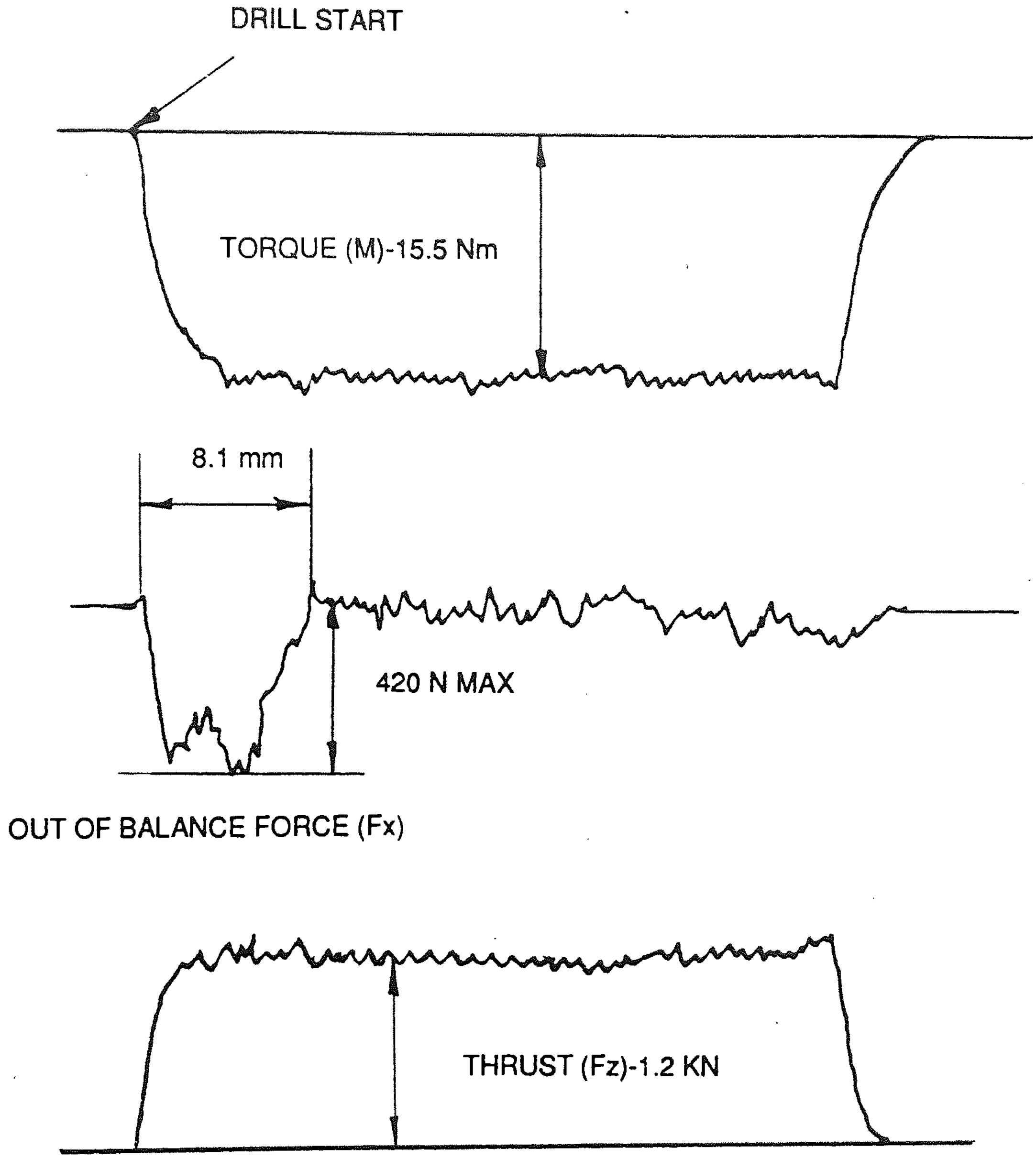



FIG 9.8 PROTOTYPE DRILL NO 6 - EXAMPLE OF U V TRACE
STATIONARY TOOL DRILLING AT1400 rpm ,0.14 mm/rev WITH
6.5 bar COOLANT PRESSURE
(NOTE HIGH OUT OF BALANCE FORCE AT DRILL ENTRY)

# CHAPTER TEN

## THE PERFORMANCE OF SANDVIK AND MITSUBISHI CARBIDE TIPPED DRILLS COMPARED WITH THE NEW PROTOTYPE DRILL No. 6.

### 10.1 INTRODUCTION

During the research with the new Prototype Drill it was considered important to identify carbide tipped and other types of drill that were either being developed or already commercially available [79]. These drills were to be suitable for drilling into steel. Two brazed insert drills from Sandvik and Mitsubishi were obtained. The testing and evaluation of these was intended to provide useful comparison data for the new Prototype Drill. It was also felt that an understanding of alternative approaches to drilling with carbide would serve as a catalyst for the research.

Recent research has involved the development of Polycrystalline Diamond tipped twist drills [80] as well as solid carbide twist drills [81] for drilling steel. Other work has included the use of end mills with carbide spiral cutting edges [82][83].

One successful development has been the Hosoi drill from Japan, which is manufactured under licence by Sandvik as the Delta Drill,[84],[85],[86],[87]. The Delta drill is a two flute twist drill with two brazed, above centre, carbide inserts. The chisel edge is ground to form an 'S' point and the hole quality and the drill performance is enhanced by through coolant holes and titanium nitride coating.

The Mitsubishi Drill is similar but instead of the 'S' point the chisel edge does not extend through the centre of the drill. Each carbide insert is ground so that a small central "trepanned" core is left. This core is subsequently sheared off in the drill flute.

Geometrical features of the Sandvik and Mitsubishi drills compared to Prototype No.6 are given in Table 10.1. End views of the three drills are shown in Fig.10.1. The type of blind hole form produced is shown in Figs.10.2 and 10.3.

## 10.2 COMPARISON OF DRILL FLUTE FORMS, FLUTE AND BODY CROSS SECTIONAL AREA, AND TORSIONAL STIFFNESS OF THE PROTOTYPE DRILL WITH SANDVIK, MITSUBISHI AND H.S.S. DRILLS.

In order to optimise the performance of the new Prototype Drill detailed design calculations were undertaken. These calculations enabled the flute cross sectional area, polar second moment of area and relative torsional stiffness to be found for Prototype Nos.1-6, (see Appendix IX). The comparison figures were also obtained for a conventional H.S.S. drill, the Sandvik Delta Drill and the Mitsubishi Drill (see Table 10.2).

On the early Prototype Nos 1-3, the flute area occupied nearly 40% of the body cross section, but 30% of the area was used for only one flute, (see Fig.9.2, Chapter 9).

The equal flute form, which was adopted on Prototype No.4 resulted in the flute area occupying only 30% of the total cross sectional area of the drill body. Extra torsional strength was obtained, and the torsional stiffness of Prototype No.4 was 35% greater than that for Prototype Nos. 1-3.

A similar equal flute form to that used on Prototype No 4 was retained on Prototype Nos 5 and 6 and the drill body diameter was increased to 18.8 mm to provide the minimum clearance, increase the torsional stiffness by a further 20% and reduce the tendency of swarf clogging around the body of the drill. The overall flute area was 32.5% of the total body cross sectional area, for Prototypes 5 and 6 (Fig.10.4).

On a conventional 19.05 mm diameter H.S.S. twist drill the flute area was about 50% of the total cross sectional area at the drill tip. The additional flute length used on the H.S.S. drill also significantly reduced the torsional strength and the torsional stiffness/unit length of the H.S.S. twist drill was only about one third of that for the carbide tipped drills. (Table 10.2).

The effect of helix angle was ignored in this analysis. In general the helical flute serves to increase the torsional stiffness compared to a straight flute configuration. Although the cutting lip torque effectively tries to unwind the drill helix, high helix angles may enable the torsional stiffness to be increased by up to 85% [88][89].

On both the Sandvik and Mitsubishi Drills the flute area at the tip accounted for about 35% of the total body cross sectional area, Fig.10.5. The torsional stiffness of the Mitsubishi Drill was similar to that calculated for the Sandvik Drill.

## 10.3 COMPARISON TRIALS - CNC LATHE TEST SET UP (APPENDIX II)

The CNC Lathe Testing Set-Up was used to evaluate both the Sandvik and Mitsubishi Drills and the results were compared with those previously obtained for Prototype No 6.

Tests were undertaken with the drill both stationary and rotating at feed rates of 0.1-0.4 mm/rev at 1500 rpm (90 m/min) at 6.5 bar coolant pressure.

## 10.4 RESULTS

The results are presented in Table 10.3 and comparison plots for torque, thrust, hole size and hole surface finish in Figs.10.6 to 10.9.

## 10.5 DISCUSSION OF RESULTS

### 10.5.1 Torque Comparison (Fig.10.6.)

For the drill stationary and rotating workpiece the Sandvik

Drill required the greatest torque, particularly at low feed rates. A possible reason for this was the presence of a chisel edge which might account for the additional 10% extra torque, together with the heavy burnishing action of the radial land. Both the Prototype and Mitsubishi Drills did not have a chisel edge and this combined with largely ineffective burnishing lead to a reduction in torque at low feed rates.

Similar results were obtained for the rotating drills except that the Prototype drill required the highest torque with increasing feed rate. This was probably due to problems of swarf evacuation in the centre of the drill.

10.5.2 Thrust Comparison (Fig.10.7.)

Both the Sandvik and Mitsubishi Drills required high thrust force across the range of feeds for the drill stationary. This was probably due to the large point angles (130°). The presence of the chisel edge in the case of the Sandvik tool, however, did not significantly increase the thrust compared with Mitsubishi, where 0.48 mm diameter of material remained uncut at the centre of the hole. This centre "pip" was subsequently sheared off against the body of the drill as it moved up the flute.

The Prototype Drill in comparison required about 50% less thrust force. This was attributed to the radiused end form and radial cutting lips.

This reduction in thrust was repeated with the drill rotating for Prototype No 6 although the tool was limited to a maximum feed rate of 0.3 mm/rev by vibration constraints.

10.5.3 Maximum Hole Oversize Comparison (Fig.10.8.)

Comparison of the hole oversize produced by the three types of drill confirmed that the Sandvik tool produced good quality holes that were within .05 mm of nominal size. The Prototype drill gave encouraging results, particularly when rotating. With the Mitsubishi Drill hole oversizes of up to 0.3 mm were measured when the feed rate was increased to 0.4 mm/rev. This oversize occurred at entry and was probably due to the point geometry configuration rather than any errors in the lip height or grinding.

10.5.4 Hole Surface Finish Comparison (Fig.10.9.)

When comparing the surface finishes obtained by the three types of drill it was observed that the Sandvik drill gave very good results with the finishes generally better than 1 μm Ra. The only exception occurred at 0.1 mm/rev with the drill rotating when a very rough finish was obtained.

The Mitsubishi drill did not produce a very good finish either stationary or rotating. This was probably due to the back taper on the radial land of the drill and insufficient burnishing action.

The Prototype drill hole finish was quite good (1 - 2.5 μm Ra) at low feeds (0.1 mm/rev) but rapidly deteriorated as the feed rate was increased. This again was attributed to an ineffective radial land and also potential swarf clogging.

## 10.6 THE USE OF CARBIDE TIPPED DRILLS ON THE RADIAL ARM DRILLING MACHINE

In order to assess the performance of the three types of carbide tipped drill on conventional machine tools, a limited series of tests were made on the Asquith Radial Arm Drilling Machine.

The machine was equipped with the Grundfoss pump and cooling system transferred from the Torshalla CNC Lathe.

The same Morse Taper Coolant Inducer was used for locating the drill on the spindle of the machine.

The workpiece was located in a housing bolted to the Dynamometer which in turn was fixed to the bed of the machine.

Test conditions were restricted by the speeds and feeds available on the machine. It was not possible to run at speeds exceeding 1130 rpm or feeds below 0.2 mm/rev on the radial arm machine without undertaking gearbox modifications.

Trials at 6.5 bar coolant pressure were therefore limited to 1130 rpm, x .20, .30 and .43 mm/rev feed rates.

### 10.6.1 Discussion of Results

Both the Sandvik and Mitsubishi Drills were used on the Radial Arm Drilling machine and the torque and thrust results were similar to those obtained on the lathe with the drill rotating.

The holes produced, however, were more oversize at entry than those produced in the more rigid CNC Lathe set up, the magnitude was 0.5 mm for Sandvik at .42 mm/rev and 0.6 mm for Mitsubishi over the first 6 mm of hole depth (feed rate 0.42 mm/rev).

With Prototype Drill No 6, severe vibration occurred at 0.2 mm/rev and although some holes were produced at 0.3 mm/rev the test was terminated for fear of breaking the drill.

The geometry and out of balance of the tool at drill entry set up the "chatter" which continued throughout the hole depth.

Whilst the Prototype drill was clearly not a fully "optimised" design the Radial Arm Drilling Machine was generally unsuitable for high metal removal rate precision hole drilling. This was demonstrated by the hole oversize which was attributed to the "float" in the spindle bearings combined with a large unsupported length of spindle. Any cantilever deflection of the radial arm was minimised by using the drilling head close to the machine support column.

The deflection of the Radial Arm Drilling Machine under high thrust forces and the effects on hole quality when drilling with H.S.S twist drills has been investigated by previous researchers [90],[91],[92]. A more rigid portal frame type set up would have been more beneficial in this case.

To overcome the bell mouthing effect and drill vibration a drilling guide bush was subsequently used for all the drills. The bush was machined to the nominal diameter of the drill and it was then clamped above the workpiece on the centre line of the drill. In this way precision holes were produced for all three drills across the range of feeds.

## 10.7 CONCLUSIONS

From the comparison tests undertaken with the three carbide tipped drills the following conclusions were drawn.

(i) The performance of the new Prototype Drill No 6 did not match that of the Sandvik Delta Drill in respect of hole quality.

(ii) Each of three drills tested had operating limitations which were exposed by the tests. Optimum performance was clearly dependent on the speed and feed rate selected.

(iii) The use of carbide tipped drills on the conventional Radial Arm Drilling Machine was not recommended without the support of drilling guide bushes. Guide Bushes help to minimise the deflection of the drill point and hence improve hole quality.

(iv) The different torque and thrust characteristics of the carbide tipped drills that were highlighted from the tests were attributed differences in tool geometry.

(v) Individual performance differences in the same drill when compared in the stationary and rotating mode were probably due to differences in the swarf flow and effects of coolant pressure loss.

(vi) Further optimisation of the drill point geometry on drill Prototype No 6 was needed to eliminate the radial out of balance forces and improve the hole quality.

(vii) The flute area and torsional stiffness of the Prototype No 6 was comparable with those calculated for the Sandvik and Mitsubishi Drills.

| DRILL TYPE | DRILL DIAMETER (mm) | POINT ANGLE | HELIX ANGLE | CLEARANCE ANGLE | CHISEL EDGE ANGLE | WEB THICKNESS (mm) | BODY DIAMETER (mm) | HEIGHT OF CUTTING LIP ABOVE CENTRE LINE (mm) | DIFFERENCE IN LIP HEIGHT |
|---|---|---|---|---|---|---|---|---|---|
| Prototype 6 | 19.05 | Ball end | 14 | 11 | none | 4.7-7.6 | 18.8 | 0 | - |
| Sandvik Delta Drill | 19.25 | 188 | 18 | 10 | 110 | 7.4 (Parallel Web) | 18.8 | 2.65 | 0 |
| Mitsubishi New Point Drill | 19.00 | 138 | 18 | 10 | none | 5.4-6.35 (Taper Web) | 18.8 | 2.07 | 0 |

<u>TABLE No.10.1</u>

**BASIC DIMENSIONS OF CARBIDE TIPPED DRILLS (All angles in degrees).**

| DRILL TYPE & DIA. (mm) | NOMINAL BODY DIA. (mm) | FLUTE LENGTH mm(L) | WEB THICKNESS (mm) | BODY C.S.A. 'A' ($mm^2$) | FLUTE AREA (F.A.) ($mm^2$) | RATIO $\frac{FA}{A}$ % | J ($mm^4$) | ** TORSIONAL STIFFNESS/ UNIT LENGTH $\propto \frac{A^4}{40J}$ |
|---|---|---|---|---|---|---|---|---|
| Prototype Nos. 1 - 3 19.05 | 18 | 75 | 5.6 | 153.2 | 101.2 * | 39.7 | 7086 | 1943 |
| Prototype No.4 (20° helix angle) 19.05 | 17.5 | 75 | 7.8 | 159.0 | 73.4 | 30.0 | 6084 | 2626 |
| Prototype No.5/6 (15° helix angle) 19.05 | 18.8 | 75 | 7.8 | 179.7 | 90.5 | 32.5 | 8032 | 3245 |
| Conventional H.S.S. Drill 19.05 | 17.6 | 135 | 2.6 | 123.3 | 123.6 | 50.8 | 5981 | 966 |
| Sandvik Delta Drill 19.25 | 18.8 | 90 | 7.4 | 176.9 | 98.7 | 34.8 | 8806 | 2780 |
| Mitsubish | 18.8 | 100 | 5.4 | 174.2 | 96.4 | 34.7 | 8413 | 2736 |

TABLE No. 10.2

COMPARISON OF BODY, FLUTE CROSS SECTIONAL AREA AND RELATIVE TORSIONAL STIFFNESS FOR CARBIDE TIPPED AND H.S.S. DRILLS

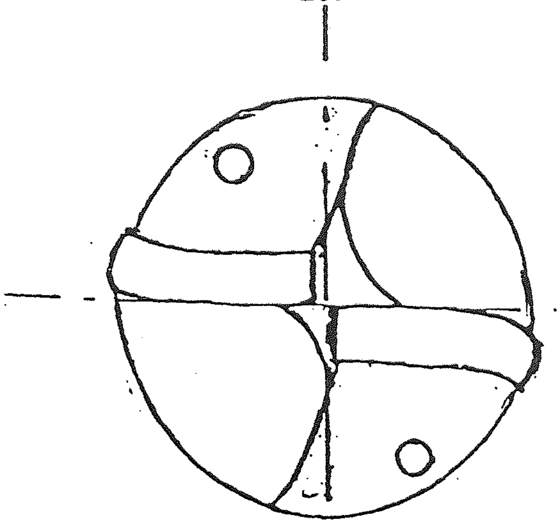
* N.B. Large Flute occupies 72.5% of total flute area. (J = Polar Second Moment of Area)

** Modulus of Rigidity G - assumed to be constant.

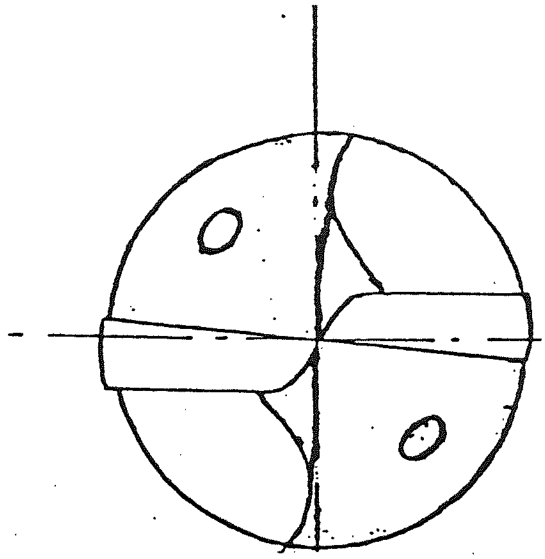
| | FEED RATE mm/rev | PROTOTYPE No.6 | | SANDVIK | | MITSUBISHI | |
|---|---|---|---|---|---|---|---|
| | | STATIONARY | ROTATING | STATIONARY | ROTATING | STATIONARY | ROTATING |
| Torque (Nm) | .1 | 12 | 13 | 17.5 | 13 | 11.5 | 11 |
| | .2 | 22 | 25 | 26.5 | 24 | 21 | 19 |
| | .3 | 33 | 35 | 32 | 32 | 30 | 29 |
| | .4 | - | - | 40.5 | 41.5 | 41.5 | 39 |
| Thrust (kN) | .1 | 0.85 | 1.25 | 1.85 | 1.8 | 1.65 | 1.3 |
| | .2 | 1.75 | 2.25 | 2.65 | 2.35 | 2.75 | 2.2 |
| | .3 | 2.75 | 2.9 | 3.25 | 3.05 | 3.2 | 3.1 |
| | .4 | - | - | 4.15 | 3.9 | 4.1 | 4.2 |
| Maximum Hole Oversize (mm) | .1 | .050 | .012 | .050 | .050 | 0 | 0 |
| | .2 | .127 | .025 | .025 | .025 | .025 | .076 |
| | .3 | .050 | .038 | .025 | 0 | .050 | .305 |
| | .4 | - | - | .025 | 0 | .330 | .228 |
| Hole Surface Finish (μmRa) | .1 | 1.4 | 2.5 | 0.4 | 5.0+ | 3.3 | 2.0 |
| | .2 | 4.5 | 4.0 | 0.3 | 0.5 | 3.5 | 2.6 |
| | .3 | 5+ | 5+ | 0.3 | 0.5 | 2.5 | 2.7 |
| | .4 | - | - | 0.7 | 1.2 | 2.5 | 3.5 |

<u>TABLE No.10.3</u>

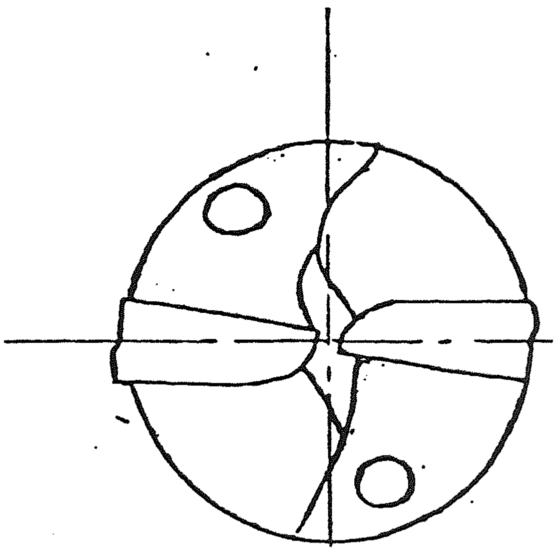
**COMPARISON OF CARBIDE TIPPED DRILL PERFORMANCE AT DIFFERENT FEED RATES AND 1500 rpm**



PROTOTYPE DRILL NO 6

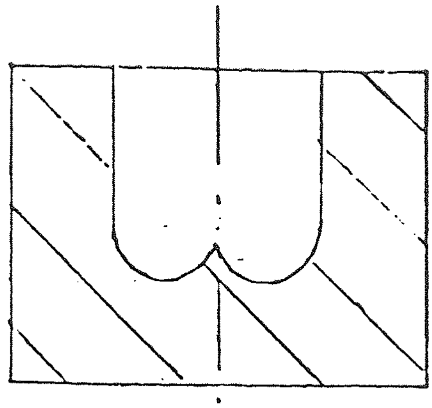


SANDVIK DELTA DRILL

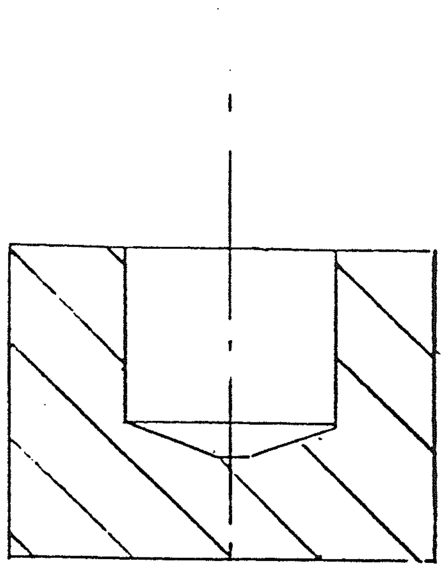


MITSUBISHI NEW POINT DRILL

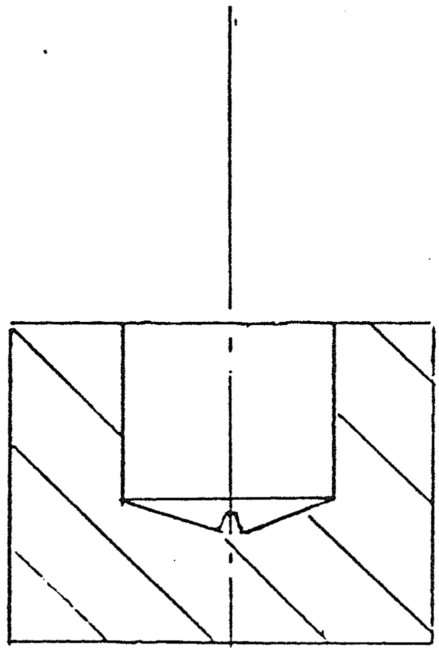
FIG 10.1 CARBIDE TIPPED DRILLS
CUTTING LIP CONFIGURATION -END VIEW



PROTOTYPE DRILL NO 6



SANDVIK DELTA DRILL



MITSUBISHI NEW POINT DRILL

FIG 10.2 CARBIDE TIPPED DRILLS
COMPARISON OF BLIND HOLE FORMS

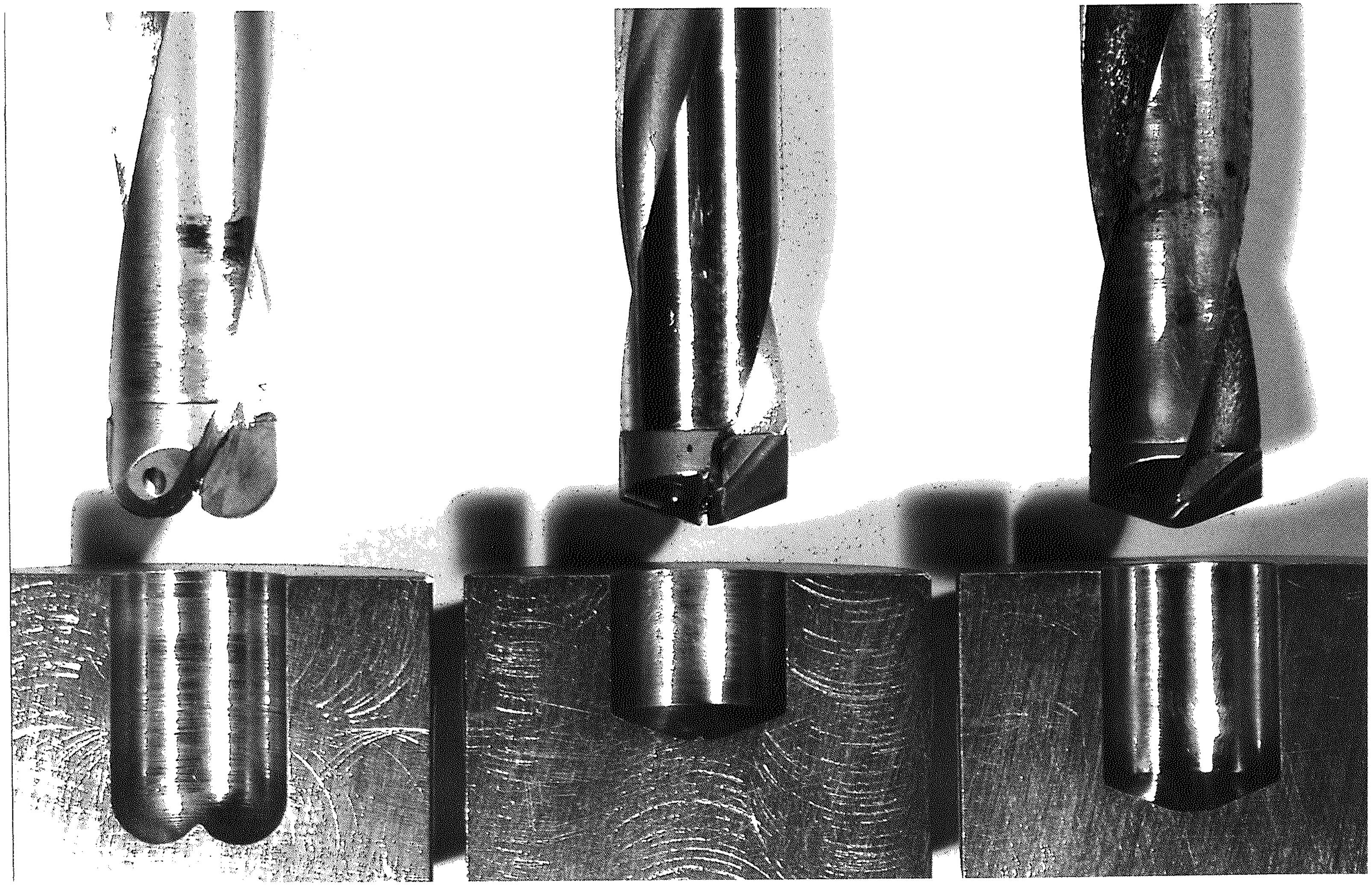


FIG 10.3 COMPARISON OF THREE TYPES OF CARBIDE TIPPED DRILL
LEFT TO RIGHT : PROTOTYPE NO 6, MITSUBISHI NEW POINT DRILL AND SANDVIK DELTA DRILL

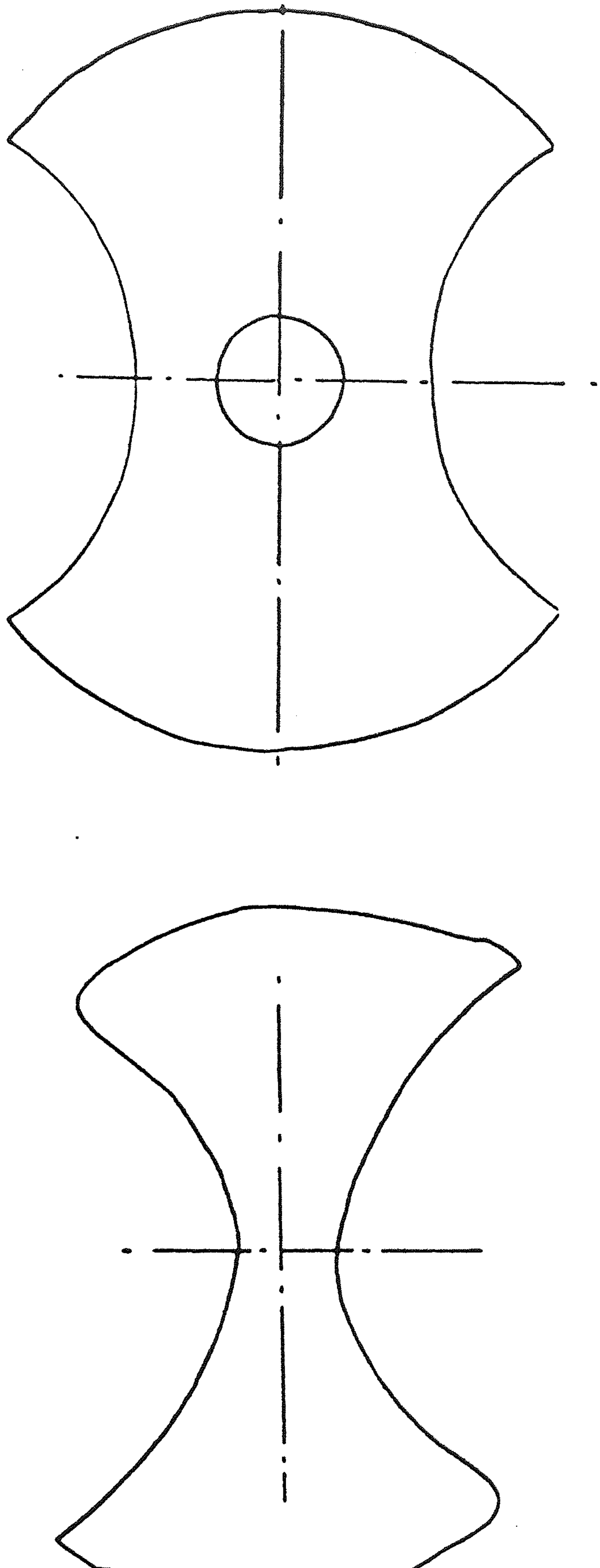


FIG 10.4 COMPARISON OF FLUTE CROSS SECTIONS -19.05 mm DIA
TOP : PROTOTYPE NOS 5 AND 6
BOTTOM:CONVENTIONAL HSS DRILL
(5 TIMES MAGNIFICATION )

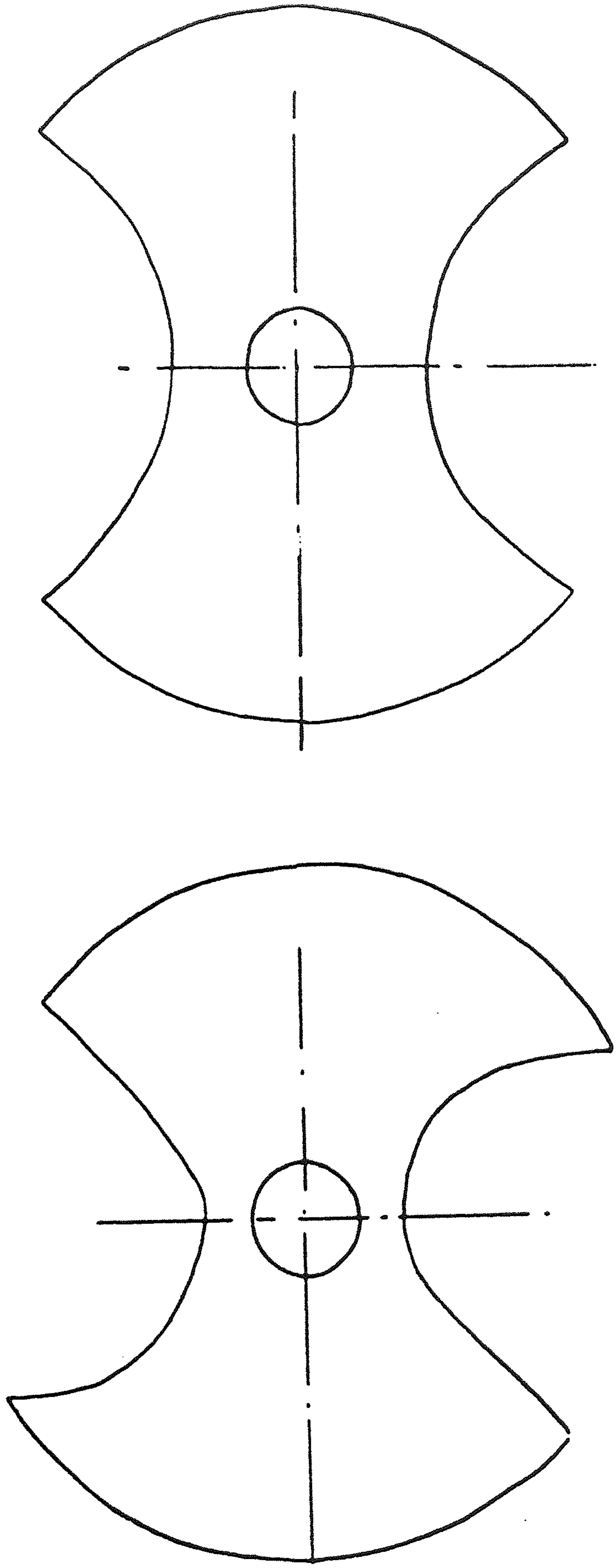
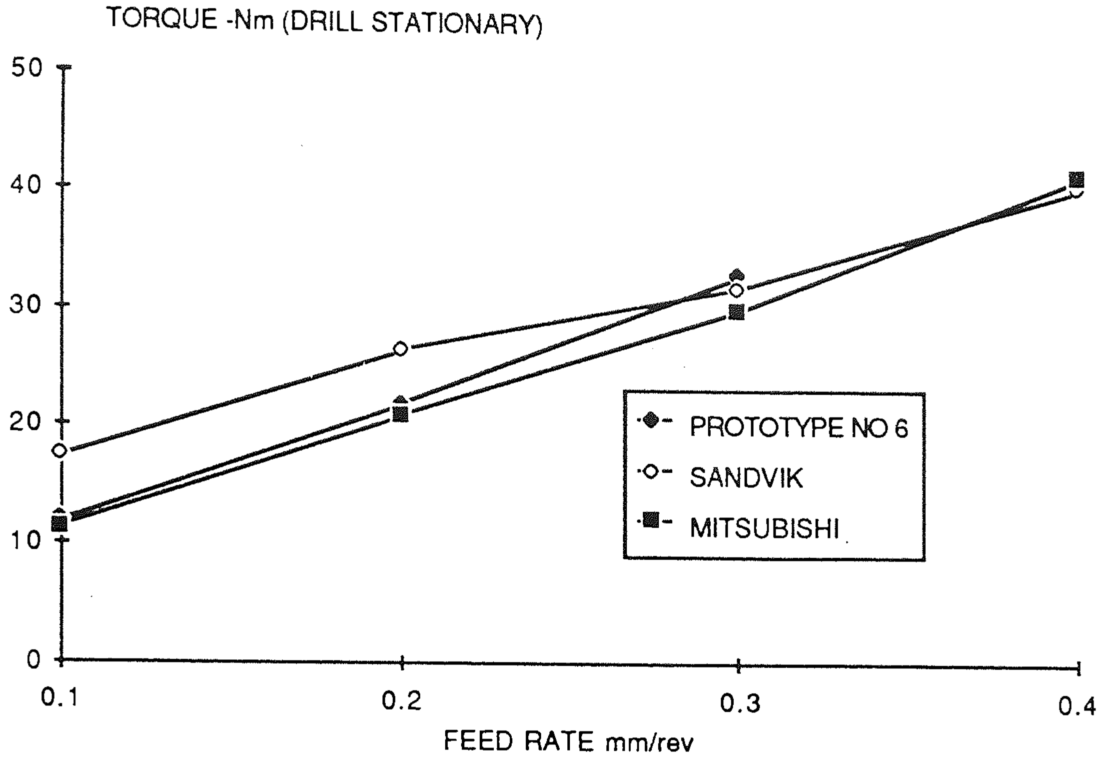


FIG 10.5 COMPARISON OF FLUTE CROSS SECTIONS
TOP : SANDVIK DELTA DRILL-19.25 mm DIA
BOTTOM : MITSUBISHI NEW POINT DRILL-19.00 mm DIA
(5 TIMES MAGNIFICATION)



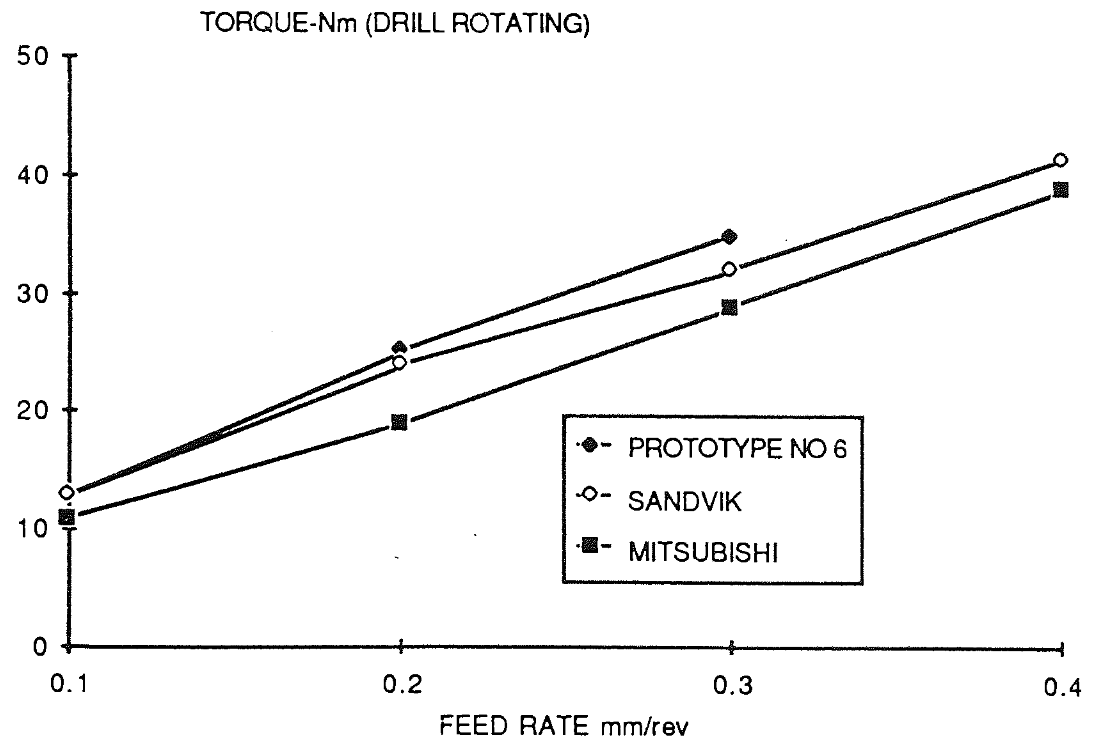
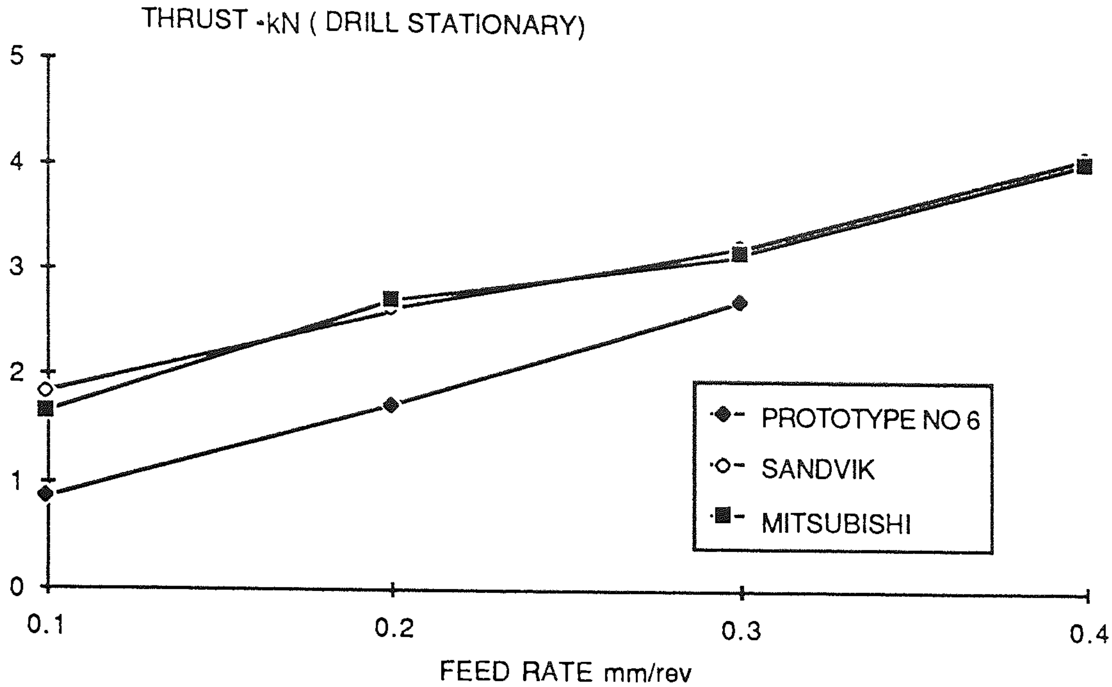




FIG 10.6 CARBIDE TIPPED DRILLS - COMPARISON OF TORQUE (Nm) FOR STATIONARY AND ROTATING MODE OF OPERTION AT 1500 rpm



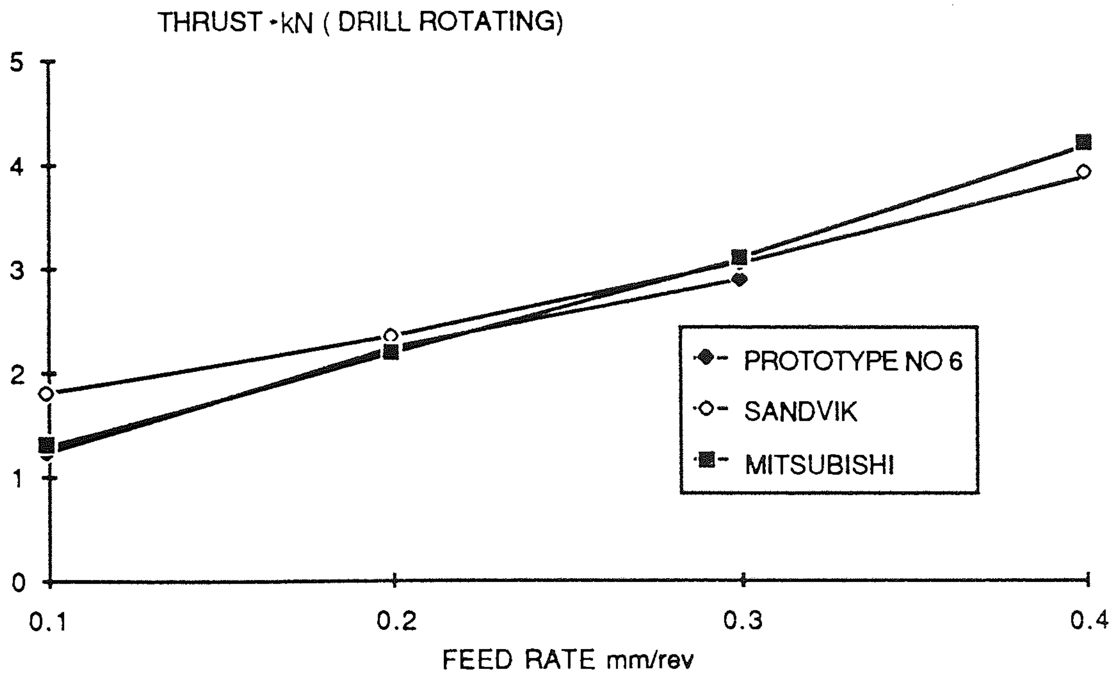
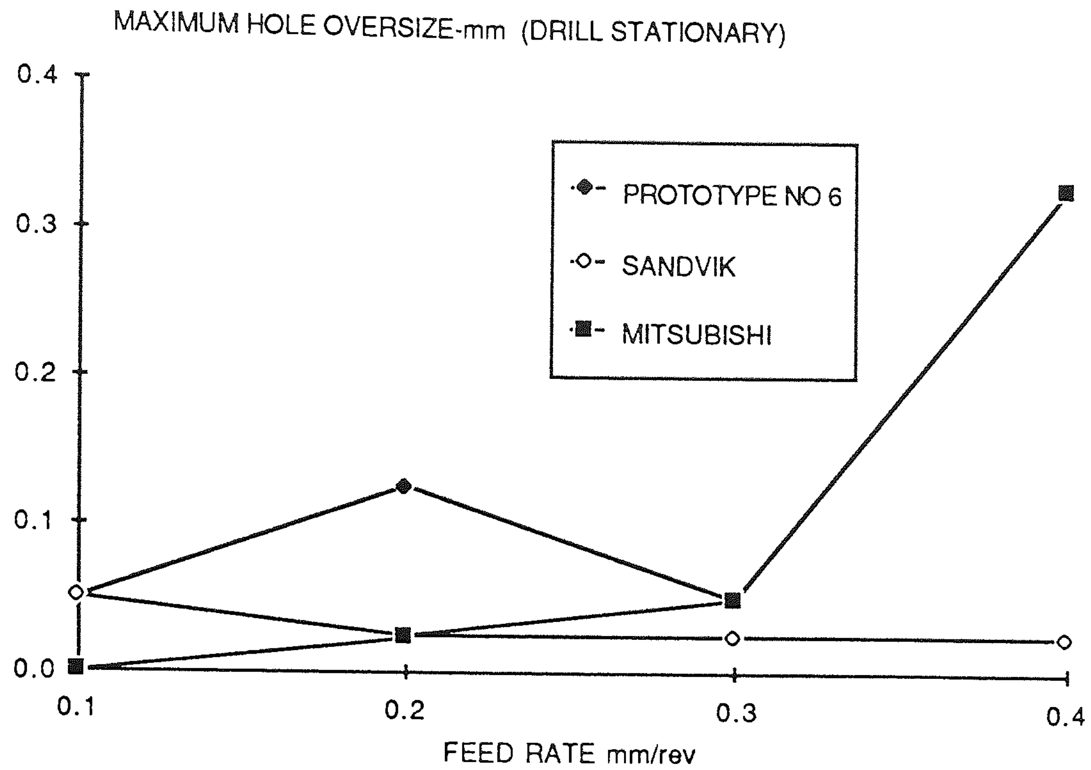




FIG 10.7 CARBIDE TIPPED DRILLS -COMPARISON OF THRUST (kN) FOR STATIONARY AND ROTATING MODE OF OPERATION AT1500 rpm



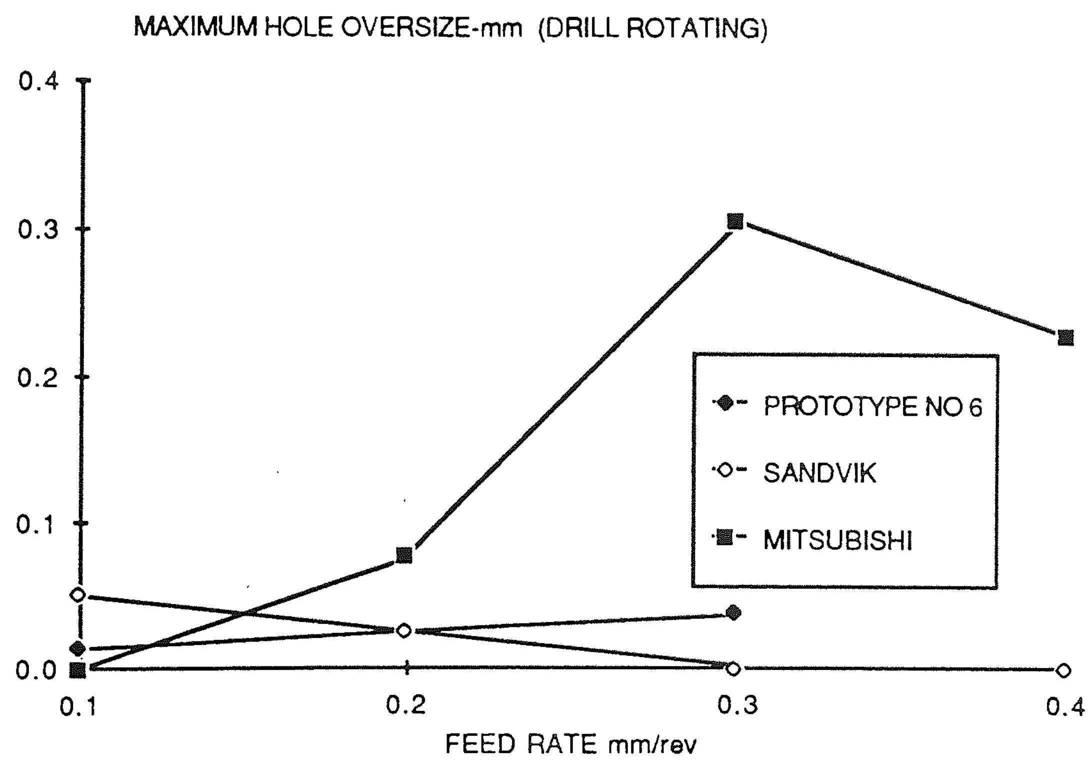
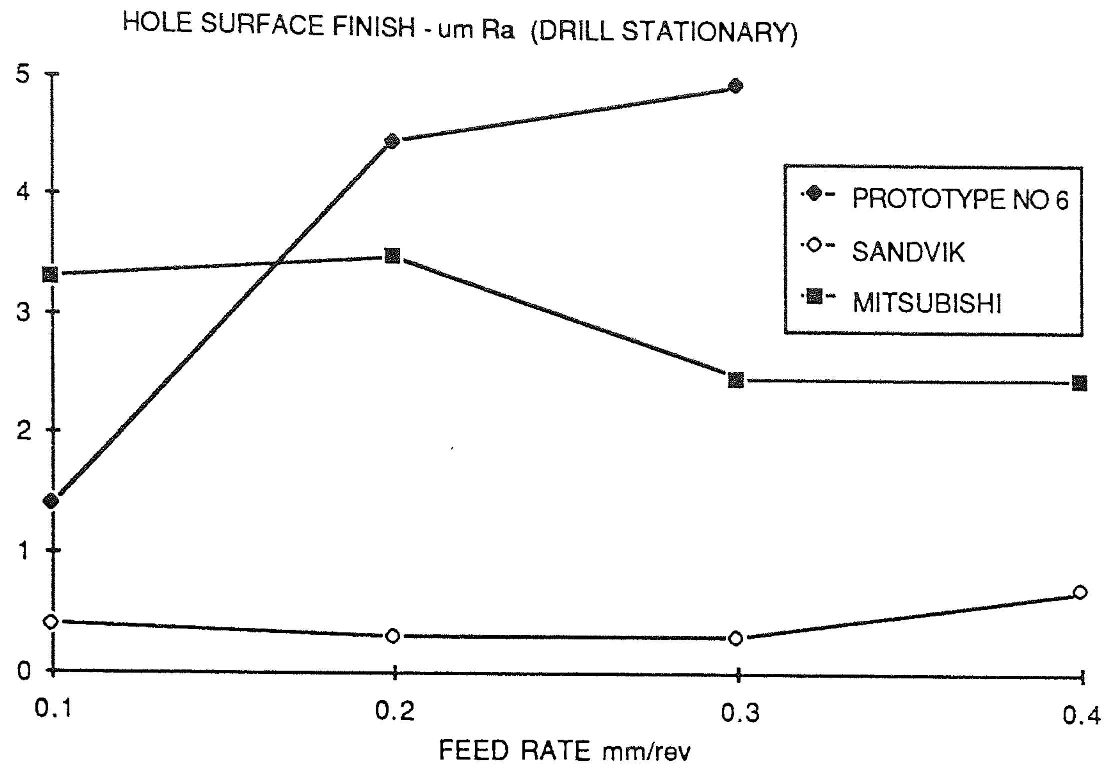




FIG 10.8 CARBIDE TIPPED DRILLS-COMPARISON OF MAXIMUM HOLE OVERSIZE (mm) FOR DRILL STATIONARY AND ROTATING MODE OF OPERATION AT 1500 rpm



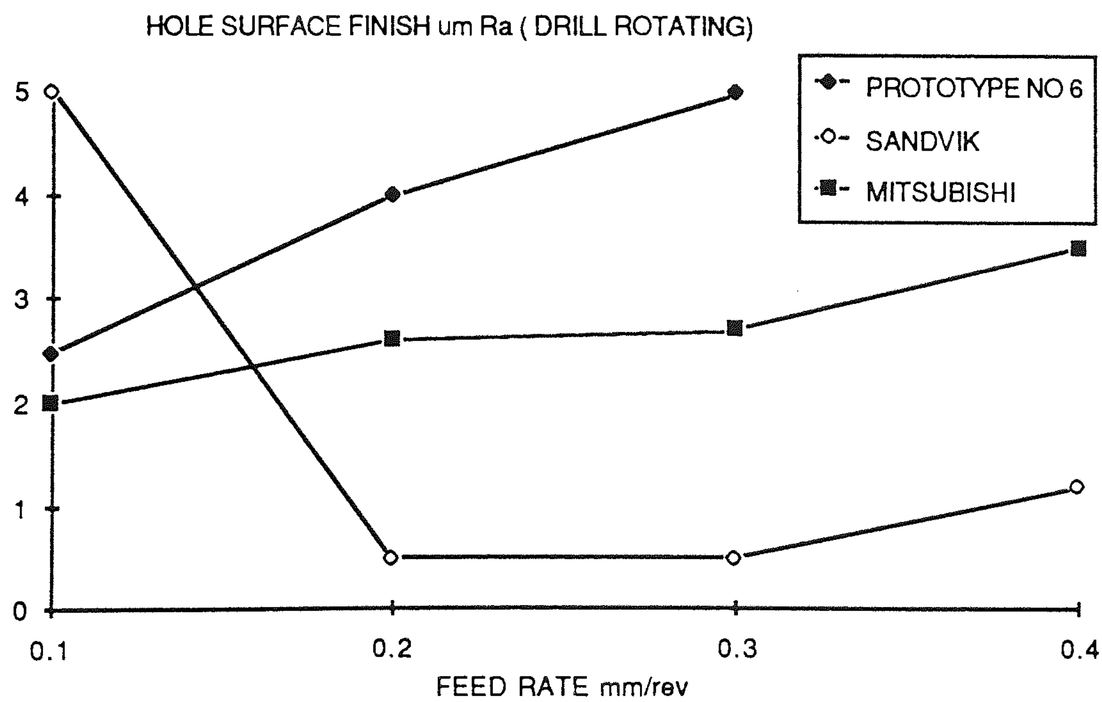




FIG 10.9 CARBIDE TIPPED DRILLS
COMPARISON OF HOLE SURFACE FINISH
STATIONARY AND ROTATING MODE OF OPERATION AT1500 rpm

# CHAPTER ELEVEN

# THE OPTIMISATION OF DRILL POINT DESIGN FOR SELF TAPPING DRILL SCREWS.

## 11.1 INTRODUCTION

Twist Drills are designed to give good tool life and be suitable for reuse after the point has been reground. The twist drill operating conditions are also selected to ensure that premature failure does not normally occur by running the drill beyond the cutting speed limitations of H.S.S.[93] or the feed limitations imposed by the drill strength and geometry[94].

An alternative approach, where the drill point may be expendable in one pass is considered for drill screws.

A drill screw usually comprises of a hexagonal headed self tapping screw 4 - 6 mm dia, the point of which is formed into a drill point.

The point of the screw also incorporates a flute form which can be produced by cold forging and/or machining (Fig.11.1). Drill screws are designed to eliminate the need for a separate hole drilling or piercing operation before the self tapping screw is fixed. The operation can thus be completed in one pass, i.e. drilling and tapping.

The use of hand held power driven screw driver tools for fixing drill screws particularly when drilling steel requires the optimum performance from the drill screw to ensure that:-

1) The minimum thrust force is required (high thrust forces cannot be extended by hand, particularly in a horizontal plane).

2) The hole is produced in the minimum time in order to maximise the production rate.

3) The hole size is maintained near to the nominal size of the drill. This will ensure good joint strength. Oversize holes will increase the tendency of a loose fitting screw.

In this Chapter detailed aspects of drill screw geometry and design were considered for six different types of drill screw designated types A-F. The performance and drilling times of these drill screws were compared with those of conventional twist drills of similar diameter.

Further research was undertaken to investigate the performance of one particular drill screw Type F. This work involved undertaking design modifications to the drill point geometry and assessing the affects on the drill screw performance and hole quality.

Previous researchers[95] have studied the effects of geometrical changes on twist drill performance. For the drill screw the design concept was different because a tool life of only one hole was required.

## 11.2 TWIST DRILL AND DRILL SCREW MEASUREMENTS

In order to compare the geometries of the drill screws type A-F with those of conventional twist drills a batch of drill screws was obtained and measured. The majority of measurements were undertaken on the Universal Measuring Machine, which incorporated a goniometer, a micrometer microscope and a linear displacement transducer with digital readout. The typical drill screw geometries from sample batches of 10 off each are presented in Table 11.1 and measurements of twist drills of the nearest available diameter to the drill screws are presented in Table 11.2. Photographs and shadow graph traces of the different types of drill screw are shown in Figs. 11.1 and 11.2.

A detailed breakdown of the individual measurements of Drill screws Type F is presented in Table 11.3.

### 11.2.1 Discussion of Results

#### 11.2.1.1. Drill Screws Types A-F

From the measurements taken of the six different types of drill screws "as supplied" it was established that each drill screw had some individual distinct features that were not necessarily repeated on the other designs. (See Table 11.1 and Figs.11.1 and 11.2). Type A incorporated a spade drill point with a positive rake angle ground along the edges of the cutting lips. In Type B the point was machined from the screw shank and a positive rake angle was obtained from a milled flute. The flute form and point angle for Type C were produced by cold forging the screw shank.

Types C and D were similar to each other in having fully machined points and flutes. For Type F the point was milled but the flute form was produced by a cold forging operation. The quality of individual types of drill screw varied because of the variability in the manufacturing process. Common errors included large lip height differences, burrs on the machined edges, different point half angles and heads that were eccentric to the screw shank.

In assessing the common features of all the drill screws considered, with the exception of Type A (the spade drill), it was apparent that when compared with conventional twist drills (Table 11.2):

(i) Drill screws were produced with greater clearance angle i.e. 22°-37° compared to twist drills (10°-14°).

(ii) On Drill screws the chisel edge angle was generally larger (128°-150°) compared to 114°-125° on twist drills.

(iii) Low helix angles of 2°-11° were used on drill screws compared to 25°-30° helix angles on the conventional twist drills.

On twist drills the flute was helical but on the drill screws a straight flute form limited the effective rake angle that could be machined.

11.2.1.2 Drill Screws Type F

From measurements taken of the Type F drill screws in the "as supplied" condition (Table 11.3), the point angle and clearance angles were found to be typically 132° and 20° respectively, chisel edge angles of about 130° were common. As well as errors in the lip height some of the screws had large burrs along one of the cutting lips and on the leading edge of the corresponding flute. The screw head also tended to be eccentric relative to the screw shank and values of up to 0.26 mm were measured.

## 11.3 DRILL SCREW POINT REGRINDING (Drill Screw Type F)

In the basic design of the drill screw Type F, an essentially straight flute was formed in the cold forming process. This resulted in a near to zero rake angle at the cutting lip and provided ample scope for increasing the clearance angle without seriously weakening the cutting lips.

Based upon initial trial tests, three point modifications to the "as supplied" drill screws were considered in order to improve the basic screw design, i.e. Point Angle, Clearance Angle and Point Thinning.

No fundamental changes to the rake angle or flute form were developed in this study.

Alternative flute designs that incorporate a positive rake angle could be produced by an extra machining operation. This may result in additional cost being incurred in the manufacturing process. A positive rake angle might be produced by cold forging, and this may be worthy of further consideration at a later date.

In order to regrind the points of drill screws it was necessary to drill a back centre in the head of the hexagon. The centring operation was undertaken on a lathe by gripping the screw thread in a three jaw chuck and centring by means of a conventional centring tool held in the lathe tailstock.

The centred drill screw was then gripped in the jaws of the Micron drill point grinding machine and a specially modified back centre used to locate and set the screw to the desired clearance angle (Fig.11.3). Four clearance angles, 25°, 30°, 35° and 40° were chosen and the ground surface generated was a relieved cone form similar to that of a conventional drill point.

Variations in the drill point angle in the range from 100°-150° were made by adjusting the position of the setting quadrant as required. A drill point angle above 150° proved to be impractical due to excessive vibration and hole oversize.

In the reground condition straight cutting lips were usually maintained across the range of point angles and even clearance angles of 40° provided an included wedge angle of 50° which was considered adequate, (see Fig.11.4)

In later trials some drill point thinning was undertaken on the Universal Grinding Machine aided by a specially designed grinding fixture. This fixture enabled material to be ground from the web of the drill and leading edges of the flutes without reducing the chisel length (Fig.11.5).

All reground drill points were carefully measured before testing to ensure that the geometry was correct with a lip height difference limit set at .05 mm.

The combination of different point and clearance angles in regrinding produced a range of different chisel edge angles (see Table 11.4) The largest chisel edge angles were achieved at 40° clearance across the range of point angles.

Some reground drill points were subsequently hardened and cadmium plated before testing (see Table 11.15). Other reground drill screws were tested in the "as ground" condition.

## 11.4 TESTING OF DRILL SCREWS

### 11.4.1 Drill Press Trials - Twist Drills and Drill Screws A-F

The test set up used was a small bench type Drill Press and all drilling tests were performed without coolant at 1500 rpm. A specially extended lever arm was incorporated on the Drill Press to carry weights for applying the constant drill thrust force. Two different loads were used, equivalent to thrusts of 330 and 440N for the drill screw types A-F, (see Fig.11.6).

The twist drills and drill screws heads were gripped in a 3 jaw chuck. The workpiece was held in a small engineers' vice which was bolted to the Kistler Drilling Dynamometer which in turn was fixed to the bed of the drill press.

The Dynamometer (Appendix III) was used to monitor the drilling forces and the output was displayed on a U.V. Recorder Trace, which also indicated the drilling time,(see Fig.11.7). Through holes were produced using mild steel 6.35 mm thick.

11.4.2 <u>Drill Press Trials - Drill Screw Type F</u>

The test set up for the Type F Drill Screw, both "as supplied" and in the reground condition, was similar to that described previously, except that three different loads were used which were equivalent to 210, 330 and 440N thrust force. Through holes were produced in 6.35 mm thick mild steel.

Some limited trials were undertaken with bright drawn mild steel 6.35 mm thick.

After deburring the hole diameters were measured on the

Universal Measuring Machine by aligning the eyepiece cross wires on one side of the hole and traversing diametrically across to the other side. The diameter was recorded on the Sylvac Digital Display Unit coupled to a linear transducer.

### 11.4.3 Hand Held Power Tool - Drill Screw Type F.

Comparative trials were undertaken with a hand held power driven screw driver. The thrust force was applied by hand horizontally and the 6.35 mm thick workpiece was gripped in a bench vice. For some of the tests the workpiece was fixed to the drilling dynamometer mounted in the vice so that the forces applied by the two different Operators 'A' and 'B' could be measured.

To overcome some of the "run out" at the drill point caused by poor fit of the hexagonal screw head in the drill socket, a special back centre pin was used to provide extra support (Fig.11.8). The centre in the head of the drill screw was drilled so that a satisfactory fit on the pin was obtained.

The socket centre significantly reduced both the run out and the drilling time and was used for all tests with the power tool except where stated. Additional tests with 10 mm thick material were made with reground and hardened drill screws.

## 11.5 DRILLING TEST RESULTS

### 11.5.1 Twist Drills and Drill Screws Type A-F

The drilling times at 330N and 440N thrust forces for twist drills and the different types of drill screw (A-F) are presented in Table 11.5 and Fig.11.9.

### 11.5.2 Drill Screw Type F

The differences in drilling times for 25° - 40° clearance angles and 100° - 150° point angles on the Drill press for three difference thrust forces, 210, 330 and 440N are given in Tables 11.6 - 11.9 (Figs.11.10 - 11.13).

The times taken at 210N thrust across the range of point and clearance angles for additional trials on the Drill Press are given in Table 11.10 and Fig.11.14. Comparative data for Operator "B" with the hand held tool is given in Table 11.11 and Fig.11.15

Hole diameter measurements at drill entry for these trials at 210N thrust are given in Table 11.12 and Fig.11.16. The equivalent hand tool results are given in Table 11.13 and Fig.11.17. The hole diameters at drill exit were all very close to the drill nominal diameter of 5.1 mm.

In order to determine the range of forces exerted by a typical operator, two sets of data are presented for operators 'A' and 'B' in Table 11.14 and Fig.11.18.

The time saved using point thinned drill screws is presented in Table 11.15 and Fig.11.19, but the additional wear compared to a conventional point is shown in Figs.11.20 and 11.21.

Differences in time to drill with the hand held power tool with and without the socket back centre are given in Table 11.16 and Fig.11.22. Comparison drilling times for drills in the "as supplied" condition together with the hole size at entry are given in Table 11.17 and Figs.11.23 and 11.24.

The effect of material hardness on drilling time is given in Table 11.18.

## 11.6 DISCUSSION OF RESULTS

### 11.6.1 Twist Drills and Drill Screws Types A-F

From Table 11.5 and Fig.11.9 it was observed that there was a dramatic difference between the time taken by conventional twist drills and drill screws to penetrate at 330N thrust. The longer time for twist drills was attributed to the features of the point geometry, particularly low clearance angles which were not used on drill screws. With increased clearance angles there was less support on the drill screw points to resist the applied thrust force and the drilling time was thus reduced.

At 330N thrust force the shortest drilling times were achieved with drill screws Types E & A which were the smallest diameter drill screws.

At 440N thrust the drill screws again achieved faster penetration rates than the equivalent twist drills and the shortest drilling times were achieved with Types E and F. In some cases high thrust forces of 440N led to a burn out of the drill screw cutting lips. This sometimes led to an increase in drilling time or a stall condition in which the drill screw point was unable to penetrate (see Types A & D Table 11.5).

11.6.2 <u>Drill Screw Type F.</u>

Initial trials on the Drill Press with the reground drill screws confirmed that increases in clearance angle lead to reductions in drilling time.

From measurements taken of the reground drill screw point it was evident that increases in clearance angle were also accompanied by increases in the chisel edge angle for any given point angle (Table 11.4). The chisel edge angle was generated from the combination of point angle, clearance angle and relative angular position in which the drill screw was gripped during point grinding.

Increases in chisel engle were generally beneficial up to about 140°, because the motion of any chip formed by each side of the chisel edge was directed more towards the flute, rather than into the body of the drill, thus reducing the tendency of swarf clogging around the chisel edge.

Very significant differences in drilling time occurred over the range of 25° - 40° clearance angles and 100° - 150° point angles (Figs.11.10 - 11.13). The drilling time was much less dependent on the point angle at 35° and 40° clearance angle. The results at 25° clearance, however, confirmed that small changes in point angle below 130° resulted in a dramatic increase in drilling time. These findings were confirmed for both the Drill Press and Hand Held Tool. (Figs.11.14 and 11.15). In the existing design, point angles of 130° and 20° clearance were used. Any manufacturing process variability which resulted in the point angle being less than 130°, therefore led to a drill screw point with a potentially long drilling time. The effect of the applied thrust force was also clearly demonstrated by these results, i.e:

> At 440N the drilling time was generally less dependent on the screw point geometry. For thrust forces of 210 and 330N, however, point angles below 120° generally resulted in increases in drilling time for 30° - 40° clearance angles. Drilling times increased dramatically for point angles below 130° at 25° clearance and 210N thrust.

There was particular interest at 210N thrust because this was considered to be the likely thrust applied by hand held power tools.

The results also confirmed that at 100° point angles stalling often occurred due to the low chisel edge angle and high negative rake forces which ultimately resulted in deformation or burning of the chisel edge. As the point angle was increased, a dramatic reduction in drilling time occurred providing that clearance angles of 30° or above were used.

When comparing the hole sizes produced across the range of point angles at 210N thrust with both hand and drill press feeds the trends were again similar. (Figs.11.16 and 11.17) Above 130° point angles the magnitude of the hole oversize increased rapidly particularly at drill entry. Both 140° and 150° point angles led to reduced drilling times but there was a much greater tendency for the drill point to "wander" and produce oversize holes.

When comparing the thrust forces exerted by two different operators (Fig.11.18) it was apparent that over a range of 110° - 130° point angles typical thrust forces did not usually exceed 300N in a horizontal plane and may in fact be much closer to 220N (Operator A).

The Drill Press Trials with drill screw points reground and subsequently hardened and tempered before cadmium plating did not produce any significant improvement in drilling time due to the increased point hardness when using 6.35 mm thick mild steel. The performance did improve for 10 mm thick material and the "tool life" was superior, enabling several holes to be drilled with the same screw.

In some cases where the reground lip had been "dulled" in the hardening process, the drilling times were sometimes slightly longer than those obtained for points in the reground condition. The benefits obtained from point thinning were generally limited to time savings in the order of 1-3 seconds (Fig.11.19). At higher thrust forces (440N) the thinned point was more likely to fail particularly at 130° point angle and 40° clearance due to point weakness (Figs.11.20 and 11.21).

A further improvement in the drilling times in the order of 2-7 seconds was achieved with the socket pin adaptor in the hand held power tool (Fig.11.22). These improvements applied to both 6.35 mm and 10 mm thick mild steel. The pin helped to stabilise the rotation of the drill screw, without the use of this pin the flats on the hexagonal screw head did not provide sufficient support and this combined with head eccentricity (up to 0.25 mm) resulted in vibration, the point running off centre and increased hole oversize.

The typical drilling times and hole oversize generated for a drill screw point as supplied and tested without the centre pin are shown in Figs.11.23 and 11.24.

The final observation recorded for the drilling trials was that material hardness and particularly surface condition play a very important part in determining the drilling time. In drilling a sample of bright drawn mild steel the drilling times almost doubled and this was attributed to a hard skin which reduced the chisel penetration rate at entry and exit. (Fig.11.25).

## 11.7 RECOMMENDATIONS - Drill Screw Type F

In order to optimise the drilling performance of the existing drill screw the following recommendations should be considered.

### 11.7.1 Improvements to be made to the Drill Point

(i) Optimum point geometry to be in the range 120° - 130°.

(ii) Clearance angle to be increased to between 35° - 40°

(iii) Point thinning is not recommended because this may weaken the point and cause point breakage, particularly on cold rolled material.

(iv) On existing "as supplied" points, eliminate burr on the leading edge of the flute and lip to reduce long drilling times.

(v) Improve point symmetry on "as supplied" screws to minimise hole oversize.

### 11.7.2 Improvements to be made to the Drill Head (Fig.11.26).

(i) Improve concentricity and shape of the hexagonal head.

(ii) Increase socket contact depth of hexagonal head by a minimum of 1 mm and eliminate back taper.

(iii) Eliminate or reduce root radius at base of head at junction with collar to provide an improved fit in socket.

### 11.7.3 Improvements in the Drill Screw Manufacturing Process

Because there was a wide variation in the drilling times of the drill screws as supplied and large hole oversizes generated, particular detailed attention is required to identify:-

(i) The variability in the manufacturing process and factors that may contribute to poor quality.

(ii) The quality assurance procedures used in the process.

## 11.8 OVERALL CONCLUSIONS

1. Drill screws achieved faster drilling times at 330N thrust force and 1500 rpm than the equivalent diameter twist drills tested under the same conditions.

2. At high thrust forces of 440N some drill screws were liable to burn out or stall before completing the drilled hole.

3. A common feature of all the different drill screws evaluated, except the spade drill Type A, was increased clearance angles compared to twist drills.

4. The spade drill (Type A) performed very well because there was

large swarf evacuation capacity behind the blade and a high positive helix angle of 33° ground along the cutting lips.

5. The optimum point geometry for the drill screw, Type F, was obtained with point angles of 120° - 130° and clearance angles of 35° - 40°.

6. Reground drill points in the range 140° - 150° tended to produce excessive hole oversize due to the point wandering.

7. Drill points of 100° - 110° tend to stall, or require high thrust forces because of the low chisel edge angle and the high negative rake cutting conditions of the chisel.

8. Increase in clearance angle from 25° to 40° reduced the drilling time at a constant thrust force without substantially reducing the point strength.

9. Point thinning of the drill screw marginally reduced the drilling time but some weakness was created that may cause breakage to occur, particularly with harder materials and high thrust forces.

10. The drilling times for reground drill points that were subsequently hardened and plated were not significantly different to those used in the reground condition. Reground and hardened points did have better tool life particularly on 10 mm thick material.

11. Significant reductions in the drilling time can be achieved by improving the quality of the hexagonal head resulting in a better fit in the drive socket.

12. Poor head quality leads to excessive run out of the point and poor drive location in the socket. This leads to excessive hole oversize occurring.

13. Wide variations were found in the drilling times of the drill screws "as supplied". As well as the poor head quality, the presence of burrs on the cutting lips and an asymmetric point configuration were detrimental to good performance on some of the drill screws.

14. Material hardness and condition significantly affected the drilling time. In the case of bright drawn mild steel a hard skin on the surface doubled the drilling time at a constant thrust force of 210N.

15. Tests to establish the thrust forces applied by two different operators confirmed that for horizontal drilling the forces applied were usually between 210 and 260N. Any drill screw design should perform satisfactorily over this range of thrust forces, and also be capable of withstanding higher thrusts likely to be exerted by hand in a vertical plane.

| DRILL DIA. (mm) | REF LETTER | POINT ANGLE | HELIX ANGLE | CLEARANCE ANGLE | CHISEL EDGE ANGLE | CHISEL LENGTH (mm) | LIP HEIGHT DIFFERENCE (mm) | HEAD ECCENTRICTY (mm) |
|---|---|---|---|---|---|---|---|---|
| 4.62 | E | 119 | 9 | 37 | 148 | 1.22 | 0-0.28 | 0.03-0.17 |
| 4.74 | A | 115 | 33 | 16 | 108 | 1.00 | 0.04-0.15 | 0.03-0.06 |
| 4.90 | B | 137 | 11 | 32 | 143 | 1.00 | 0-0.13 | 0.09 |
| 5.10 | F | 132 | 2 | 22 | 128 | 1.00 | 0-0.13 | 0.08-0.26 |
| 5.38 | C | 115 | 7 | 26 | 150 | 1.78 | Corner Radius | 0.03-0.04 |
| 5.46 | D | 120 | 9 | 37 | 145 | 1.35 | 0-0.13 | 0-0.24 |

**TABLE 11.1** AVERAGE MEASUREMENTS OF DRILL SCREW GEOMETRIES AS SUPPLIED TYPES A-F (SAMPLE BATCHES OF 10)
(All Angles in Degrees - Type A was a spade end drill screw)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4.62 | E | 118 | 25 | 10 | 118 | 1.18 | - |
| 4.77 | A | 120 | 29 | 12 | 117 | 0.94 | - |
| 4.95 | B | 119 | 25 | 14 | 118 | 1.00 | 0.05 |
| 5.10 | F | 119 | 29 | 12 | 125 | 1.09 | - |
| 5.41 | C | 118 | 27 | 12 | 114 | 1.00 | - |
| 5.54 | D | 118 | 30 | 11 | 118 | 1.24 | - |

**TABLE 11.2** MEASUREMENTS OF TWIST DRILL GEOMETRIES OF SIMILAR DIAMETERS TO THE DRILL SCREWS CONSIDERED.

| No. | HALF ANGLES POINT | POINT ANGLE | HELIX ANGLE | CLEAR -ANCE ANGLE | CHISEL EDGE ANGLE | LIP HEIGHT DIFFERENCE mm (h) | CHISEL LENGTH mm | HEAD ECCENT-RICITY mm (e) |
|---|---|---|---|---|---|---|---|---|
| 1 | 65-68 | 133.0 | 2.0 | 20.0 | 122 | 0.038 | 0.96 | 0.17 |
| 2 | 64+68 | 132.0 | 0 | 20.0 | 128 | 0.127 | 1.02 | 0.26 |
| 3 | 67+67 | 134.0 | 1.0 | 22.0 | 131 | 0.127 | 0.95 | 0.25 |
| 4 | 66+66 | 132.0 | 0 | 26.0 | 132 | 0 | 0.93 | 0.19 |
| 5 | 66.5+66.5 | 133.0 | 2 5 | 20.0 | 130 | 0.063 | 1.09 | 0.16 |
| 6 | 66+65 | 131.0 | 0 | 23.0 | 129 | 0 | 0.94 | 0.09 |
| 7 | 67+65.5 | 132.5 | 1.0 | 19.5 | 128 | 0 | 0.91 | 0.25 |
| 8 | 65.5+66 | 131.5 | 4.0 | 18.0 | 129 | 0.025 | 1.08 | 0.08 |
| 9 | 64+67 | 131.0 | 4.5 | 19.0 | 131 | 0.038 | 1.04 | 0.17 |
| 10 | 65.5+65.5 | 132.0 | 3.0 | 18.0 | 130 | 0 | 0.98 | 0.23 |

TABLE No. 11.3

**MEASUREMENTS FOR DRILL SCREWS AS SUPPLIED**
**(all angles in degrees)**

| POINT ANGLE | CLEARANCE ANGLES | | | |
|---|---|---|---|---|
| | 25° | 30° | 35° | 40° |
| | CEA | CEA | CEA | CEA |
| 100° | 112 | 115 | 116 | 122 |
| 110° | 117 | 124 | 121 | 129 |
| 120° | 130 | 131 | 135 | 139 |
| 130° | 135 | 141 | 147 | 149 |
| 140° | 144 | 146 | 150 | 155 |
| 150° | 150 | 155 | 156 | 160 |

**TABLE No. 11.4**

**REGROUND DRILL SCREW POINT GEOMETRY**
**THE EFFECT OF POINT AND CLEARANCE ANGLE ON CHISEL EDGE ANGLE (CEA).**

| DRILL DIA (mm) | REF LETTER | DRILLING TIMES (Seconds) TO PENETRATE 6.35 mm THICK M.S. | | | |
|---|---|---|---|---|---|
| | | DRILL SCREW THRUST | | TWIST DRILL THRUST | |
| | | 330N(Sec) | 440N(Sec) | 330N(Sec) | 440N(Sec) |
| 4.62 | E | 4.7 | 3.0 | 12.0 | 7.8 |
| 4.74 | A | 4.3 | 4.5 | 9.3 | 5.2 |
| 4.90 | B | 8.1 | 5.4 | 24.0 | 14.0 |
| 5.10 | F | 4.7 | 3.0 | 10.0 | 5.5 |
| 5.38 | C | 6.9 | 3.6 | 12.4 | 7.5 |
| 5.46 | D | 8.4 | 10.8 | 31.8 | 19.2 |

**TABLE 11.5** **COMPARISON OF DRILLING TIMES(SEC) TO PENETRATE 6.35 mm THICK M.S. WITH DRILL SCREWS TYPES A-F AND EQUIVALENT DIAMETER TWIST DRILLS AT 330N AND 440N THRUST.**

| APPLIED THRUST FORCE | | | |
|---|---|---|---|
| POINT ANGLE | 210N secs | 330N secs | 440N secs |
| 100° | * | 20.7 | 8.1 |
| 110° | * | 11.3 | 6.0 |
| 120° | * | 6.6 | 6.0 |
| 130° | 14.7 | 7.7 | 4.8 |
| 140° | 10.2 | 9.1 | 5.0 |
| 150° | 11.4 | 7.0 | 4.5 |

**TABLE No. 11.6**

REGROUND DRILL POINTS
TIME (IN SECONDS) TO PENETRATE 6.35 mm WITH 25° CLEARANCE ANGLE USING THE DRILL PRESS.

* Drills did not penetrate through 6.35 mm.

| APPLIED THRUST FORCE | | | |
|---|---|---|---|
| POINT ANGLE | 210N secs | 330N secs | 440N secs |
| 100° | 64.0 | - | - |
| 110° | 52.0 | - | 20.0 |
| 120° | 14.4 | 9.7 | 4.8 |
| 130° | 12.6 | 7.3 | 5.1 |
| 140° | 13.6 | 5.8 | 4.2 |
| 150° | 12.0 | 4.5 | 3.8 |

**TABLE No. 11.7**

REGROUND DRILL POINTS
TIME (IN SECONDS) TO PENETRATE 6.35 mm WITH 30° CLEARANCE ANGLE USING THE DRILL PRESS

| | THRUST APPLIED | | |
|---|---|---|---|
| POINT ANGLE | 210N secs | 330N secs | 440N secs |
| 100° | 43.8 | 14.0 | 6.6 |
| 110° | 19.7 | 7.5 | 7.3 |
| 120° | 10.8 | 5.8 | 6.0 |
| 130° | 12.6 | 7.5 | 4.8 |
| 140° | 12.6 | 8.1 | 4.9 |
| 150° | 16.2 | 9.7 | 5.3 |

TABLE No. 11.8

REGROUND DRILL POINTS
TIME (IN SECONDS) TO PENETRATE 6.35 mm WITH 35° CLEARANCE ANGLE USING THE DRILL PRESS.

| | THRUST APPLIED | | |
|---|---|---|---|
| POINT ANGLE | 210N secs | 330N secs | 440N secs |
| 100° | 12.2 | 10.0 | 4.8 |
| 110° | 10.8 | 9.3 | 5.1 |
| 120° | 11.1 | 6.6 | 4.5 |
| 130° | 10.2 | 6.8 | 3.6 |
| 140° | 10.2 | 11.0 | 3.6 |
| 150° | 13.8 | 9.5 | 5.0 |

TABLE No. 11.9

REGROUND DRILL POINTS
TIME (IN SECONDS) TO PENETRATE 6.35 mm with 40° CLEARANCE ANGLE USING THE DRILL PRESS.

| POINT ANGLE | CLEARANCE ANGLES | | | |
|---|---|---|---|---|
| | 25° | 30° | 35° | 40° |
| 100° | * | 64.0 | 43.8 | 22.2 |
| 110° | * | 52.0 | 19.8 | 10.8 |
| 120° | * | 14.4 | 10.8 | 11.1 |
| 130° | 14.7 | 12.6 | 12.6 | 10.2 |
| 140° | 10.2 | 13.6 | 12.6 | 10.2 |
| 150° | 11.4 | 12.0 | 16.2 | 13.8 |

TABLE No. 11.10

DRILL PRESS - REGROUND DRILL POINTS
DRILLING TIMES (seconds) FOR 210N THRUST.

(* Drills did not penetrate through 6.35 mm thick Mild Steel - stall on chisel).

| POINT ANGLE | CLEARANCE ANGLES | | | |
|---|---|---|---|---|
| | 25° | 30° | 35° | 40° |
| 100° | * | * | * | * |
| 110° | * | 9.6 | 8.4 | 7.2 |
| 120° | * | 9.6 | 12.0 | 6.6 |
| 130° | 8.4 | 9.0 | 8.4 | 7.2 |
| 140° | 9.0 | 7.8 | 9.6 | 9.0 |
| 150° | 8.4 | 10.2 | 12.0 | 8.4 |

TABLE No. 11.11

HAND HELD POWER TOOL - REGROUND DRILL POINTS
DRILLING TIMES (seconds) FOR OPERATOR B.

(* Drills did not penetrate through 6.35 mm thick Mild Steel).

| POINT ANGLE | CLEARANCE ANGLES | | | |
|---|---|---|---|---|
| | 25° | 30° | 35° | 40° |
| 100° | * | 5.38 | 5.21 | 5.26 |
| 110° | * | 5.33 | 5.28 | 5.33 |
| 120° | * | 5.46 | 5.46 | 5.43 |
| 130° | 5.33 | 5.38 | 5.51 | 5.36 |
| 140° | 5.38 | 5.30 | 5.43 | 5.56 |
| 150° | 5.54 | 5.43 | 5.33 | 5.79 |

TABLE No. 11.12

DRILL PRESS - REGROUND DRILL POINTS
HOLE DIAMETER (mm) AT DRILL ENTRY (6.35 mm M.S. AT 210N THRUST)

(* Drills did not penetrate through 6.35 mm thick Mild Steel).

| POINT ANGLE | CLEARANCE ANGLES | | | |
|---|---|---|---|---|
| | 25° | 30° | 35° | 40° |
| 100° | * | * | * | 5.26 |
| 110° | * | 5.26 | 5.18 | 5.28 |
| 120° | * | 5.18 | 5.31 | 5.26 |
| 130° | 5.18 | 5.21 | 5.31 | 5.51 |
| 140° | 5.18 | 5.23 | 5.56 | 5.07 |
| 150° | 5.23 | 5.48 | 5.46 | 5.66 |

TABLE No. 11.13

HAND HELD POWER TOOL - REGROUND DRILL POINTS
HOLE DIAMETER (mm) AT DRILL ENTRY FOR 6.35 mm M.S.

(* Drills did not penetrate through 6.35 mm thick Mild Steel - stall on chisel).

| HOLE No. | POINT ANGLE | POINT TYPE | FORCE EXERTED (N) | |
|---|---|---|---|---|
| | | | Operator'A' | Operator'B' |
| 1 | 110° | G | 240 | 310 |
| 2 | 110° | G & T | 210 | 270 |
| 3 | 120° | G | 240 | 270 |
| 4 | 120° | G & T | 240 | 290 |
| 5 | 130° | G | 250 | 300 |
| 6 | 130° | G & T | 175 | 270 |
| 7 | 130° | AS | 230 | 260 |
| 8 | 130° | AS & T | 210 | 250 |

TABLE No. 11.14

FORCES EXERTED BY OPERATORS 'A' and 'B' FOR 6.35 mm THICK
BRIGHT DRAWN MILD STEEL WITH HARD SKIN
FORCE RANGE: 175 to 310N.

Key to point type:
G = Reground
G & T = Reground and Thinned
AS = As Supplied
AS & T = As Supplied and Thinned

| THRUST | 210N | | 330N | | 440N | |
|---|---|---|---|---|---|---|
| POINT ANGLE | CONV. POINT | THINNED POINT | CONV. POINT | THINNED POINT | CONV. POINT | THINNED POINT |
| 110° | 13.2 | 9.6 | 9.3 | 7.8 | 6 | 4.8 |
| 120° | 9.8 | 8.6 | 6.6 | 4.8 | 5 | 3.8 |
| 130° | 9.6 | 7.4 | 6.8 | 4.6 | 3.9 | 3.6 |

TABLE No. 11.15

DRILL PRESS TRIALS
GROUND, HARDENED AND CADMIUM PLATED DRILL POINTS - THE EFFECT OF POINT THINNING ON DRILLING TIMES (SECONDS). (6.35 mm THICK M.S.)

| DRILLING TIMES | | | | |
|---|---|---|---|---|
| POINT ANGLE | 10 mm THICK MILD STEEL | | 6.5 mm THICK MILD STEEL | |
| | SOCKET PIN | | SOCKET PIN | |
| | WITH | WITHOUT | WITH | WITHOUT |
| 110° | 23 | 31 | 10.2 | 15.0 |
| 120° | 15 | 23 | 9.0 | 16.2 |
| 130° | 15 | 20 | 11.8 | 15.5 |

TABLE No. 11.16

HAND HELD POWER TOOL DRILLING TIMES : OPERATOR 'A'
WITH AND WITHOUT SOCKET PIN SUPPORT
(6.35 mm AND 10 mm THICK MILD STEEL).

| HOLE No. | DRILLING TIME (secs) | HOLE DIAMETER AT ENTRY (mm) |
|---|---|---|
| 1 | - | 5.64 |
| 2 | 19.0 | 5.72 |
| 3 | 10.0 | 5.60 |
| 4 | 19.0 | 5.68 |
| 5 | 38.0 | 5.58 |
| 6 | 26.0 | 5.76 |
| 7 | 11.5 | 5.81 |
| 8 | 13.5 | 5.81 |
| 9 | 24.0 | 5.70 |
| 10 | 22.5 | 5.85 |
| 11 | 13.0 | 5.79 |

TABLE No. 11.17

HAND HELD POWER TOOL : OPERATOR 'A'
DRILLING TIME AND HOLE DIAMETER (WITHOUT SOCKET PIN)
AT DRILL ENTRY FOR DRILL SCREWS "AS SUPPLIED".
(6.35 mm THICK MILD STEEL).

| POINT ANGLE x 40° CLEARANCE | TIME (secs) | |
|---|---|---|
| | BRIGHT DRAWN M.S. (6.35 mm THICK) | MILD STEEL (6.35 mm THICK) |
| 110° | 39.4 | 22.2 |
| 120° | 27.0 | 10.8 |
| 130° | 19.2 | 11.1 |

TABLE 11.18

THE EFFECT OF MATERIAL HARDNESS ON DRILLING TIME AT A CONSTANT THRUST FORCE OF 210N (DRILL PRESS)

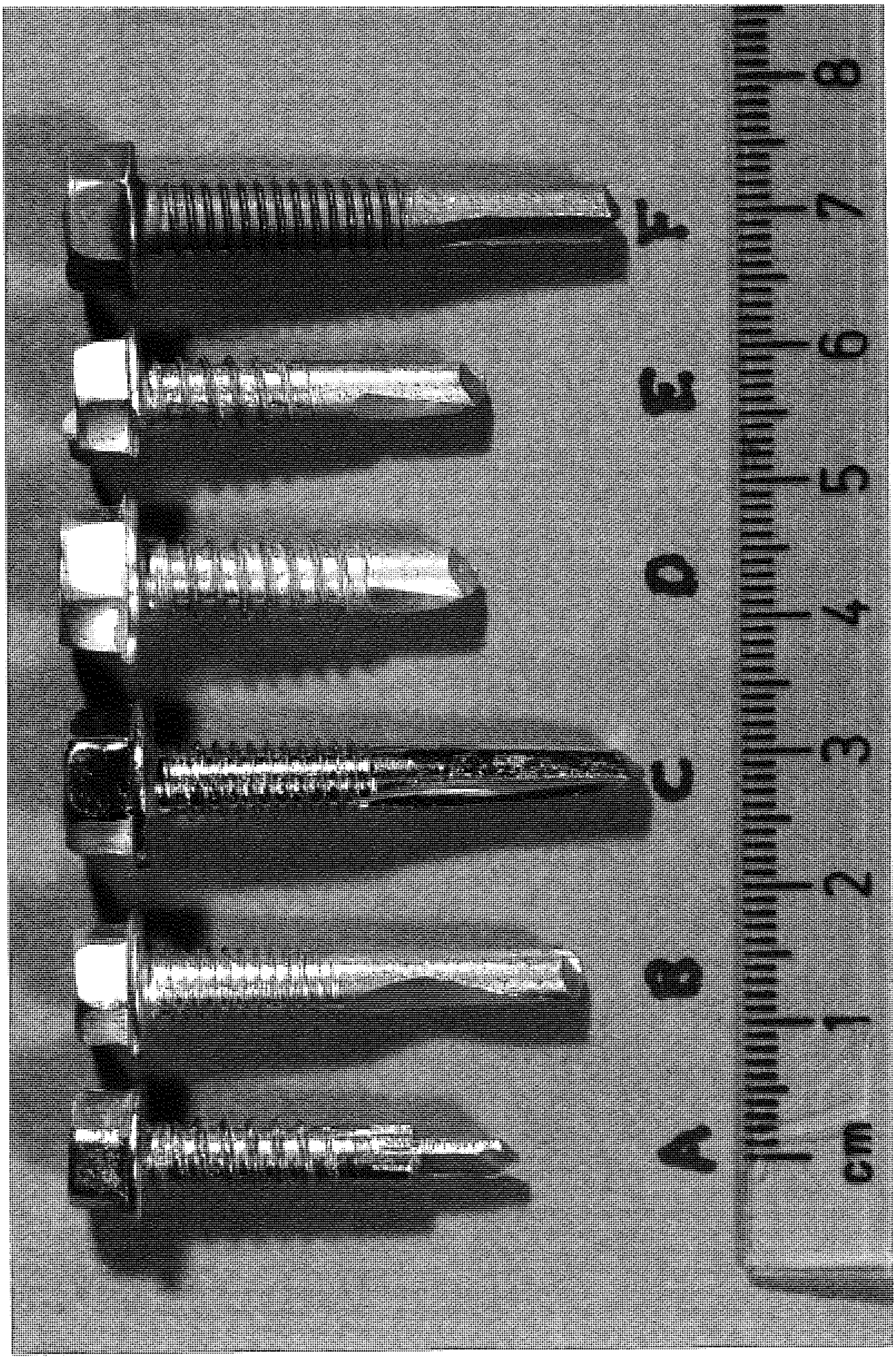



FIG. 11.1 DETAILS OF DRILL SCREWS TYPES A-F

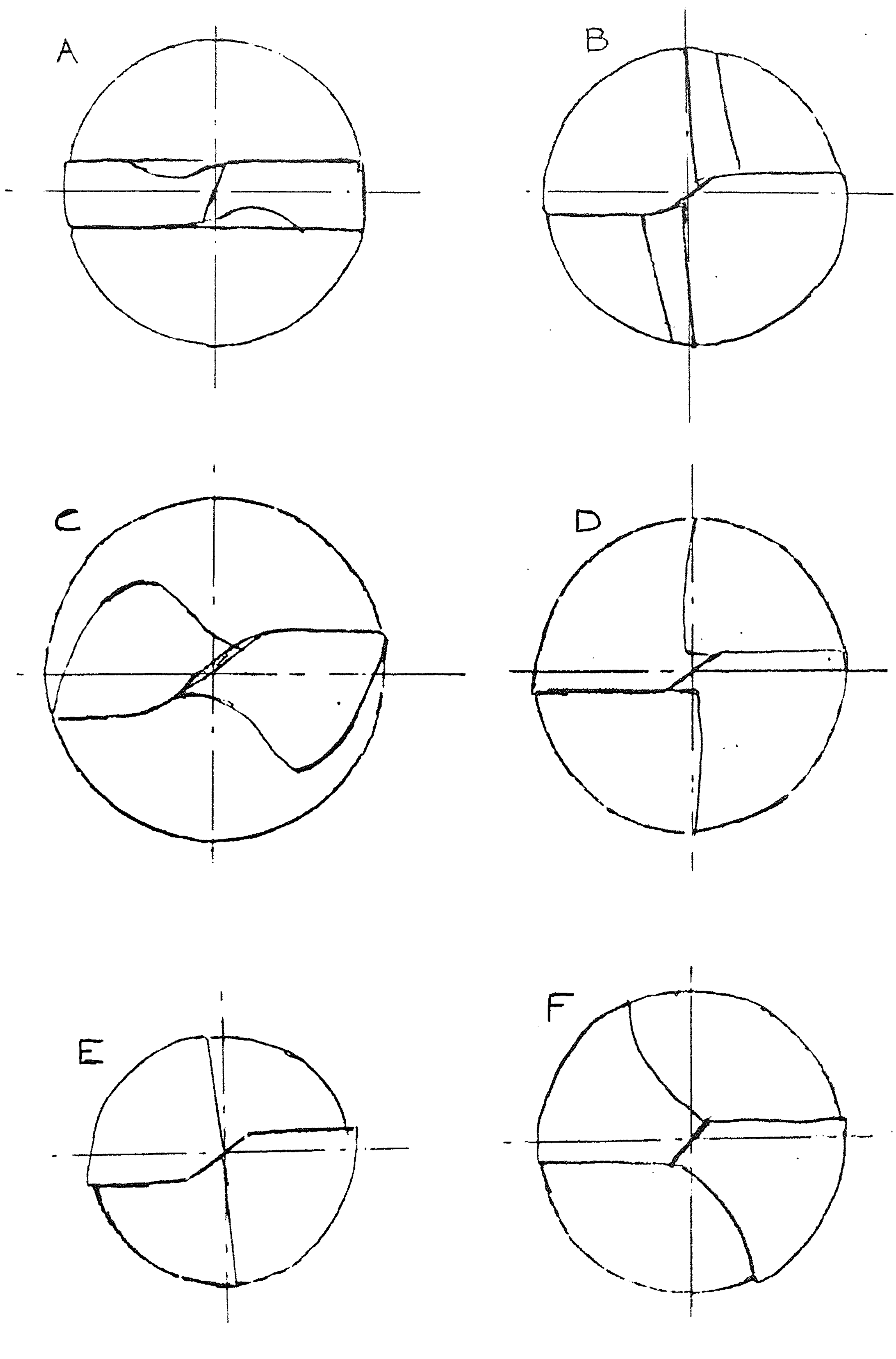



FIG 11.2 DRILL SCREWS TYPES A-F POINT CONFIGURATION FROM SHADOW GRAPH PROJECTION (MAGNIFICATION 10 TIMES)

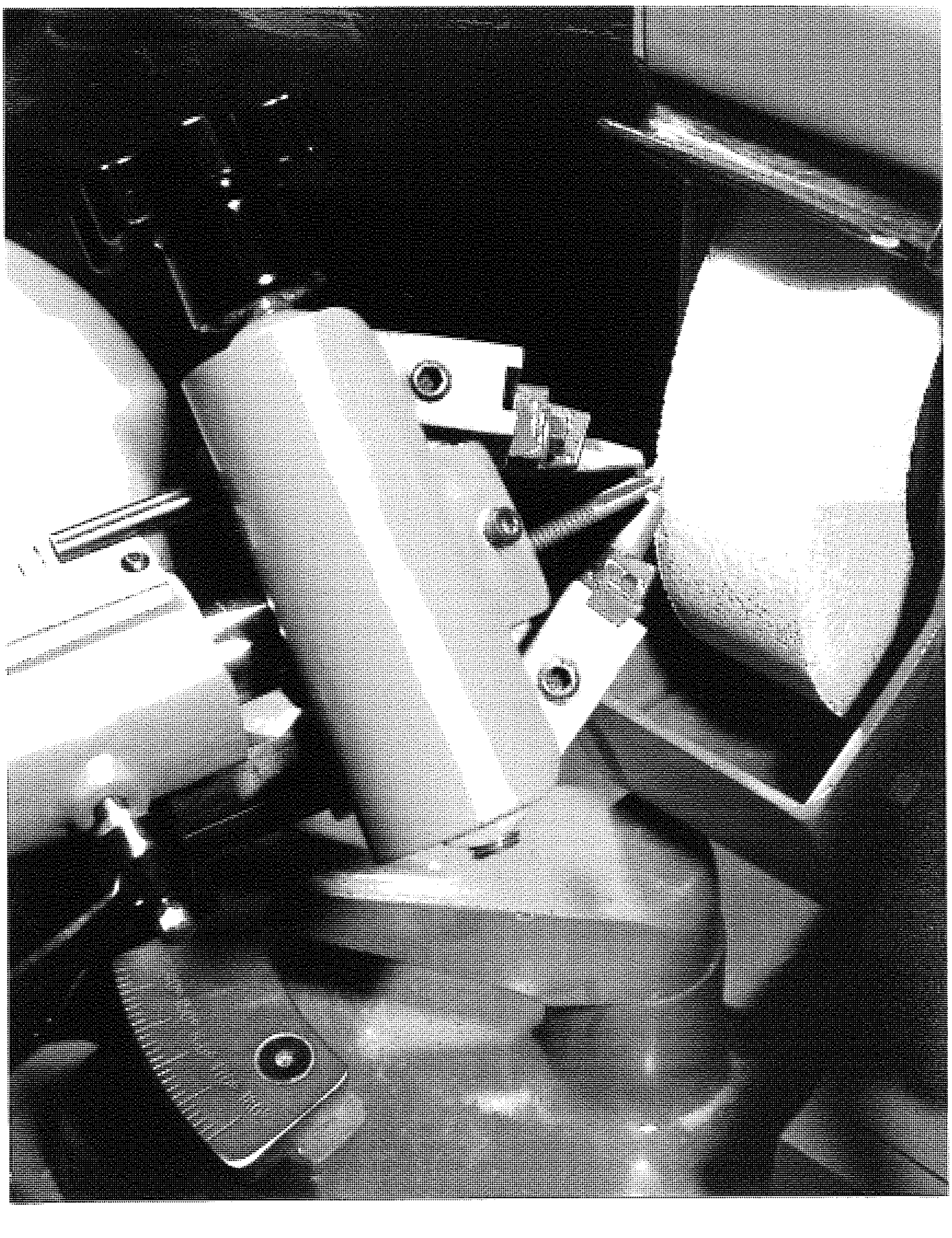


FIG 11.3 GRINDING OF DRILL SCREW POINTS ON THE MICRON DRILL POINT GRINDING MACHINE

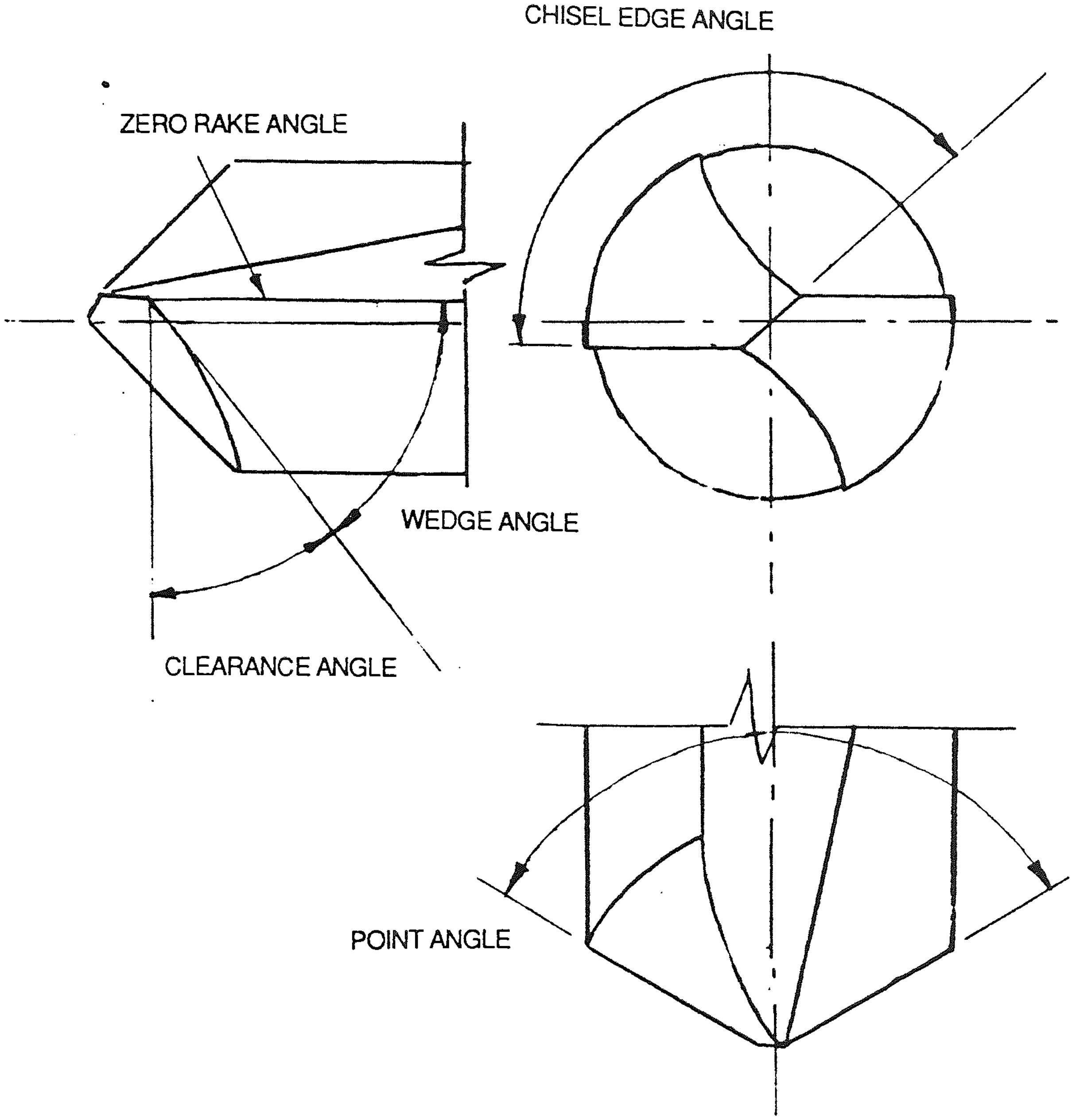
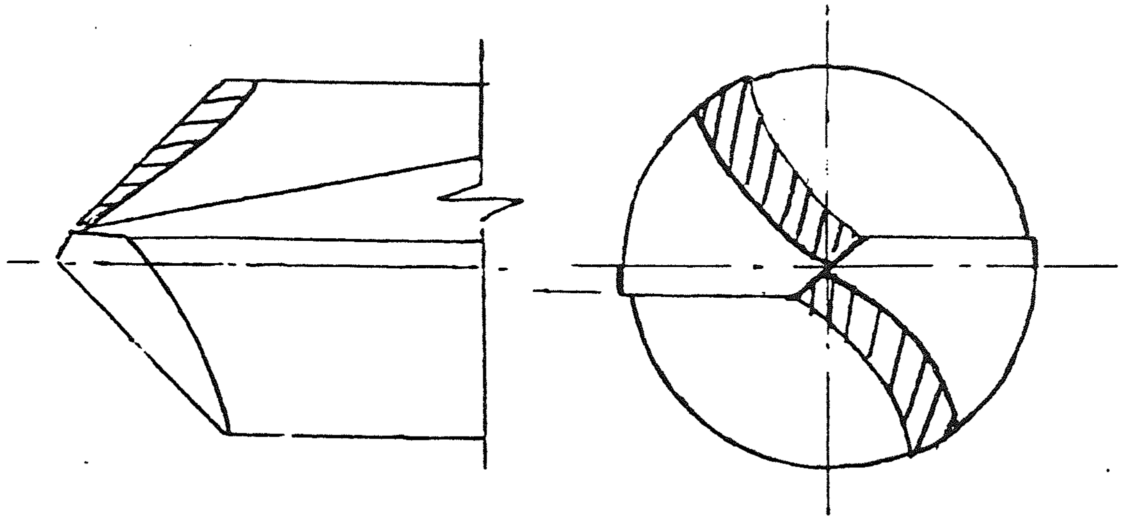



FIG 11.4 DRILL SCREW NOMENCLATURE - TYPE " F"
(1ST ANGLE PROJECTION 10 TIMES MAGNIFICATION )



POINT THINNING BY GRINDING
ON LEADING EDGES OF FLUTES
ON SHADED PORTIONS SHOWN

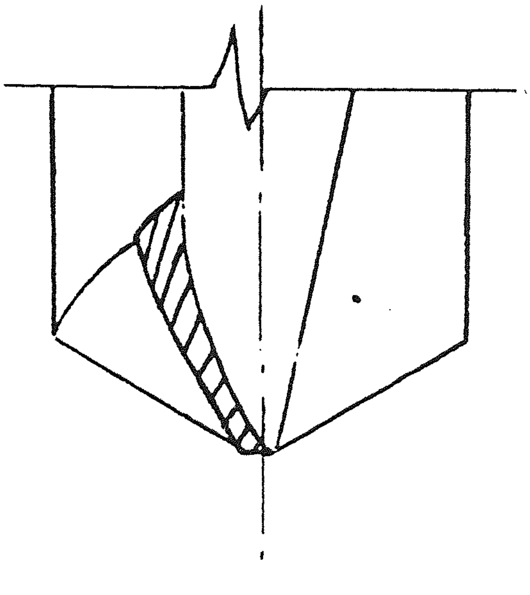


FIG 11.5 DRILL SCREW -POINT THINNING - TYPE " F"

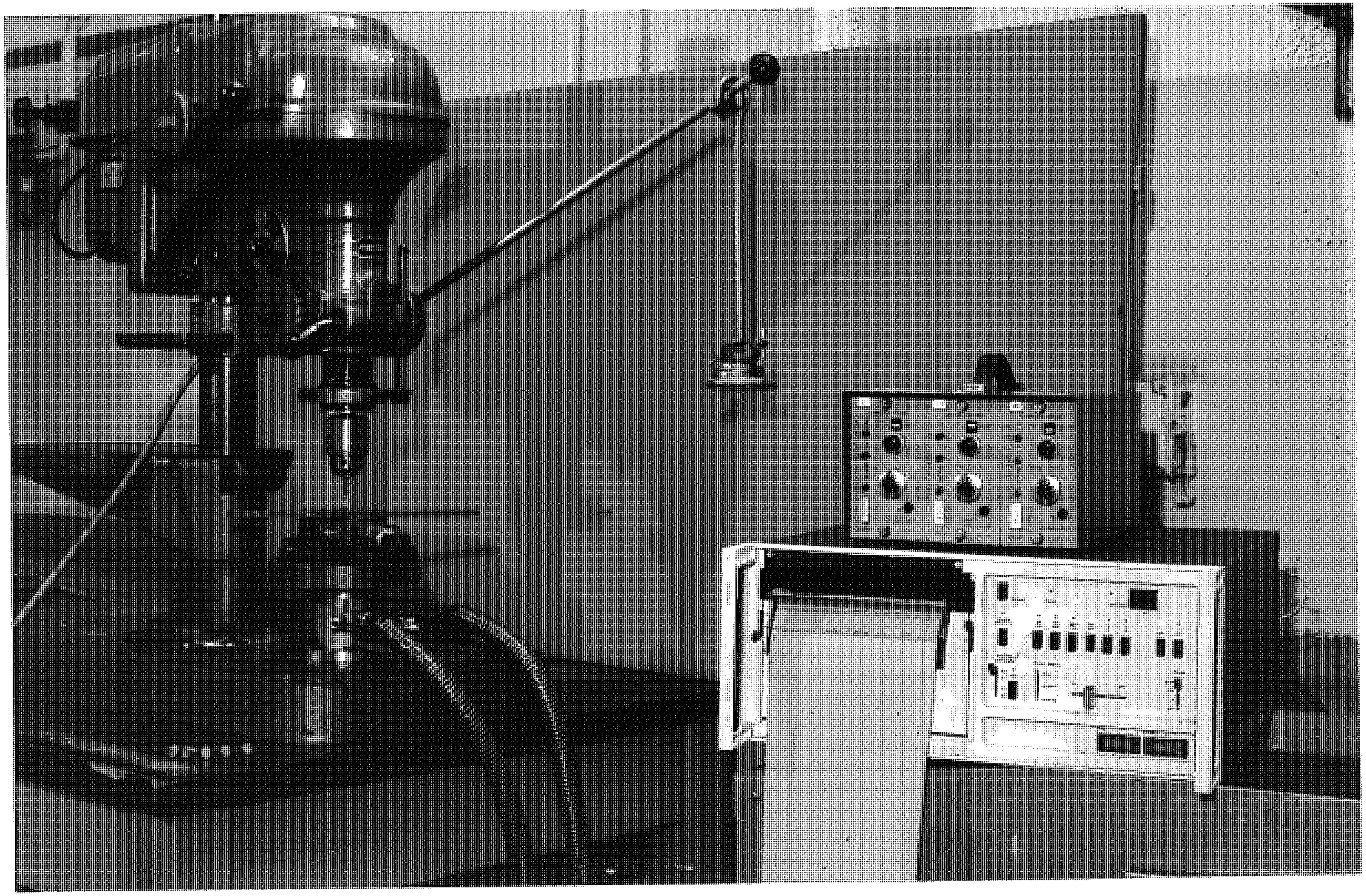


FIG 11.6 DRILL PRESS WITH EXTENDED LEVER ARM FOR APPLYING CONSTANT THRUST FORCE

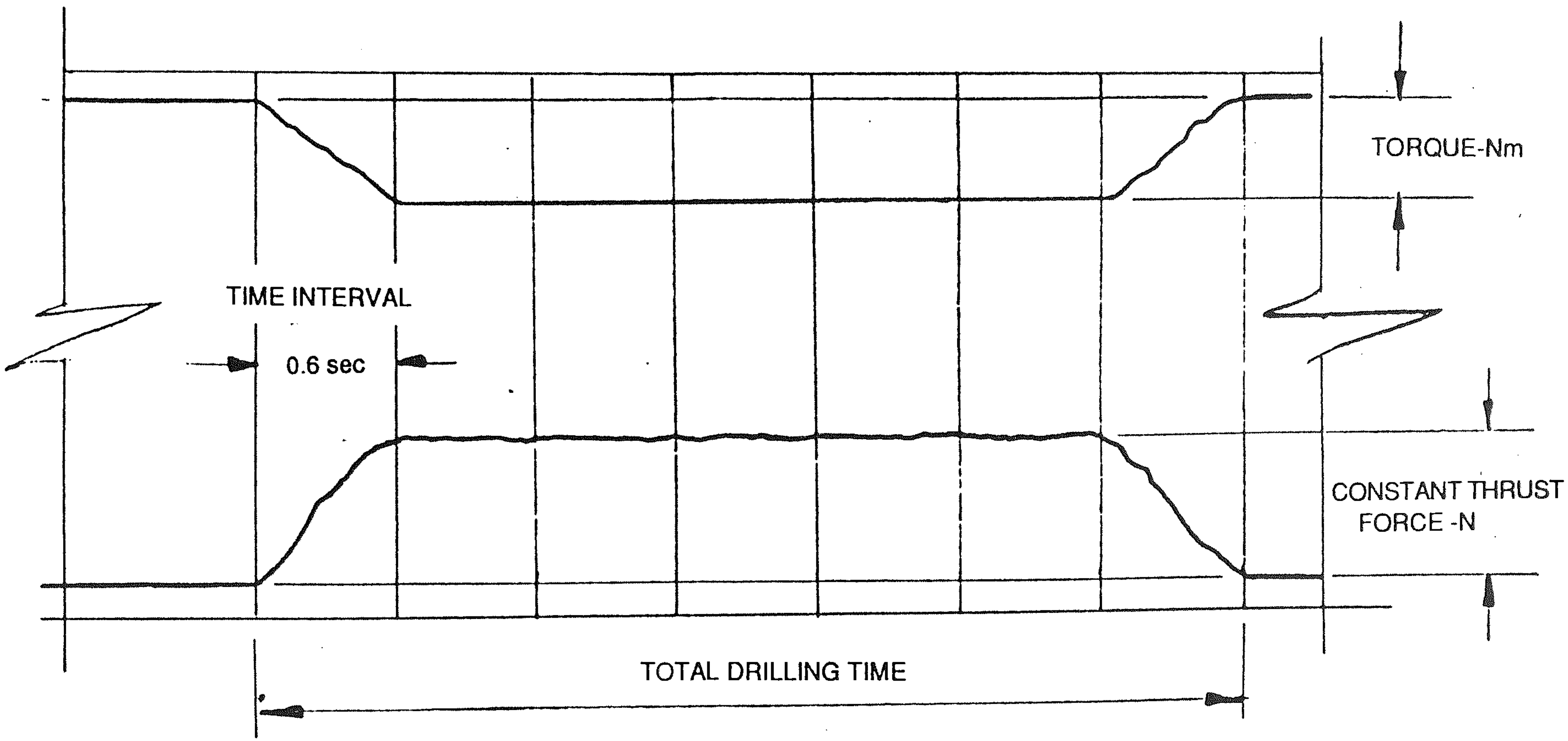



FIG 11.7 EXAMPLE OF U.V. TRACE FORM FOR DRILLING ONE HOLE

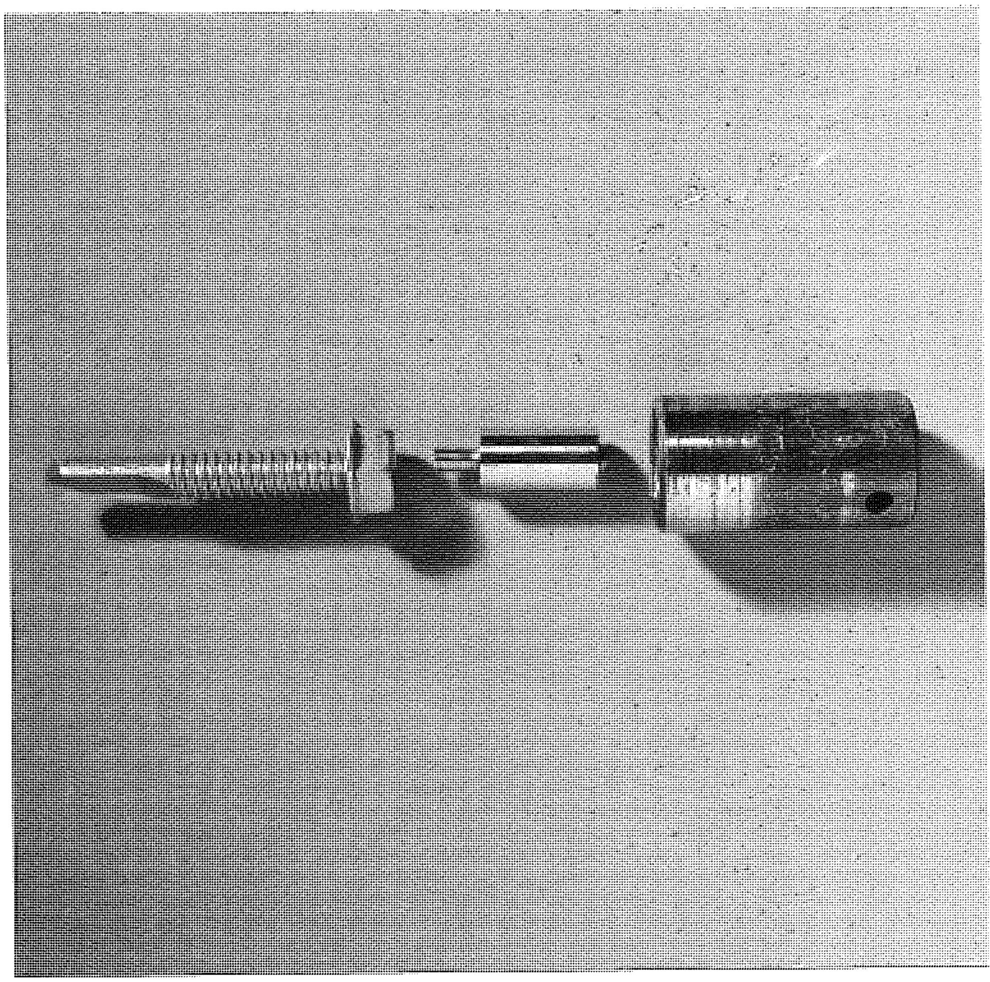


FIG 11.8 HAND HELD POWER TOOL - DRILL SCREW SET UP FOR IMPROVED HEAD SUPPORT WITH SOCKET CENTRE PIN

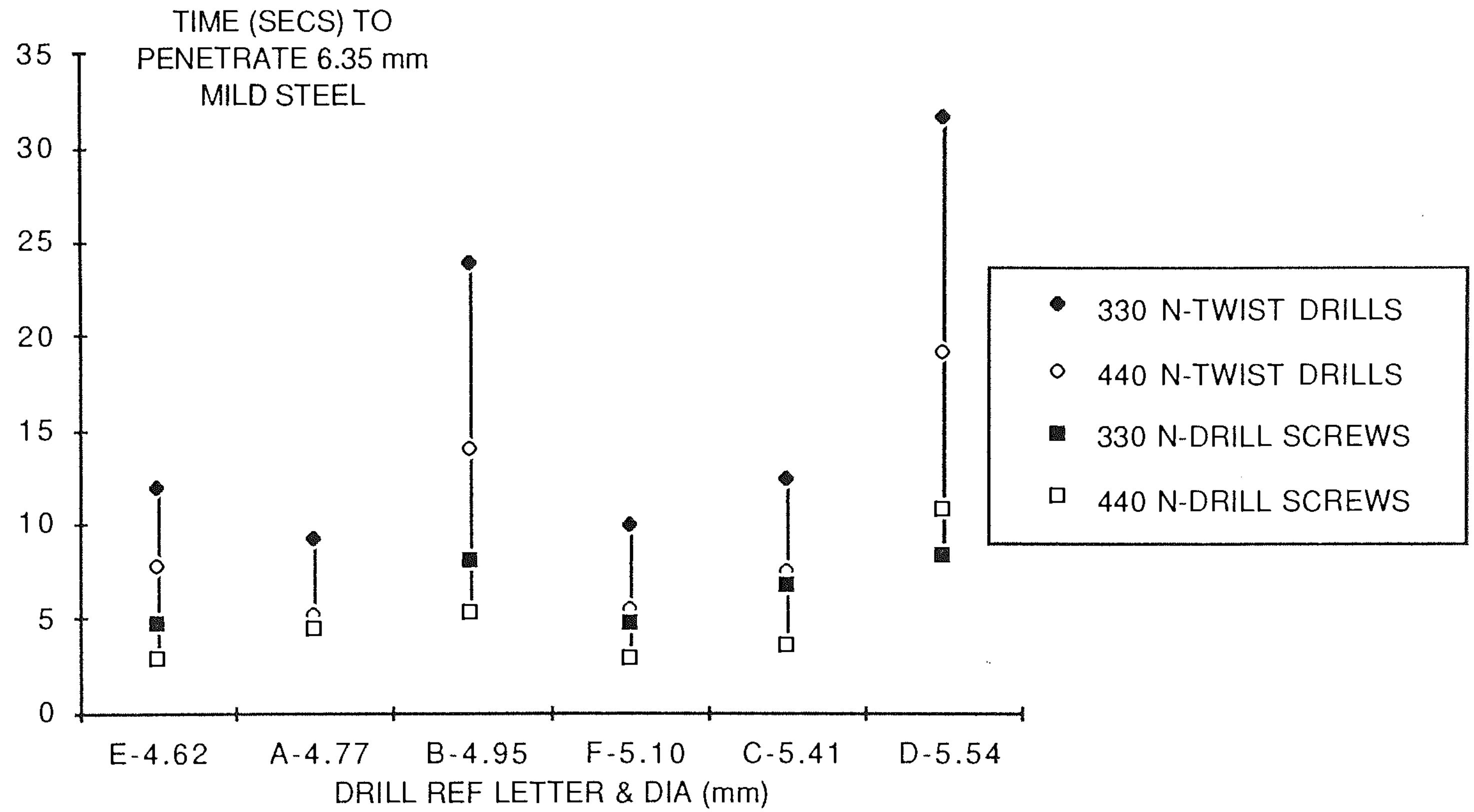



FIG 11.9 COMPARISON OF DRILLING TIMES (SEC) AT A CONSTANT THRUST FORCE OF BOTH 330 N AND 440 N FOR 6 DIFFERENT TYPES OF DRILL SCREW (A-F) AND THE NEAREST DIAMETER CONVENTIONAL TWIST DRILLS

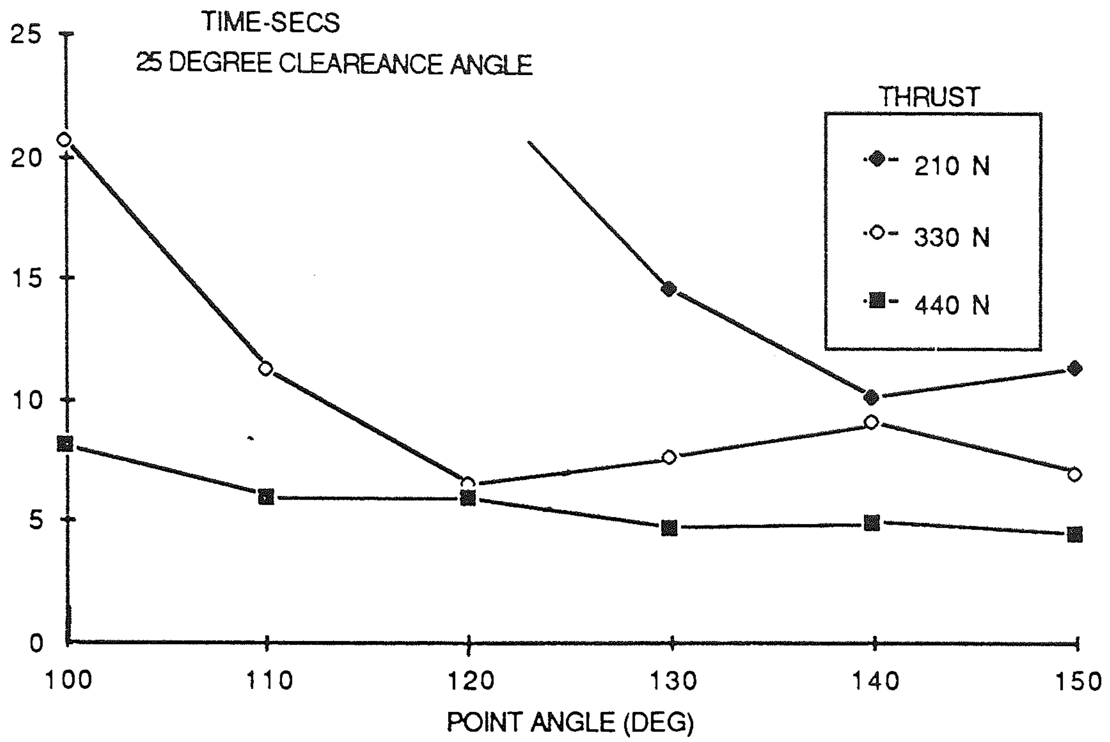



FIG 11.10 DRILL PRESS TRIALS -DRILLING TIMES (SECS) FOR THROUGH HOLES IN 6.35 mm THICK MILD STEEL FOR DRILL SCREWS GROUND TO 25 DEGREE CLEARANCE ANGLE AND DIFFERENT POINT ANGLES

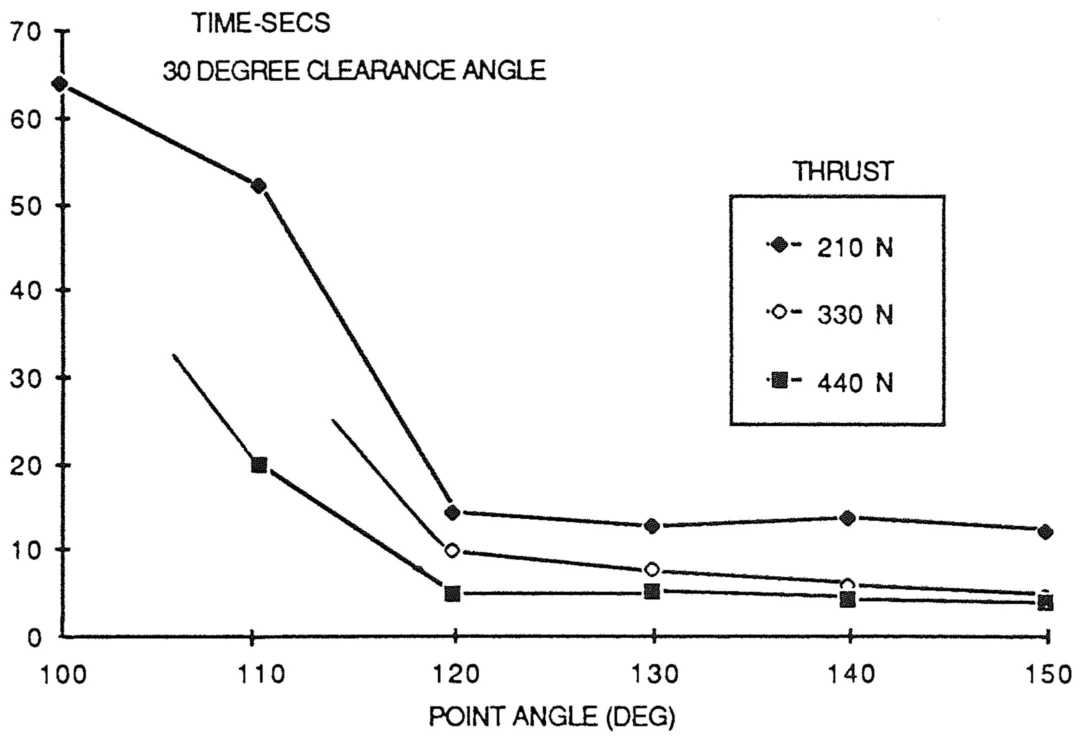



FIG 11.11 DRILL PRESS TRIALS -DRILLING TIMES (SECS) FOR THROUGH HOLES IN 6.35 mm THICK MILD STEEL FOR DRILL SCREWS GROUND TO 30 DEGREE CLEARANCE ANGLE AND DIFFERENT POINT ANGLES

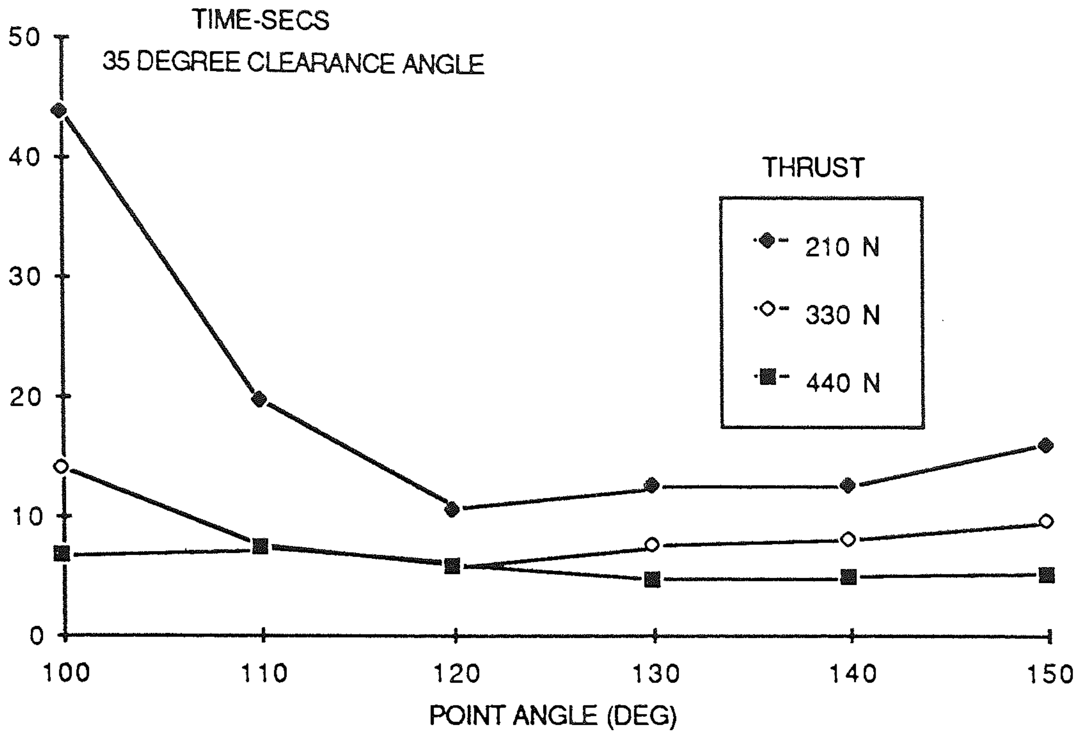



FIG 11.12 DRILL PRESS TRIALS -DRILLING TIMES (SECS) FOR THROUGH HOLES IN 6.35 mm THICK MILD STEEL FOR DRILL SCREWS GROUND TO 35 DEGREE CLEARANCE ANGLE AND DIFFERENT POINT ANGLES

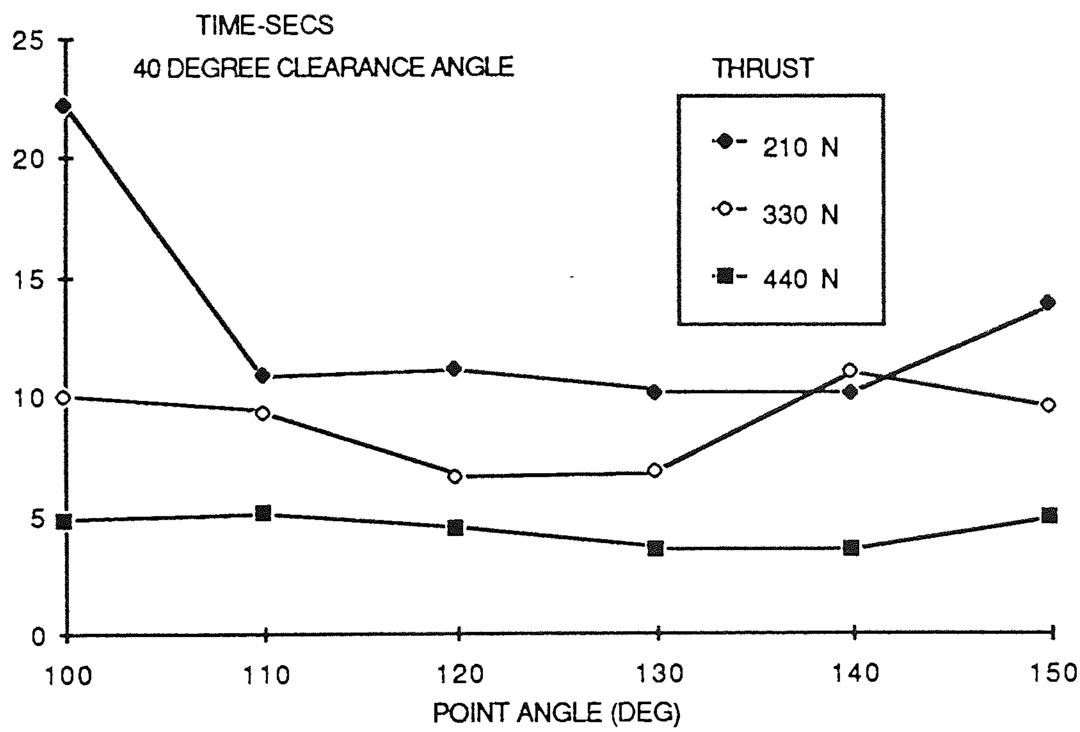



FIG 11.13 DRILL PRESS TRIALS -DRILLING TIMES (SECS) FOR THROUGH HOLES IN 6.35 mm THICK MILD STEEL FOR DRILL SCREWS GROUND TO 40 DEGREE CLEARANCE ANGLE AND DIFFERENT POINT ANGLES

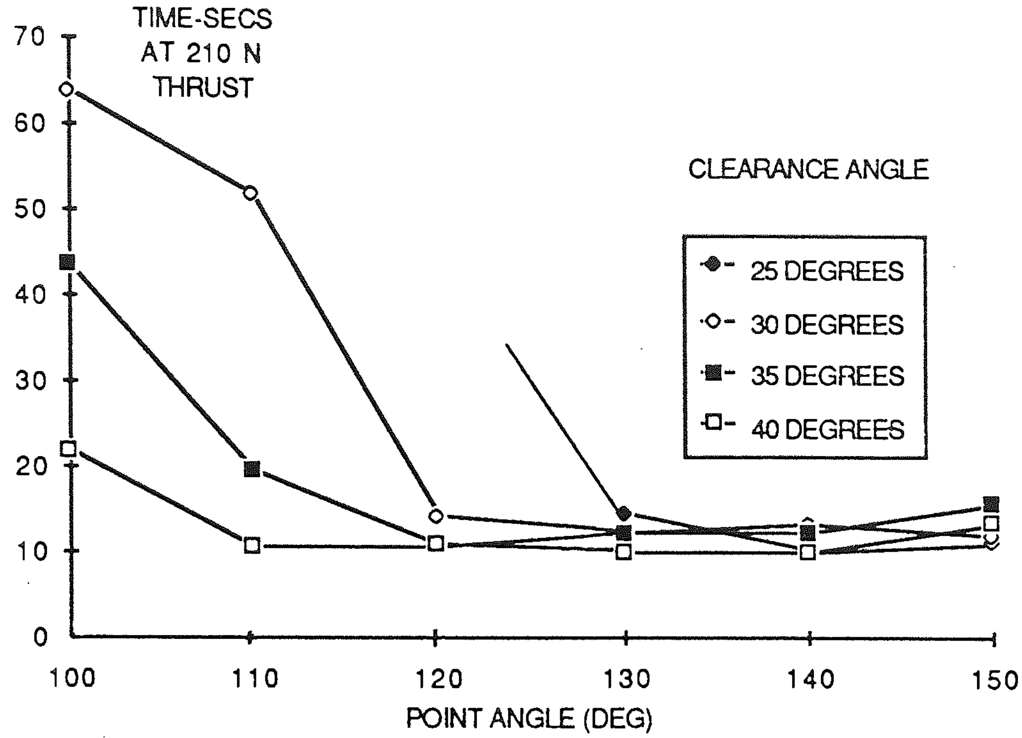



FIG 11.14 DRILL PRESS TRIALS -DRILLING TIMES (SECS) AT A THRUST OF 210 N FOR THROUGH HOLES IN 6.35 mm THICK MILD STEEL DRILL SCREWS GROUND TO 4 DIFFERENT CLEARANCE ANGLES

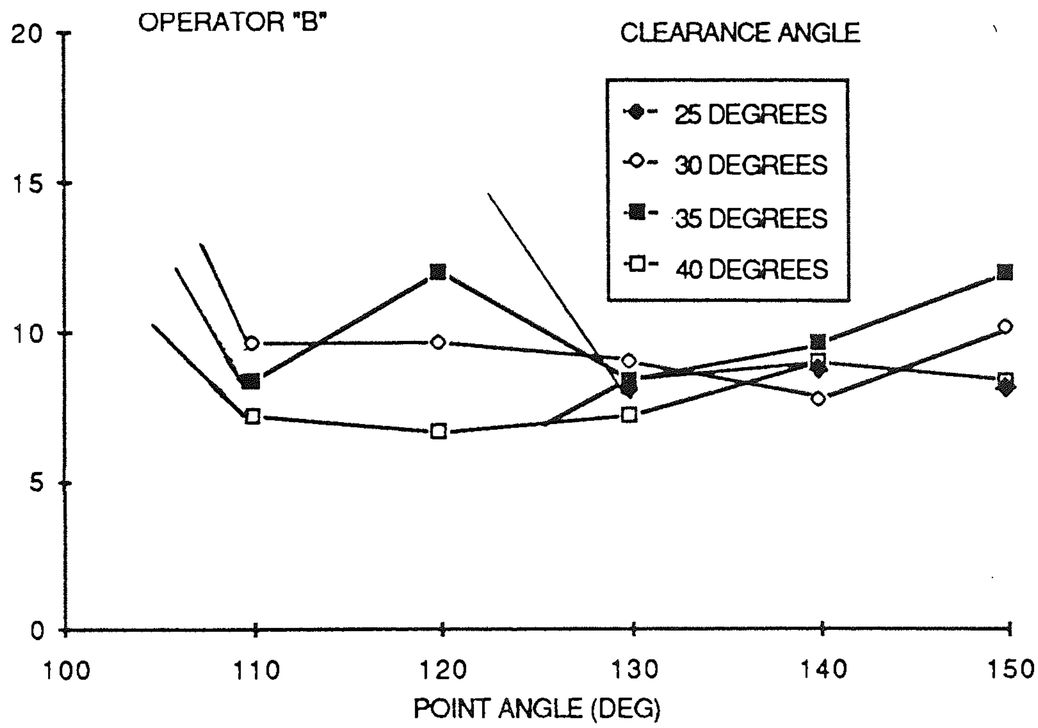



FIG 11.15 HAND HELD POWER TOOL -DRILLING TIMES (SECS) FOR OPERATOR "B" THROUGH HOLES IN 6.35 mm THICK MILD STEEL FOR DRILL SCREWS GROUND TO 4 DIFFERENT CLEARANCE ANGLES

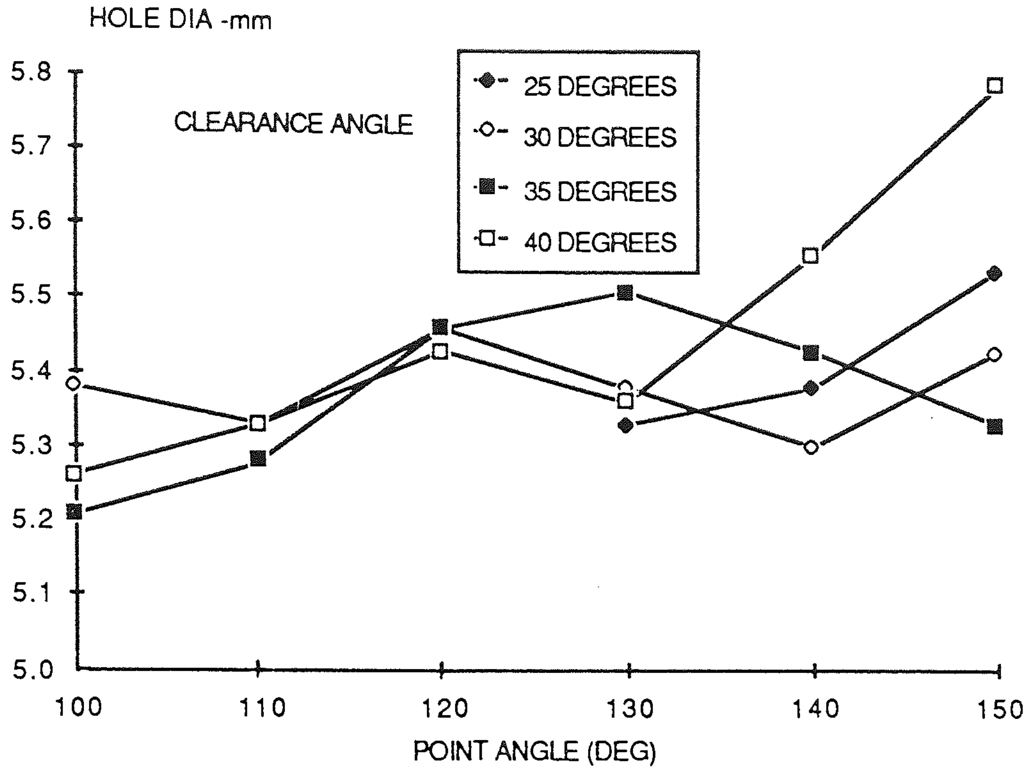



FIG 11.16 DRILL PRESS - HOLE DIAMETER (mm) AT DRILL ENTRY WITH 210 N THRUST AND 6.35 mm THICK MILD STEEL ( NOMINAL DRILL DIAMETER = 5.1 mm )

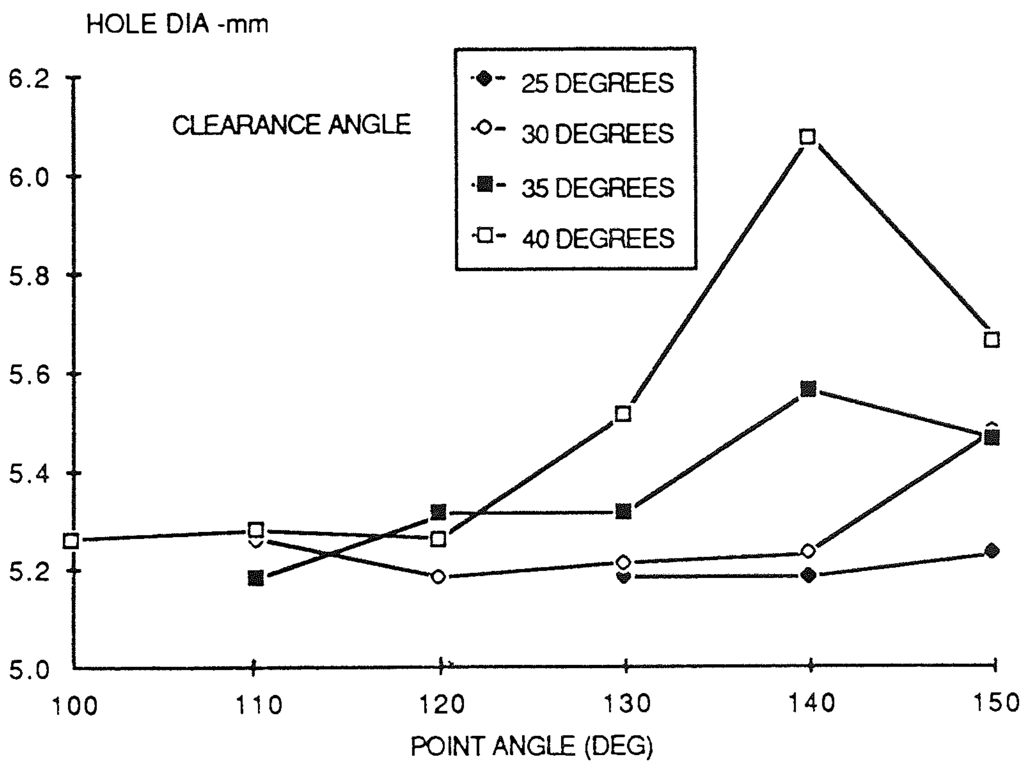



FIG 11.17 HAND HELD POWER TOOL - HOLE DIAMETER (mm) AT DRILL ENTRY WITH OPERATOR "B" USING 6.35 mm THICK MILD STEEL ( NOMINAL DRILL DIAMETER = 5.1 mm )

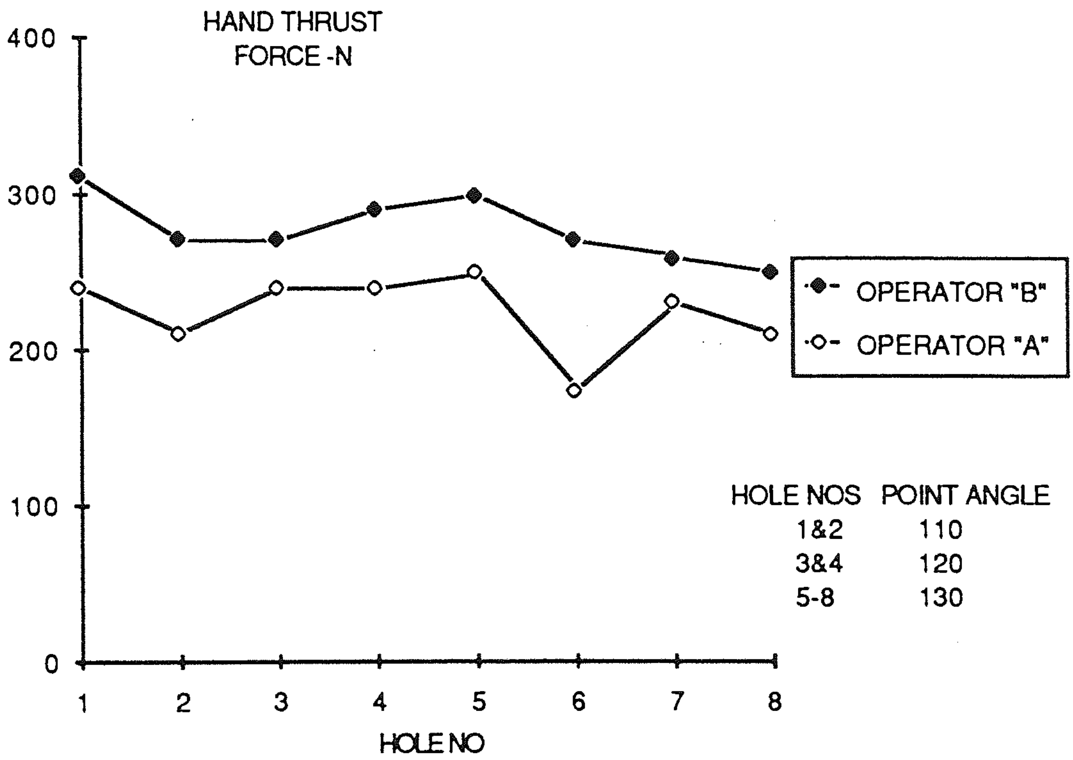



FIG 11.18 HAND HELD POWER TOOL -THRUST FORCE EXERTED AT BENCH VICE BY TWO OPERATORS "A" AND "B" IN HORIZONTAL DRILLING WITH DRILL SCREWS

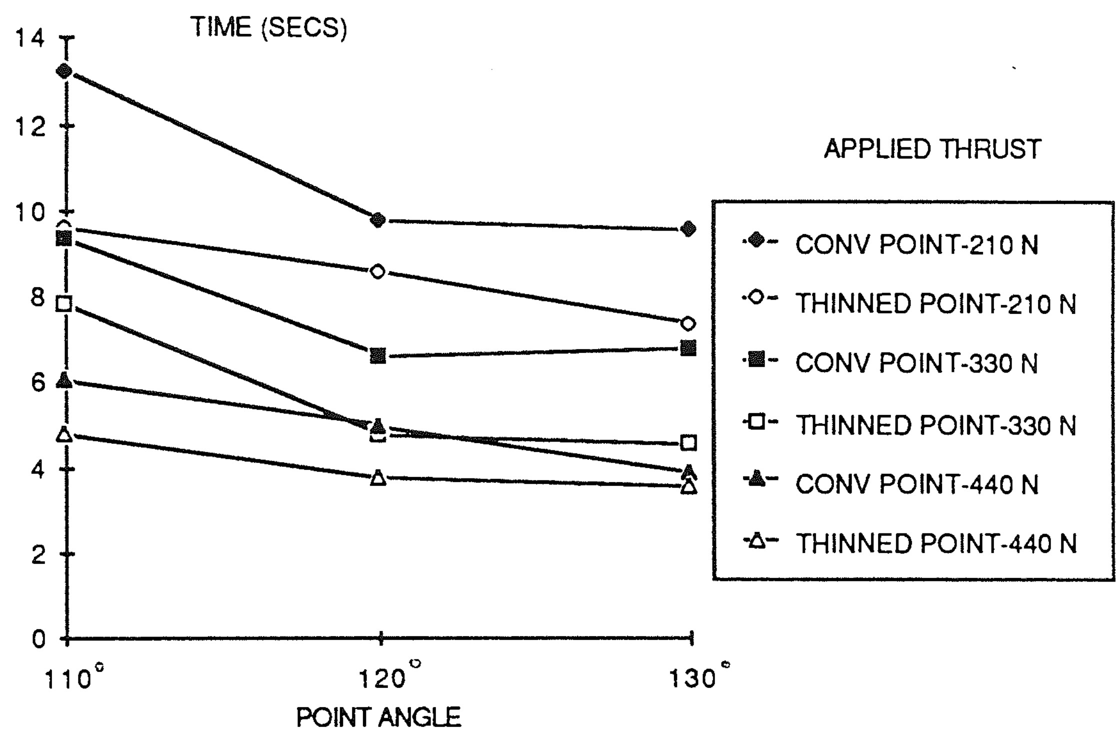



FIG 11.19 DRILL PRESS TRIALS - DRILLING TIMES AT 40 CLEARANCE ANGLE FOR CONVENTIONAL AND THINNED POINTS WITH POINT GROUND, HARDENED AND CADMIUM PLATED SCREWS-6.35 mm MS

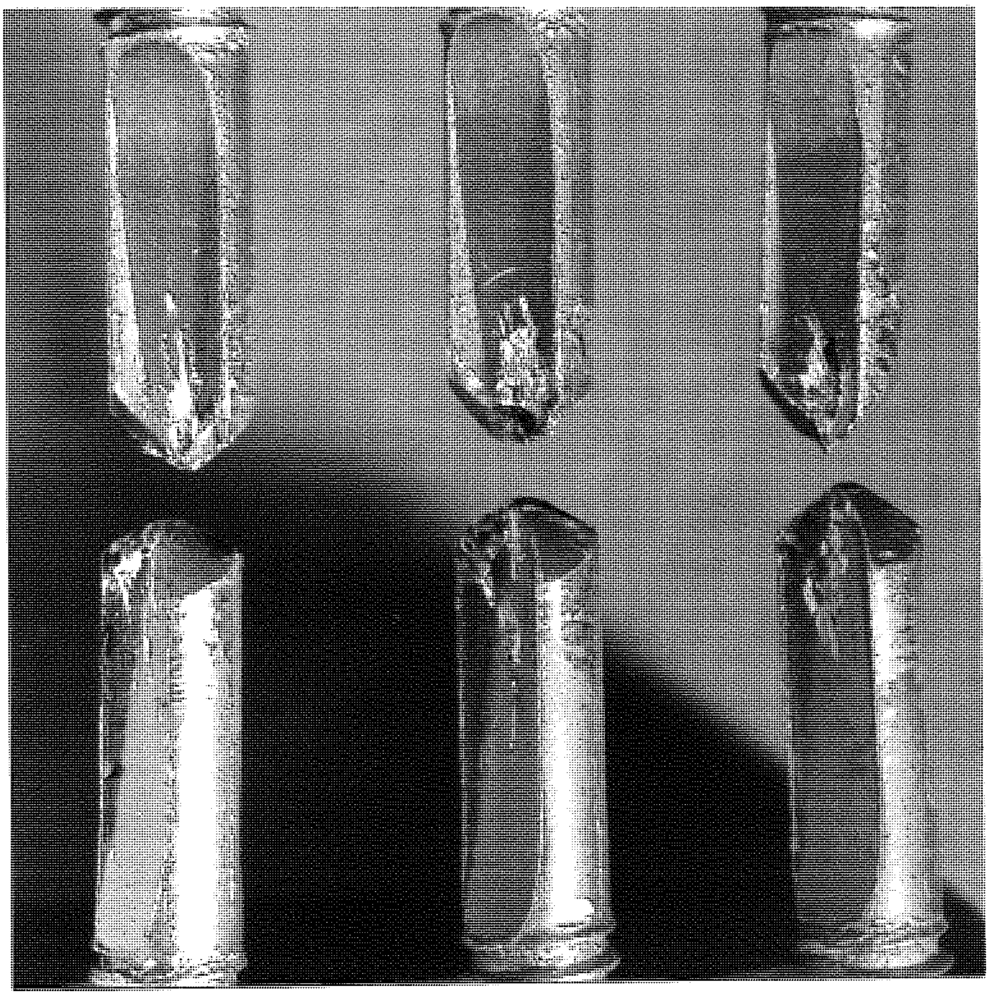


FIG 11.20 DRILL PRESS TRIALS -440 N THRUST. WEAR ON REGROUND DRILL POINTS AFTER HARDENING AND CADMIUM PLATING

POINT ANGLES LEFT TO RIGHT :
TOP ROW : THINNED POINTS 130 ,120 , 110
BOTTOM ROW : CONVENTIONAL POINTS 130 ,120, 110

(POINTS HAVE 40 CLEARANCE -6.35 mm THICK BDMS WITH HARD SKIN )

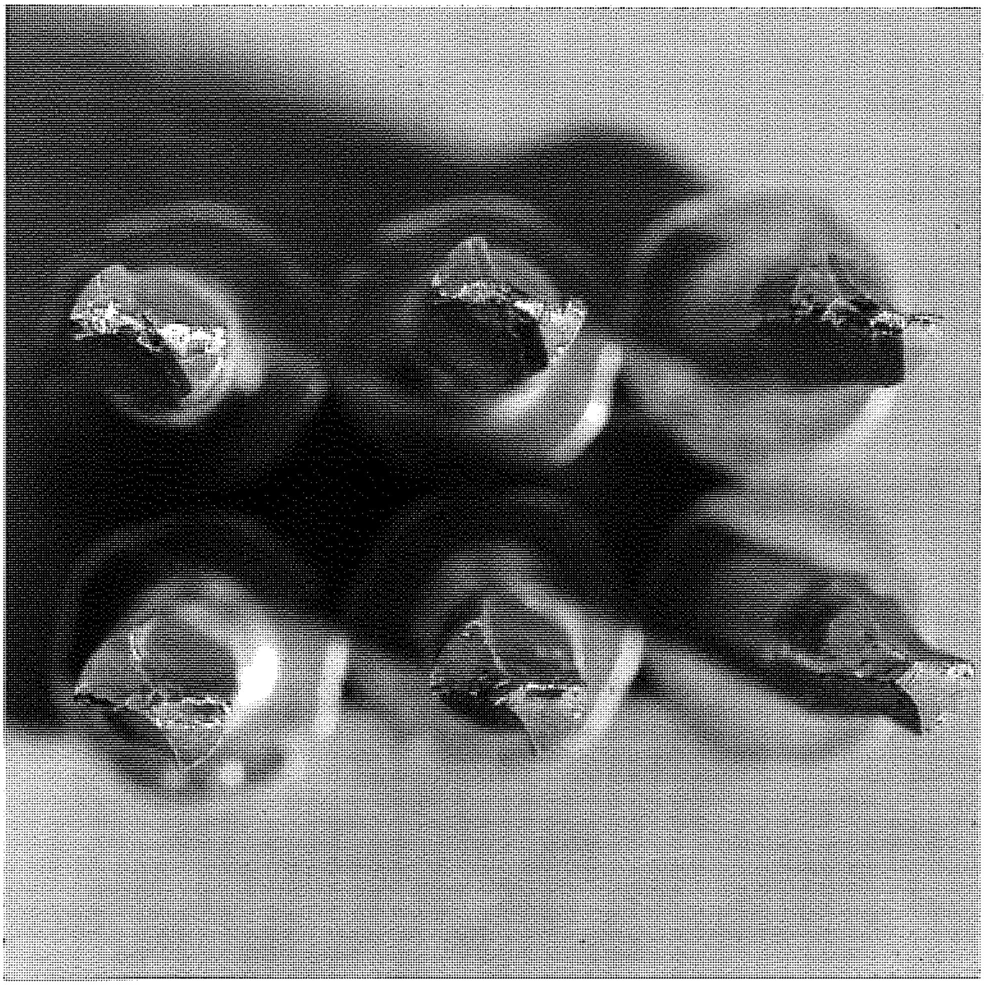


FIG 11.21 DRILL PRESS TRIALS -440 N THRUST
WEAR ON REGROUND DRILL POINTS
AFTER HARDENING AND CADMIUM PLATING

POINT ANGLES LEFT TO RIGHT :
TOP ROW : THINNED POINTS 130 ,120 , 110
BOTTOM ROW : CONVENTIONAL POINTS 130 ,120, 110

(POINTS HAVE 40 CLEARANCE -6.35 mm THICK BDMS WITH HARD SKIN )

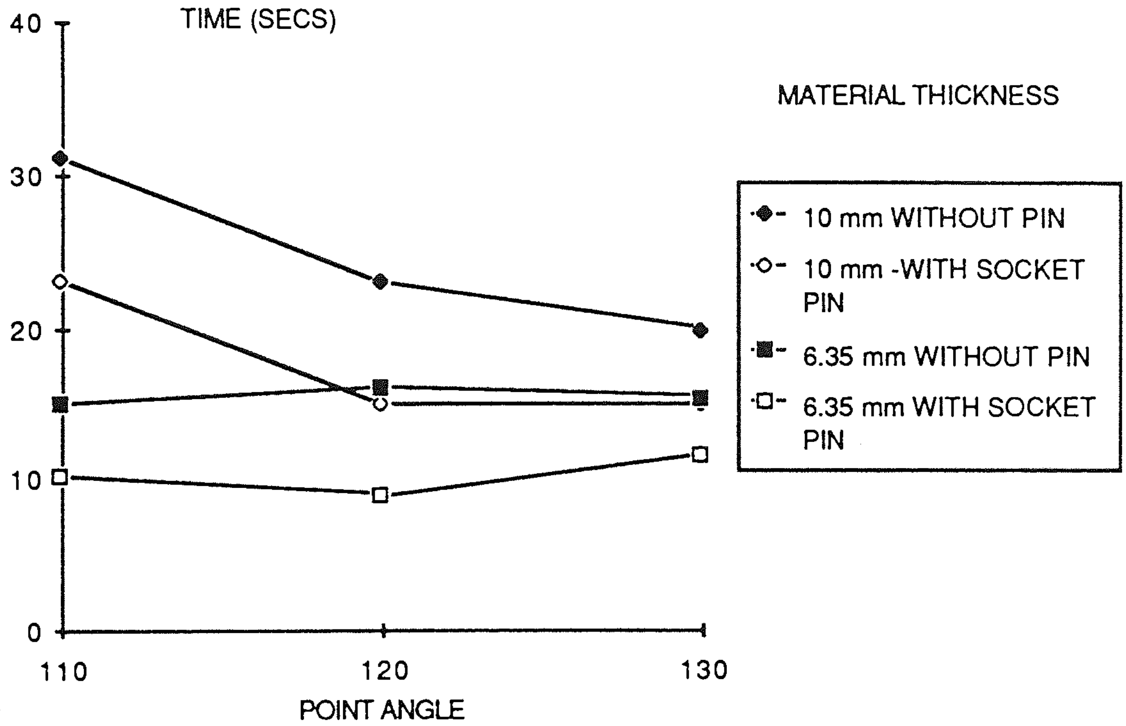



FIG 11.22 HAND HELD POWER TOOL -DRILLING TIMES FOR OPERATOR "A" WITH AND WITHOUT SOCKET PIN SUPPORT (REGROUND HARDENED AND PLATED SCREWS WITH 40 CLEARANCE)

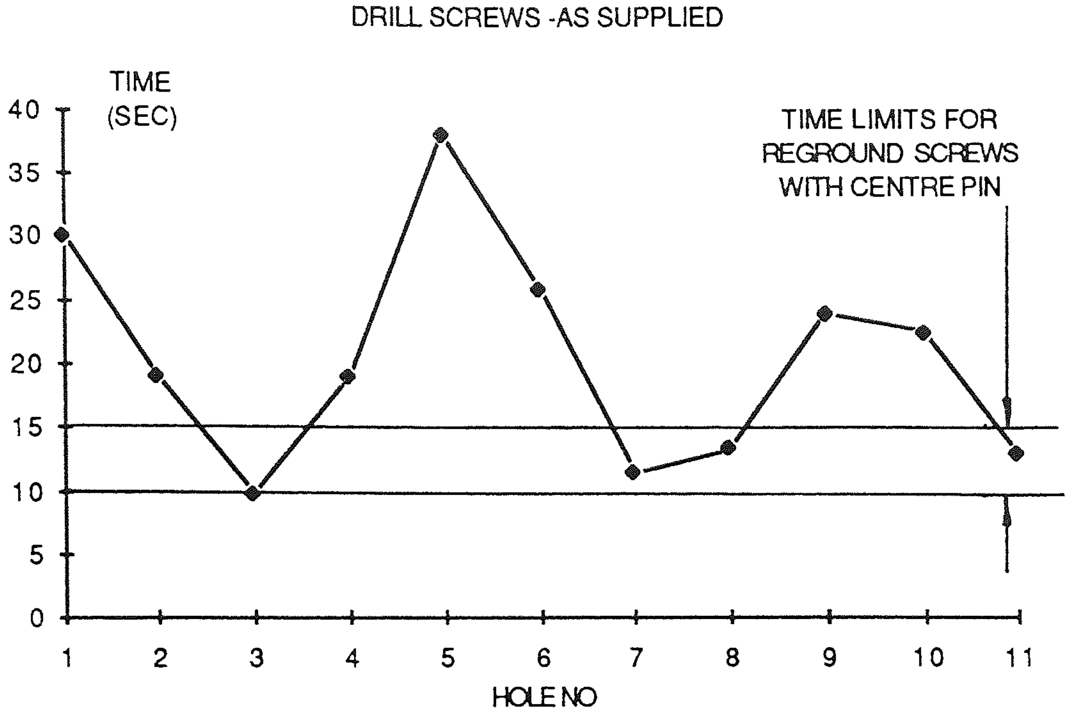



FIG 11.23 HAND HELD POWER TOOL -VARIATION IN DRILLING TIMES
FOR DRILL SCREWS IN THE AS SUPPLIED CONDITION
(TIMES FOR OPERATOR "A" WITHOUT THE SOCKET CENTRE PIN)

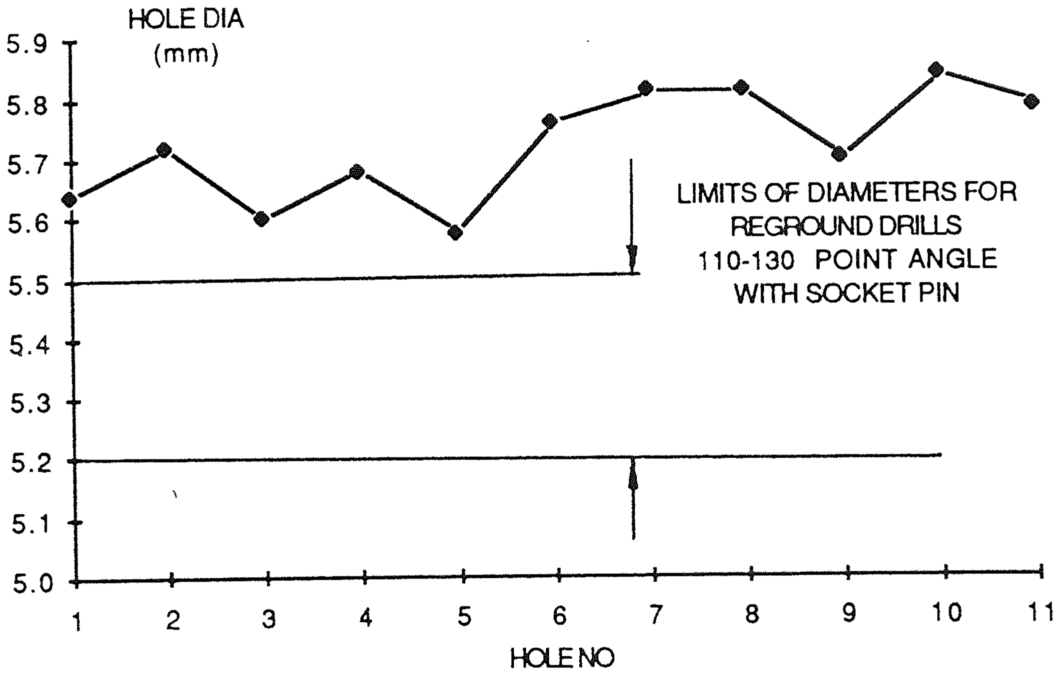



FIG 11.24 HAND HELD POWER TOOL -HOLE DIAMETER AT ENTRY
FOR DRILL SCREWS AS SUPPLIED
(WITHOUT SOCKET PIN)-6.35 mm THICK MILD STEEL

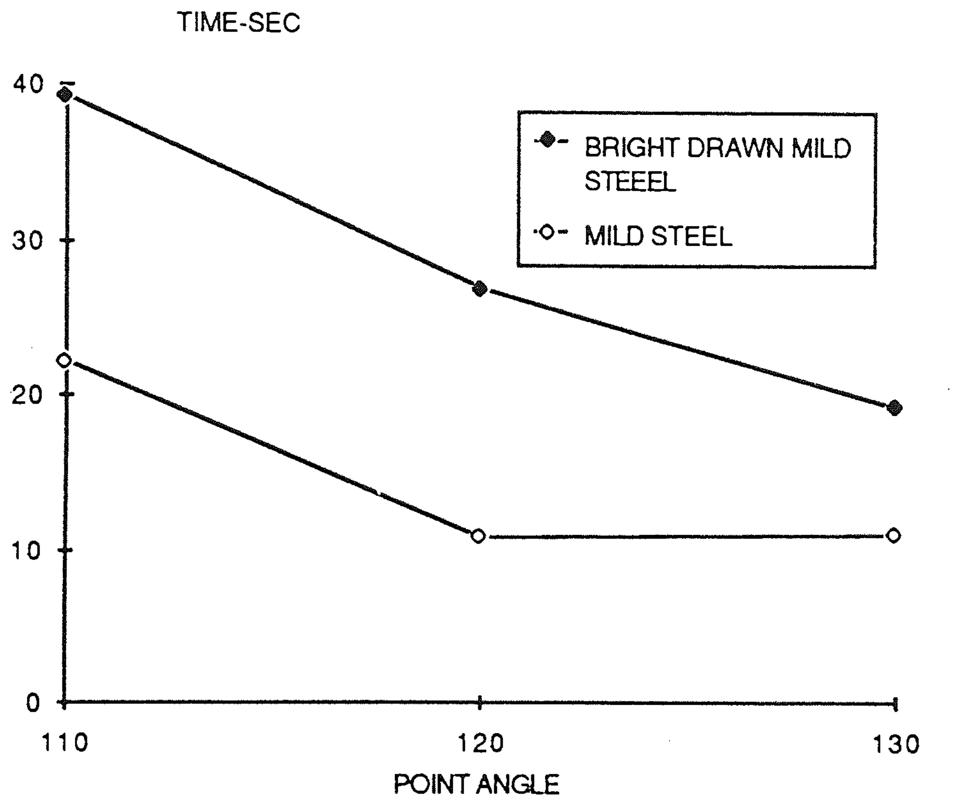



FIG 11.25 DRILL PRESS- THE EFFECT OF MATERIAL HARDNESS ON DRILLING TIME AT 210 N THRUST USING DRILL SCREWS WITH 40 DEGREE CLEARANCE AND 6.35 mmTHICK MATERIAL

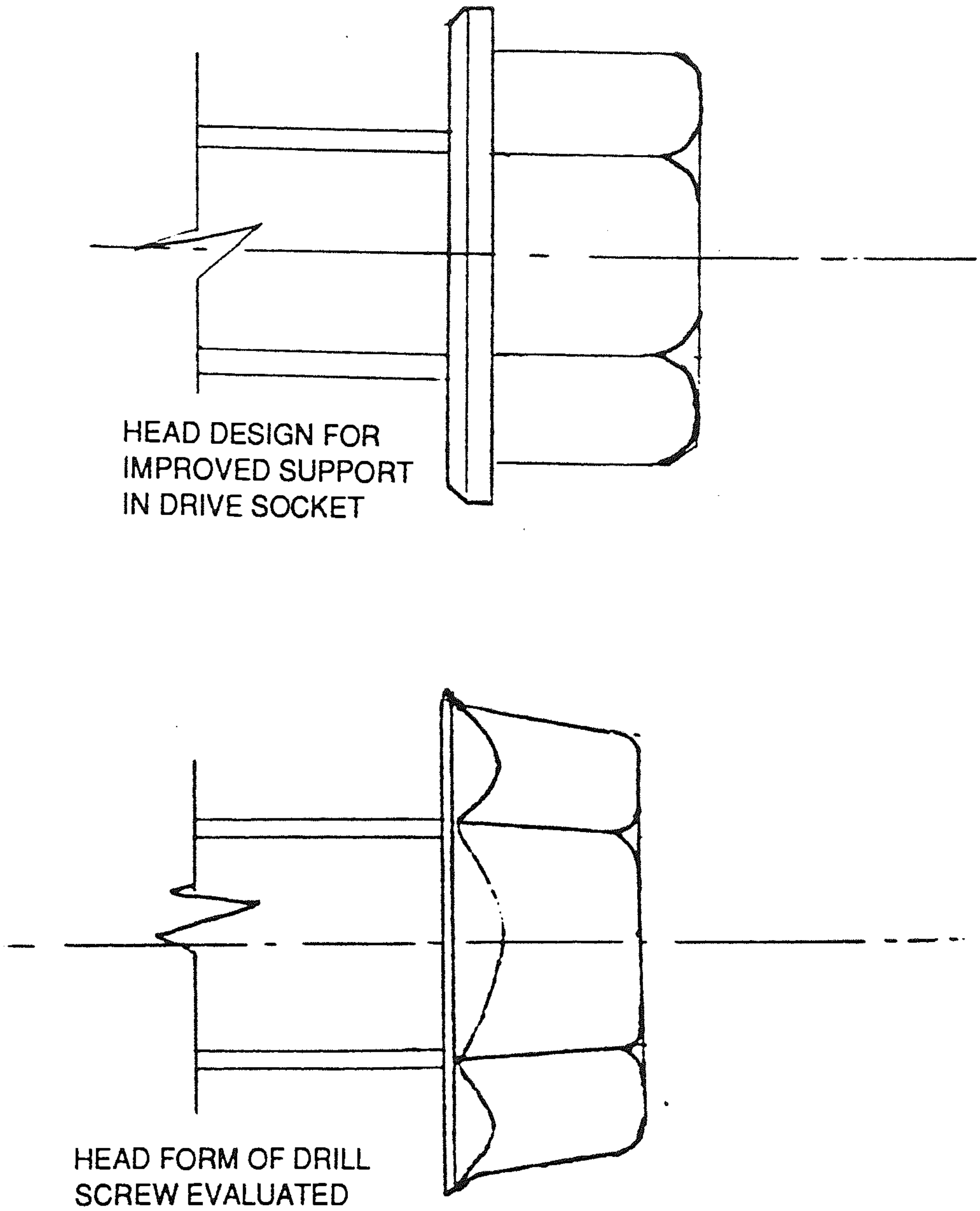



FIG 11.26 IMPROVEMENTS TO DRILL SCREW HEAD DESIGN
(HEAD PROPORTIONS IN RELATION TO SIZE OF THREAD)

# CHAPTER TWELVE

## GENERAL DISCUSSION

Although twist drills were identified as probably the most common of all metal cutting tools, major improvements in drill performance have not until recently been attainable.

New drilling developments, particularly the use of pressure fed coolants, tungsten carbide drill materials and surface coating techniques, have enabled improved hole qualities and enhanced drill penetration rates to be achieved. These developments have resulted in the need for better understanding of drill performance.

The effect of drill geometry and different operating conditions (speed and feed) was therefore investigated and the drill performance and hole quality measured.

The ability to measure and predict the cutting forces was an important facet of the work, which enabled some drill point optimisation to be undertaken. The Kistler Drilling Dynamometer which was used to measure drill thrust, torque and radial force, was therefore very important to the whole study.

Throughout the research program the fundamental approach was firstly to identify and measure all aspects of the drill geometry. It was established that very small changes and errors in the drill point configuration, or the way in which the drill was used, often produced significant differences in the drill performance characteristics.

From the early days with the spear point drill and the first twist drills, accurate control of the drill point grinding process was identified as one of the most important factors in correct drill usage. The correlation between grinding errors, particularly lip height difference and hole oversize were predicted and established in the research. Drills with large lip height differences were likely to produce an unequal chip thickness distribution in the flutes and in the limiting condition cut on only one lip. This problem of unequal chip thickness was exacerbated by the use of fine feed rates when the feed per lip was very small.

Twist drills were always traditionally regarded as roughing tools which were unsuitable for producing precision holes. This approach stemmed from two fundamental difficulties of twist drill usage in general engineering conditions, i.e. precision grinding and precision measurement of ground points. Whilst correctly ground twist drills were unable to achieve the tolerances obtained by reaming, there was considerable scope for improving the drilled hole quality by firstly improving the drill point symmetry and geometry.

In the analysis to predict the torque and thrust in drilling the approach adopted was the hypothesis that the chip flow at the drill cutting lips could be considered as orthogonal and therefore analysed by Modified Merchants Equations.

When a sample of the spiral drilling swarf was superimposed in the drill flute the direction of chip flow was initially towards the drill web at approximately right angles to the lip (i.e. orthogonal).

When the axial and orthogonal rake angles were compared at sections along the drill cutting lip it was discovered that the values were almost identical to any drill radius, ranging from 0° near the chisel to 30° at the outside diameter. These findings were very useful because small changes in the direction of the chip flow were not therefore accompanied by any significant change in the lip rake angle.

When the theoretical value of the ratio of feed to cutting force ($F_{TL}/F_{CL}$) at the lip of a 19.05 mm dia drill was compared to the actual ratios obtained from an orthogonal cutting test, these corresponded to a mean effective rake angle of about 15° (i.e. the mean axial and orthogonal rake angles).

Other data from the orthogonal cutting test, including the friction angle and shear angle were used to build up a set of predictive equations for the effective Shear Stress ($\tau_{SE}$), cutting force $F_{CL}$ and feed force $F_{TL}$ for the drill lip.

Note that the shear stress was dependent upon feed and higher values were obtained at both low and high feed rates. This was possibly due to the tool rubbing at fine feeds and the effect of BUE as the feed rate was increased.

In order to predict the thrust and torque for a 15.875 mm dia drill an interpolated shear stress was used which was mid way between the stress values calculated for a 19.05 and 12.70 mm dia. drills.

The predicted values of thrust and torque were established from the modified Merchants Equations together with empirical allowances for the chisel edge and drill lands. The empirical relationships confirmed that up to 75% of the drill thrust force occurred at the chisel edge and about 10% of the total torque was used by the chisel edge and lands.

Comparison of the actual and predicted torque and thrust results for a 15.875 mm dia. twist drill confirmed that the analysis provided a very close estimation of drill torque. The predicted drill thrust force was up to 14% greater than that actually measured.

The investigation undertaken with coolant fed twist drills provided a very useful part of the analysis because little published information existed on the benefits of coolant feeding techniques.

For a 19.05 mm dia coolant fed twist drill, minimum coolant pressures of 4 bar were required to provide good swarf evacuation and improve the hole quality. The use of high pressure coolant required the use of effective guarding techniques to prevent loss of coolant and to protect the operator from the effects of inhaling atomised vapour. This was the main limitation on using pressures greater than 15 Bar.

When tool life comparison tests were undertaken, it was established that even in shallow holes of two diameters deep, the coolant fed drill enabled improved hole tolerances and surface finishes to be obtained compared to those produced by conventional drills.

Coolant feeding techniques enabled improved tool life, compared to a conventional drill, to be obtained by virtue of lower cutting lip temperatures and reduced BUE formations. The onset of tool wear for a coolant fed drill occurred after a much greater number of holes than the equivalent conventional drill. The use of coolant fed drills may also enable cutting speeds to be increased by up to 60% without any significant increase in drill thrust or tool wear. The lower temperatures at the drill/workpiece interface of a coolant fed drill resulted in up to 10% greater torque being measured compared to a conventional drill. The reduction in built up edge on the coolant feed drill, however, led to 10% reduction in thrust force compared to a conventional drill.

Whilst the use of coolant feeding techniques served to enhance drill life and hole quality another recent drilling development, with possibly even greater potential, was the application of TiN surface coatings to the drill.

The purpose of the TiN coating was to reduce the friction in the flutes and on the lands as well as improve the tool life. A very extensive testing program was undertaken with five different types of commercially available TiN coatings applied to 12.70 mm dia bright finished Jobber drills in order to assess the effects of TiN coatings on drill performance.

The TiN coatings varied in adherence and thickness but certain fundamental properties of the TiN were apparent from the test results. The ceramic nature and low coeffeicent of friction of the coating enabled significant reductions in drilling torque and thrust to be achieved in the order of 10-20%. The coating provided a thermally insulating barrier around the H.S.S. substrate which enabled improved drill life to be achieved. The swarf produced by TiN coated drills was also very smooth and it was apparent that TiN coating helped to reduce or eliminate build up edge formation on the drill. Another advantage of TiN coated drills was the improved hole quality that was achieved. Holes that were produced by TiN coated drills were superior in tolerance, surface finish and roundness compared to those made with conventional drills.

One of the main advantages of the TiN coating was that drilling speeds could be increased by up to 3 times those specified for H.S.S. drills, without any significant increase in cutting forces. Feed rates could be increased by about 20%.

Some drill failures were recorded with TiN coated drills that were attributed to loss of coating, particularly from the lands of the drill. The failure mechanism was similar to that for a conventional H.S.S. twist drill in that rapid breaking down of the outer corner of the cutting lip occurred. In some cases the failure propagated up the drill lands and when the drill cut undersize the edge of the hole served to "peel off" additional land.

Other instantaneous failures of TiN coated drills occurred. These were probably due to the nature of the coating surface. Sometimes the TiN surface was uneven in thickness or texture and therefore likely to selectively expose the H.S.S. substrate to abrasive and adhesive wear particularly at high speeds.

In order to resist the abrasive wear mechanisms, the coating producers needed to maintain coating thicknesses greater than the height of any surface asperities on the drills and TiN thickness of 5 microns were usually sufficient.

When the TiN coated drill was reground the loss of coating from the chisel edge and flank faces led to increases in thrust force. The improved hole quality and ability to run at increased surface speeds was still retained by a reground TiN coated drill, however, providing that the coating remained on the lands and in the flutes of the drill.

The use of carbide tips on drills also provided the opportunity of increasing the cutting speeds.

With the new Prototype Drill the actual design of the cutting lip resulted in an asymmetric configuration which produced high out of balance cutting forces and hole oversizes of up to 0.5 mm on a 19.05 mm dia. drill.

The adoption of an equal flute form, and the use of helical twisted inserts, with radial cutting lips provided improved results with a 'M' shaped design of drill point. This design eliminated the chisel edge and the thrust force was therefore up to 20% lower than the equivalent H.S.S. twist drill.

The need to retain a small central web between the inserts to prevent the drill splitting up the centre of the web prevented an entirely symmetrical configuration being developed.

The use of pressure fed coolant through holes drilled in the flank faces of the Prototype drill provided improved hole quality compared to the flute coolant holes which tended to block with swarf.

The 'M' shaped point configuration was difficult to accurately reproduce on each lip of the drill until a new special grinding fixture was developed. The drill performance was very sensitive to differences in lip height particularly because of the fine feed rates used.

In comparison trials on the CNC Lathe with a Sandvik Delta Drill and a Mitsubishi New Point Drill, the Prototype drill compared favourably in respect of torque and thrust characteristics. The hole quality with the Prototype drill did not match that of the Sandvik Delta Drill and this was attributed to differences in the radial land. On the Delta Drill, the inserts were finished with a wide radial land without axial back taper. This land helped to burnish the drilled hole and provide a very good hole tolerance and finish.

With the Prototype drill No.6, a back taper on the land prevented any effective burnishing and isolated deep tool marks were sometimes present in the drilled hole surface due to swarf pick up.

One advantage of the ball end design of the Prototype drill was that entirely burr-free holes were produced, whereas both the Sandvik and Mitsubishi drill produced carry over burrs on drill exit from the workpiece.

In developing the drill body design the final flute shape adopted for Prototype No.6 was of similar cross sectional area to those of the Sandvik and Mitsubishi Drills.

The torsional stiffness per unit length of the Prototype Drill No.6 was about 15% greater than the Sandvik and Mitsubishi Drills and about three times that of a conventional H.S.S. twist drill.

Tests on the Radial Arm Drilling Machine with the three types of carbide tipped drill were unsuccessful without the use of drill guide bushes. The drilling set up lacked rigidity and the high spindle speeds necessary for high penetration rate drilling.

In drilling tests the point geometry of Prototype Drill No.6 set up severe vibration in the Radial Arm Spindle. Tool breakage occurred with the Sandvik Delta Drill.

The twist drill geometry comprising of a 118° point angle and a straight cutting lip with a 30° helix angle gave reasonable tool life provided that the drill was correctly point ground and the clearance angle was maintained at about 10°. If the clearance angle was greater than about 15° however this led to a weakening of the cutting lip wedge such that the wedge included angle at the drill circumference was 45° or less.

In tests on a drill press with a constant thrust force of up to 440N twist drills of about 5 mm dia. were very slow to penetrate through 6.35 mm mild steel. This was due to the negative rake cutting at the chisel edge and additional support provided by the low clearance angle. To develop a design of drill point with a faster penetration rate for the same thrust force involved detailed changes to the point configuration.

In the design and evaluation of drill screw points the minimum thrust force was required so that hand held power tools could be used. For the drill screw considered there was considerable variation in the drilling times for the screws in the "as supplied" condition. This was due to the often asymmetric point configfurations, burrs at the cutting lip, or the eccentricity in the screw head of the Type 'F' drill screws.

A detailed design evaluation study was undertaken with drill screw points with point angles ranging from 100° to 150° and clearance angles of up to 40°. High clearance angles were used because there was a zero rake angle which prevented excessive weakening of the cutting lip on Type 'F'.

The drilling times at constant thrust forces were compared. It was confirmed that increased clearance angles provided less support for the drill point and the drilling time was reduced. The drill screw point angle also had a significant effect on the drilling time. At acute point angles of 100°-110° the drilling times were generally longer because there was an increased time with negative rake cutting at the chisel edge. The drilling times were sometimes shorter with 140°-150° point angles but the point tended to wander and produce oversize holes.

The optimum geometry of the drill screw point was therefore obtained with point angles betwen 120°-130° and clearance angles of 35°-40°. Test results with points that were hardened and ground confirmed that the above geometry was satisfactory on hole depths of up to 10 mm.

# CHAPTER THIRTEEN

## OVERALL CONCLUSIONS

1. Precision drill point grinding techniques are essential in order to produce precision holes with twist drills.

2. Measurements of drill point geometries confirmed that small errors in the lip height contributed to increased hole oversize, particularly at drill entry when using fine feed rates.

3. Drills that were asymmetrically ground were unsatisfactory because they produced an unequal chip thickness distribution, which in the limiting condition lead to the drill cutting on only one lip.

4. The amount of hole oversize generated by a asymmetrically ground drill was predicted and compared with actual values. In practice the actual oversize depended upon the true running of the drill and spindle, hole depth, feed rate, drill length and rigidity of the drilling set up, as well as the lip height errors.

5. The selection of a 118° point angle for a conventional twist drill represented a compromise between optimum point configuration and tool life. The tool life and drill performance was sensitive to changes in point angle of ±6°.

6. The use of a Drilling Dynamometer to determine drill performance characteristics was very useful, especially for torque and thrust measuremnents. Small changes in drill geometry or differences in cutting conditions were detected and recorded on U.V. paper.

7. From the orthogonal cutting tests undertaken on the lathe, using a Turning Dynamometer to measure the cutting forces, the shear angle and friction angle were established. The tests covered the same range of rake angles on a 19.05 mm dia twist drill, together with the same material and the same surface speeds and feeds used in drilling.

8. Use of the orthogonal cutting test data was made in establishing a set of predictive equations which were developed from analysis of the torque and thrust of a 12.70 mm and 19.05 mm dia. drill together with modified Merchants equations.

9. By comparing the ratio of the feed force to the cutting force in orthogonal cutting to the theoretical ratio of feed force per lip in drilling it was possible to determine an effective rake angle which was near to 15° for a 30° helix drill (12.70 and 19.05 mm dia.)

10. For both a 12.70 and 19.05 mm dia. drill the axial rake angle corresponded very closely to the orthogonal rake angle

measured at right angles to the cutting lip.

11. Empirical results established that about 75% of the total thrust force for a 19.05 mm dia. twist drill was attributable to the chisel region.

12. The torque and thrust for a 15.875 mm dia. twist drill was predicted by using a value of shear stress that was obtained by interpolation from the theoretical shear stress results for the 12.70 and 19.05 mm dia. drills.

13. The actual torque and thrust for a 15.875 mm dia. drill compared very closely with the predicted values.

14. Tests to establish the minimum pressure requirements for a 19.05 mm dia. coolant fed twist drill confirmed that improved hole qualities were obtained provided that a minimum pressure of 4 bar was maintained. Higher pressures may be beneficial in deep holes where swarf evacuation from the drill flutes may be a problem.

15. The use of coolant fed drills enabled improved hole tolerances and surface finishes to be obtained compared to those produced by conventional drills.

16. Coolant feeding techniques enhanced tool life by virtue of lower cutting lip temperatures and reduced built up edge formation on the cutting lip.

17. The torque taken by a coolant fed drill was sometimes greater than the equivalent conventional drill and this was attributed to lower temperatures at the material in contact with the cutting lip.

18. The thrust required by a coolant fed drill was similar to that of a conventional H.S.S. drill at normal cutting speeds. Cutting speed increases of 60% were possible with the coolant fed drill without significant increases in thrust or tool wear that occurred with conventional drill with the same speed increase.

19. The application of TiN coatings to twist drills may enable cutting speeds to be increased by up to three times and feed rates by 20% of those applicable to conventional H.S.S. drills.

20. TiN coated twist drills enabled improved tool life and hole quality to be obtained, compared to those produced by conventional H.S.S. drills.

21. TiN coatings led to reduced friction conditions at the cutting lips, chisel edge and in the flutes of the twist drill. The lower friction contributed to reductions in both torque and thrust compared to a conventional drill.

22. Even after regrinding, when the TiN coat was lost from the flank faces and chisel edge of the drill, the retention of the

coating on the lands and in the flutes of drill led to improved tool life and hole quality compared to a conventional steam tempered drill.

23. There were considerable differences in TiN coating quality, thickness and adherence of the various commercially available TiN coatings considered. These differences were significant and sometimes contributed to poor TiN coated drill performance.

24. An entirely new type of drill design was developed which incorporated helically twisted tungsten carbide radial cutting lips. The new prototype drill used an 'M' type point configuration which eliminated the negative rake cutting associated with the chisel edge of a conventional drill.

25. The new prototype drill generally required lower thrust force than an equivalent H.S.S. twist drill.

26. The use of carbide cutting lips enabled the cutting speeds to be increased by up to three times those specified for a H.S.S. drill.

27. Although a symmetrical flute configuration was adopted for the new design, some difficulty was experienced in grinding the M shaped point and completely balancing the cutting forces.

28. Improved hole quality was obtained when the Prototype drill

was supplied with pressurised coolant in flank coolant holes and completely burr free holes were produced at drill exit from the workpiece.

29. In comparison trials with Sandvik and Mitsubishi carbide tipped drills, the new prototype design compared favourably in respect to torque and thrust characteristics.

30. Differences in drill performance were observed according to the mode of operation. The use of a rotating drill helped to lift the swarf from the drilled hole, but loss of coolant pressure sometimes occurred through centrifugal effects in the inducer housing.

31. The hole quality produced by the new Prototype Drill did not match that obtained with Sandvik Delta Drill. The reasons for this were attributed to the back taper on the radial load, which prevented any effective burnishing of the drilled surface.

32. The flute area and torsional stiffness of the new design was comparable to those used on the Sandvik and Mitsubishi Drills.

33. The use of carbide tipped drills was not recommended for conventional Radial Arm Drilling Machines because the drilling set-up lacked rigidity and insufficient speed was available for opltimum cutting conditions with tungsten carbide.

34. Drill screws required an entirely different philosophy in their design to that employed on the twist drill. To minimise the thrust force and drilling time whilst obtaining a tool life of one hole with a drill screw point, an alternative drill point design must be considered.

35. For the drill screws evaluated a reduction in drilling time was achieved by grinding additional clearance at the cutting lip. The extra clearance enabled the area of contact between the flank faces of the drill point and the workpiece to be reduced, thus providing less resistance to the thrust force.

36. Changes in the drill screw point angle also lead to variations in the drilling time. Acute point angles less than 110° were not preferred because these resulted in the chisel point dwelling on the workpiece and "burning out". More obtuse angles (greater than 140°) were also unsatisfactory because the point tended to wander and this led to increased hole oversize.

37. The optimum geometry of the drill screw design was obtained with point angles of between 120-130° and clearance angles of 35-40°.

38. Drilling times were increased for drill screws as supplied when the points were asymmetric. Any eccentricity in the screw head relative to the shank of screw, or poor head fit in the drive socket, also contributed to longer drilling times.

39. The typical thrust forces that were exerted in a horizontal plane by two operators were between 210-260N. Any drill screw design should therefore perform satisfactory over this thrust range and also be capable of withstanding additional loads applied vertically.

APPENDIX I

# THE OLIVETTI RIGID N.C. MILLING MACHINE

## 1. AUTOMATIC TAPE CONTROL

The machine is controlled in three dimensions (X, Y and Z) by a punched paper tape. The working area is rectangular and the workpiece remains stationary whilst all the motions are carried out by the cutter.

The program tape is fed into a tape reading head on the machine control unit which stands separate from the milling machine.

The control commands are transmitted to the moveable machine parts by a hydraulic cylinder by means of electrical servo valves.

The range of spindle speeds are manually selected by, firstly choosing the high/low speed range of the two speed spindle motor and then inserting the appropriate change gears in the top of the gear box.

All other movements are determined from the commands on the paper tape.

The technical specifications are as follows:-

## 2. "RIGID" N.C. MILLING MACHINE MODEL KAB - 50N

### TECHNICAL SPECIFICATION

| | |
|---|---|
| Table Size: | 500 x 1100 mm (Y and X directions) |
| Maximum Traverse Strokes | X - 27.5 (700 mm) |
| | Y - 13.5 (343 mm) |
| | Z - 9.75 (248 mm) |

N.B. All program commands in inch units

| | |
|---|---|
| Stepless Hydraulic Feed Range | |
| (in X, Y, Z) | 10 - 700 mm/min |
| Spindle Motor 2 speed | 1500/3000 rpm |
| Motor Power | 2.2 - 3.0 kW |
| Output Speed Range | 94 - 2120 rpm |

## 3. EXPLANATION OF PROGRAM CODES FOR 50 HOLE DRILLING PROGRAM

N = Block No.

X,Y,Z = Co-Ordinates 000.0000 inch units.

(NB All digits must be filled to avoid a program error,

eg. one inch = 001.0000

R = Traverse in Z direction to given co-ordinate

M03 = Spindle "ON" clockwise

M08 = Coolant "ON"

M30 = End of program and tape rewind

M00 = Intermediate program stop (Cancels M03 and M08)

F = Feed Rate (in/min) e.g. One inch per minute = F001.00

G54 = Rapid Traverse in X and Y only

G55 = Cancels G54

G81 = Drilling Cycle - Brings head down at commanded feed rate to stated Z position and then head up in rapid traverse.

G80 = Cancels G81.

The 50 hole drilling program used for 12.70 mm dia drills is shown in Fig.I-1.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| N001 | G54 | | | | | R-0009000 | M03 |
| N002 | G55 | | | Z-0023000 | F01696 | | M08 |
| N003 | G54 | | | | | R0000000 | |
| N004 | | X-0126250 | Y-0001250 | | | | |
| N005 | | | | | | R-0023300 | |
| N006 | G81 | | | Z-0037300 | F01696 | | |
| N007 | | Y-0134370 | | | | | |
| N008 | | Y-0142490 | | | | | |
| N009 | | Y-0150610 | | | | | |
| N010 | | Y-0158730 | | | | | |
| N011 | | Y-0166850 | | | | | |
| N012 | | Y-0174970 | | | | | |
| N013 | | Y-0183090 | | | | | |
| N014 | G80 | | | | | R-0023300 | |
| N015 | G54 | | | | | R0000000 | M00 |
| N016 | G54 | X0000000 | Y0000000 | | | | M03 |
| N017 | | | | | | R-0009000 | M08 |
| N018 | G55 | | | Z-0023000 | F01696 | | |
| N019 | G54 | | | | | R0000000 | M05 |
| N020 | | X-0090000 | Y-0060000 | | | | M00 |
| N021 | G54 | X-0126250 | Y-0011750 | | | | M03 |
| N022 | | | | | | R-0023300 | M08 |
| N023 | G81 | | | Z-0037300 | F01696 | | |
| N024 | | X-0134370 | | | | | |
| N025 | | X-0142490 | | | | | |
| N026 | | X-0150610 | | | | | |
| N027 | | X-0158730 | | | | | |
| N028 | | X-0166850 | | | | | |
| N029 | | X-0174970 | | | | | |
| N030 | | X-0183090 | | | | | |
| N031 | | X-0191210 | | | | | |
| N032 | G80 | | | | | R-0023300 | |
| N033 | G54 | | | | | R0000000 | M00 |
| N034 | G54 | X0000000 | Y0000000 | | | | M03 |
| N035 | | | | | | R-0009000 | M08 |
| N036 | G55 | | | Z-0023000 | F01696 | | |
| N037 | G54 | | | | | R0000000 | M05 |
| N038 | | X-0090000 | Y-0060000 | | | | M00 |
| N039 | G54 | X-0126250 | Y-0021250 | | | | M03 |
| N040 | | | | | | R-0023300 | M08 |
| N041 | G81 | | | Z-0037300 | F01696 | | |
| N040 | | X-0134370 | | | | | |
| N043 | | X-0142490 | | | | | |
| N044 | | X-0150610 | | | | | |
| N045 | | X-0158730 | | | | | |
| N046 | | X-0166850 | | | | | |
| N047 | | X-0174970 | | | | | |
| N048 | | X-0183090 | | | | | |
| N049 | | X-0191210 | | | | | |
| N050 | G80 | | | | | R-0023300 | |
| N051 | G54 | | | | | R0000000 | M00 |
| N052 | G54 | X0000000 | Y0000000 | | | | M03 |
| N053 | | | | | | R-0009000 | M08 |
| N054 | G55 | | | Z-0023000 | F01696 | | |
| N055 | G54 | | | | | R0000000 | M05 |
| N056 | | X-0090000 | Y-0060000 | | | | M00 |
| N057 | G54 | X-0126250 | Y-0031250 | | | | M03 |
| N058 | | | | | | R-0023300 | M08 |
| N059 | G81 | | | Z-0037300 | F01696 | | |
| N060 | | X-0134370 | | | | | |
| N061 | | X-0142490 | | | | | |
| N062 | | X-0150610 | | | | | |
| N063 | | X-0158730 | | | | | |
| N064 | | X-0166850 | | | | | |
| N065 | | X-0174970 | | | | | |
| N066 | | X-0183090 | | | | | |
| N067 | | X-0191210 | | | | | |
| N068 | G80 | | | | | R-0023300 | |
| N069 | G54 | | | | | R0000000 | M00 |
| N070 | G54 | X0000000 | Y0000000 | | | | M03 |
| N071 | | | | | | R-0009000 | M08 |
| N072 | G55 | | | Z-0023000 | F01696 | | |
| N073 | G54 | | | | | R0000000 | M05 |
| N074 | | Y-0090000 | Y-0060000 | | | | M00 |
| N075 | G54 | Y-0126250 | Y-0041250 | | | | M03 |
| N076 | | | | | | R-0023300 | M08 |
| N077 | G81 | | | Z-0037300 | F01696 | | |
| N078 | | Y-0134370 | | | | | |
| N079 | | X-0142490 | | | | | |
| N080 | | X-0150610 | | | | | |
| N081 | | X-0158730 | | | | | |
| N082 | | X-0166850 | | | | | |
| N083 | | X-0174970 | | | | | |
| N084 | | X-0183090 | | | | | |
| N085 | | X-0191210 | | | | | |
| N086 | G80 | | | | | R-0023300 | |
| N087 | G54 | | | | | R0000000 | M00 |
| N088 | G54 | X0000000 | Y0000000 | | | | M03 |
| N089 | | | | | | R-0009000 | M08 |
| N090 | G55 | | | Z-0023000 | F01696 | | |
| N091 | G54 | | | | | R0000000 | M05 |
| N092 | | Z-0090000 | Y-0060000 | | | | M00 |
| N093 | G54 | X0000000 | Y0000000 | | | | M30 |
| N094 | G55 | | | | | | |

FIG I-1 OLIVETTI MILLING MACHINE - NC PROGRAM FOR 50 HOLES

APPENDIX II

# TORSHALLA S-160 CNC LATHE

The Torshalla numerically controlled production lathe type S-160 CNC was operated by a d.c. motor via a separate gearbox to the spindle. It featured four speed ranges of 20-600, 40-1200 and 160-4800 rpm. The carriage and cross-slide were located behind the spindle, with the carriage above the cross-slide. The lathe was equipped with a hydraulically-indexing toolpost with double toolholder, each unit accommodating eight tools. The lathe was provided with a fully enclosing plate guard offering scope for extractor connection.

## 1. MANUAL CONTROL

Spindle speed ranges were shifted by push-buttons on the machine's control panel. When each push-button was depressed, a gear-shifting cycle was automatically initiated, whereby rotational speed was adjusted to gear change speed, the sliding gears change postion, and the set speed was engaged. Setting of spindle speed within each specific speed range was accomplished by push buttons via the control system.

Carriage and cross-slide control, starting of spindle clockwise and counterclockwise rotation, spindle stopping, coolant engagement and disengagement, hydraulic unit starting and stopping, chip conveyor starting and stopping, and 1/8th revolution tool indexing were also managed from the machine's control panel. Spindle speed was displayed on a speed indicator. Spindle drive motor loading was displayed on an ammeter.

## 2. CNC CONTROL

Programming instructions were entered by either the CNC computer keyboard or alternatively by feeding punch tape to the Machine Control Unit.

A typical CNC drilling programme used in the coolant fed drilling trials is outlined below.

## 3. CNC PROGRAMMING - COOLANT FED DRILL

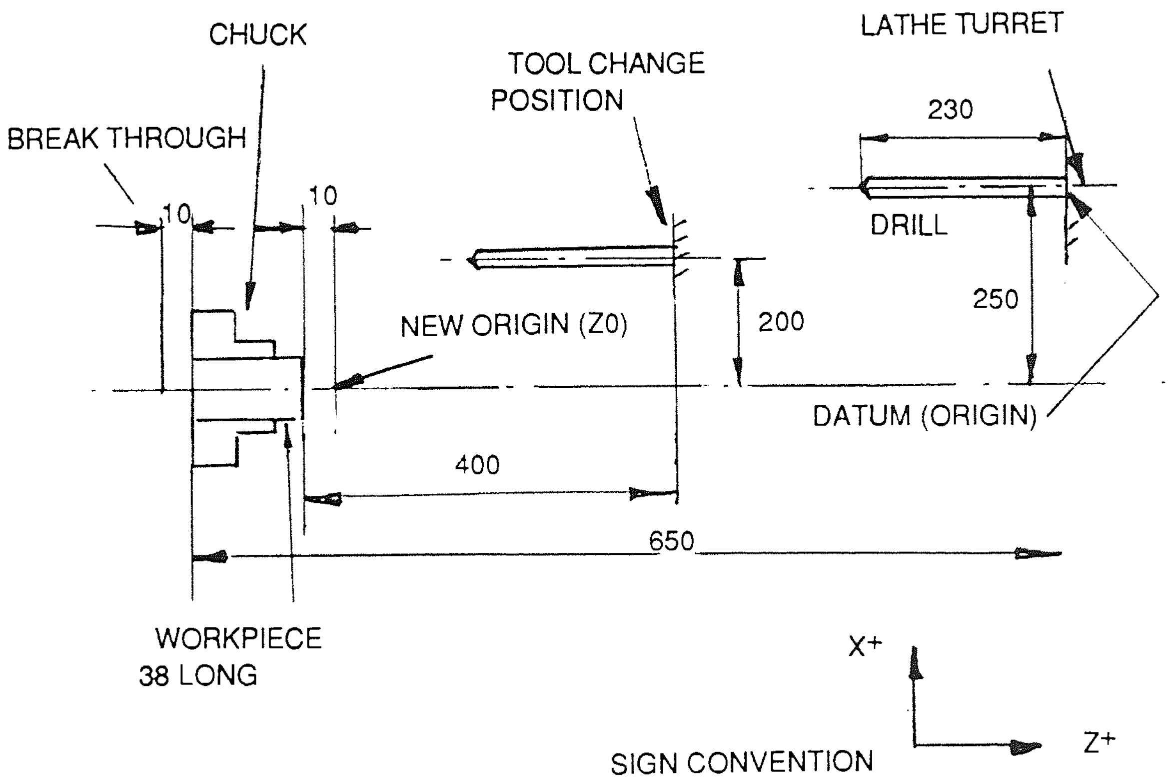



FIG II-1 CNC LATHE - PLAN OF SET UP FOR DRILLING WITH COOLANT FED DRILLS

(ALL DIMENSIONS IN mm-DECIMAL PLACES OMITTED FOR COVENIENCE)

3.1 Program to Drill 19.05 mm Dia. Through Hole in 38 mm Long Workpiece. (As per Fig. II-1).

| Program | Explanation |
|---|---|
| D0 X250 Z612 | Limits of Movement Before Drilling |
| N10 G90 G0 X200 Z400 D0 | Move to tool change position. |
| N20 G91 G92 Z-230 | Zero Offset (No Movement) |
| N30 G91 G0 X0 Z-390 | Drill Start Position |
| N40 G97 S600 M3 M8 | Start Spindle and Coolant |
| N50 G95G1 X-58 F0.4 | Drill Hole |
| N60 G0 X0 MS | Retract Drill Stop Spindle/Coolant |
| N70 G91 G92 Z230 | Cancel Zero Offset |
| N80 G90 X200 Z400 | Tool Change Position |
| N90 G25 X2 Z2 M2 | Return to Reference Datum (End of Program) |

3.2 Key to Programming Codes for X and Z Coordinates

| | |
|---|---|
| N | Block No, D0 = Compensation Memory (To take account of workpiece size). |
| G90 | Absolute Programming |
| G91 | Incremental Programming |
| G92 | Programmable zero offset (No movement) |
| G0 | Rapid Traverse |
| G1 | Linear Cutting |
| G97 | Spindle Roation ('S'rpm) - (M3 = Anti clockwise) |
| M8 | Coolant on |
| G95 | Feed Traverse Rate ('F' - mm/rev) |
| M5 | Coolant off and stop spindle |
| G25 | End of programe return to reference datum (X2, Z2, M2) |

## 4. TORSHALLA S160 CNC LATHE : TECHNICAL DATA

### Working Area - Slide Movements.

| | |
|---|---|
| Centre Distance | 750 mm |
| Maximum swing with 8 tools | 320 mm |
| Maximum swing with 16 tools | 200 mm |
| Maximum swing over longitudinal slide | 340 mm |
| Maximum swing with cross slide | 650 mm |
| Saddle Movement (Z direction) | 650 mm |
| Cross slide movement (X direction) | 250 mm |

### Spindle Drive

| | |
|---|---|
| D C Motor (Reversible) Power | 16 kW |
| Spindle speeds | 20 - 600 rpm |
| | 40 - 1200 rpm |
| | 80 - 2400 rpm |
| | 160 - 4800 rpm |

### Feeds

| | Z | X |
|---|---|---|
| Length of movement | 650 mm | 250 mm |
| Maximum feed force | 7 kN | 7 kN |
| Maximum feed speed (Rapid) | 10 m/min | 10 m/min |
| Smallest program measure | 1 µm | 1 µm |
| Smallest tool compensation | 1 µm | 1 µm |
| Position accuracy | ±25 µm | ±25 µm |
| Repeating accuracy | ±5 µm | ±2.5 µm |
| Resolution | 1 µm | 1 µm |

APPENDIX III

# INSTRUMENTATION - FORCE MEASUREMENT

## 1. KISTLER DRILLING DYNAMOMETER (TYPE 9273)

The Dynamometer consisted of two two-component load washers fitted under high preload, one above the other between a base plate and a cover plate. Each load washer contained two sets of quartz disks which were arranged direction-oriented in relation to their sensitivity. Each load washer yielded a charge proportional to each of the four components, i.e. torque M, thrust $F_Z$ and radial forces $F_X$ and $F_Y$. The resulting charges were led to connectors on the side of the dynamometer body. The components were measured, virtually without displacement, in a high rigidity set up.

The technical specification of the Dynamometer is as follows:-

| | $F_X, F_Y$ | $F_Z$ | M |
|---|---|---|---|
| Operating Range | ±5 kN | -5+20kN | ±100Nm |
| Threshold (min) | 0.02N | 0.02N | 0.02Ncm |
| Sensitivity | -3.5pC/N | -1.9pC/N | -1.5pC/N |
| Linearity % | <±1 | <±1 | <±1 |
| Hysterisis % | <1 | <1 | <1 |
| Rigidity | 0.1 kN/μm | 2 kN-μm | 30 Ncm/μm |
| Natural Frequency KHz | 1.5 | 3 | - |

In order to measure the dynamometer output, the electrical charges generated were fed into charge amplifiers which were used to convert the charge into an analogue D.C. voltage.

## 2. KISTLER CHARGE AMPLIFIERS (TYPE 5006)

A charge amplifier was required for each channel on the dynamometer, but in practice only 3 three channels were used at any one time, ie $F_Z$, M and either $F_X$ or $F_Y$.

The appropriate sensitivity of the transducer was set on the amplifier and a measuring range selected from 12 possible steps 1, 2, 5 etc., equivalent to ±10 to ±500,000pC. The Amplifier output range was ±10VDC, ±60mA. The measuring range scale was such that each step unit selected was displayed on 1 cm of U.V. recorder paper. A plug in low pass filter of 10 Hz was used to filter out all higher frequencies from being transmitted to the U.V. Recorder (see Fig. III-1)

## 3. GOULD BRYANS U.V. RECORDER

A six channel oscillograph was used to obtain a graphical representation of the amplifier output. Moving coil mirror galvanometers were selected to provide a suitably damped frequency response for the signal applied without overshoot. Fluid Damped type SM1/L galvanometers were used, each with a natural frequency of 1650 Hz, together with "dummy" galvanometers to provide reference base lines. Movement of the galvanometer mirror was directly proportional to the applied current. A light source reflecting of the mirror was hence used by the recorder to provide a trace on ultra-violet (U.V.) sensitive paper. The paper speed was adjusted according to the duration of the drilling time and grid timing lines were also incorporated on to the trace to provide an indication of the actual time taken.

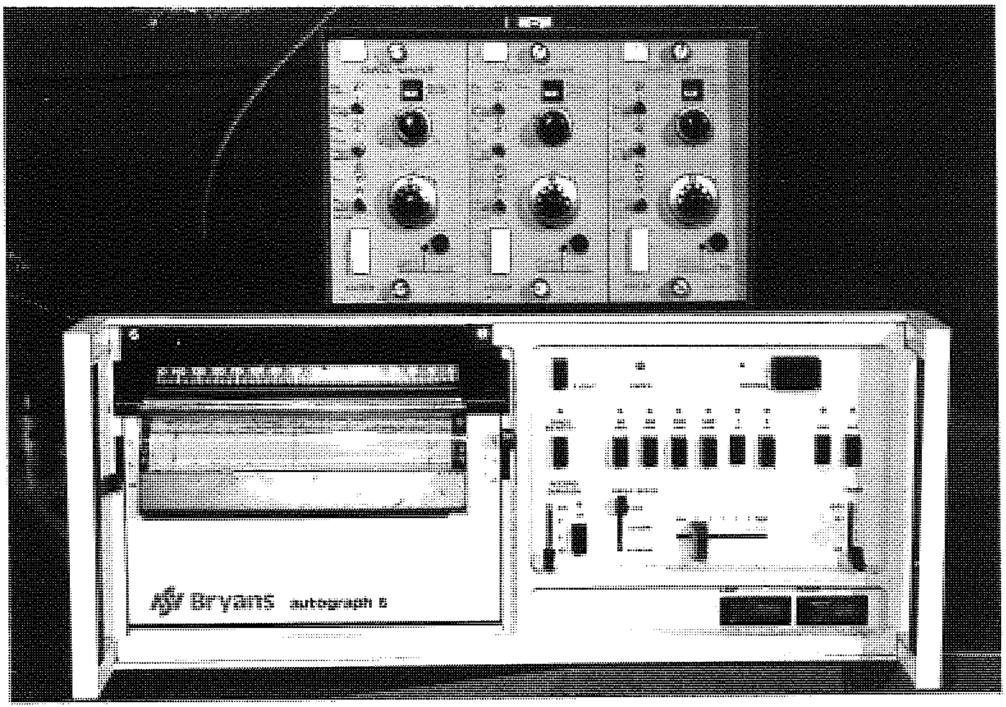



FIG III - 1 THE CHARGE AMPLIFIER AND UV RECORDER

APPENDIX IV

## ORTHOGONAL CUTTING TEST -

## CALCULATION OF WIDTH OF CUT, FEEDS AND SPEED.

1. LIP LENGTH (Fig.IV-I)

For the tubular workpiece used on the D.S.G. Centre Lathe, the tubular wall thickness was turned so that the thickness was equal to the lip length of the 19.05 mm dia. twist drill.

'$\ell$' lip length $= \dfrac{d-dc}{2\sin x}$

dc = chisel dia = 2.54 mm

d = drill dia = 19.05 mm

x = half point angle = 59°

therefore $\ell$ = 9.63 mm

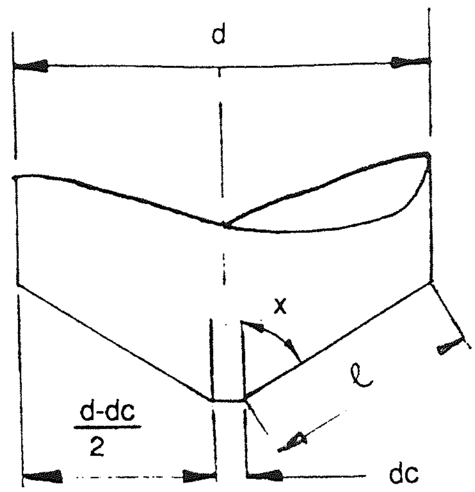



FIG IV-1
LIP LENGTH

2. FEED RATE PER LIP (Fig.IV-2)

For a twist drill symmetrically ground with equal lip heights the feed per lip $= \dfrac{f}{2}$

The undeformed chip thickness per lip $= \dfrac{f}{2} \sin x$

Feed range used for 19.05 mm dia twist drill

= 0.1-0.6 mm/rev = 0.05-0.3 mm/lip.

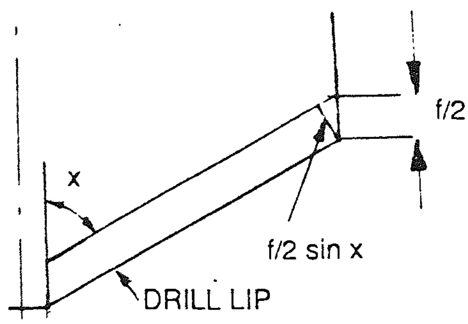



FIG IV-2
FEED RATE PER LIP

The equivalent feed rates for Orthogonal Cutting and the nearest values available on the DSG Lathe are given below:

| Drilling Axial Feed per lip $\frac{f}{2}$ (mm) | Orthogonal Feed $\frac{f}{2}$ sin x (mm) | Nearest Available Feed on Lathe mm/rev |
|---|---|---|
| .05 | .043 | .043 |
| .10 | .086 | .089 |
| .15 | .128 | .127 |
| .20 | .171 | .178 |
| .25 | .214 | .221 |
| .30 | .257 | .254 |

3. CUTTING SPEED

For drilling at 600 rpm

surface speed $v = \pi dN$

$= 36$ m/min

$\Delta$ Speed on 50.8 mm dia. tubular work piece to give an equivalent surface speed to drilling

$$N = \frac{36 \times 1000}{\pi \times 50.8} = 225 \text{ rpm}$$

**APPENDIX V**

## MERCHANTS ANALYSIS

1. To determine Friction Angle ($\tau$)

$$\tan(\tau = \gamma) = \frac{FT}{FC} \qquad \text{(see Fig. 5.5)}$$

2. To determine Shear Angle ($\phi$)

$$\tan\phi = \frac{rc \cos\gamma}{1 - rc \sin\gamma} \qquad \text{(see Fig. 5.5)}$$

where $\gamma$ = rake angle

$\tau$ = friction angle

$rc$ = cutting ratio.

3. Merchants Modified Equation:

$$2\phi + \tau - \gamma = \text{constant}$$

for constant friction conditions $\tau$ = constant

therefore, $2\phi - \gamma = C^1$ (where $C^1 = C - \tau$)

therefore, $\phi = \frac{\gamma}{2} + \frac{C^1}{2}$ ($C^1$ is a new constant)

This is the equation of a straight line.

By plotting $\phi$ versus $\gamma$ the intercept on the $\phi$ axis will be $\frac{C^1}{2}$ and the the theoretical slope of the curve equal to 0.5.

From Fig.5.2 $\frac{C^1}{2} = 13.59°$

therefore, $C^1 = 27.18°$

and taking a value of $\tau = 31°$, $C = C^1 + \tau = 51.18°$

Comparison of Actual and Theoretical Constants.

| Rake Angle | Actual Results of $2\phi + \tau - \gamma$ from Table 5.2 | Theoretical Result using $\tau = 31°$ and $\phi = 13.59°$ |
|---|---|---|
| 0 | 54.83 | 58.18 |
| 5 | 52.39 | |
| 10 | 57.11 | |
| 15 | 62.96 | |
| 20 | 63.60 | |
| 25 | 64.68 | |
| 30 | 65.96 | |

APPENDIX VI

# 19.05 mm DIA. TWIST DRILL - METHOD OF DETERMINING AXIAL AND ORTHOGONAL RAKE ANGLE

(Fig.VI-1)

## 1. AXIAL RAKE

For the axial rake angle of the drill, sections were ground axially in plane A-A at 0.75 mm radial increments. The axial rake angle was measured in the plane A-A with a goniometer.

## 2. ORTHOGONAL RAKE

The orthogonal or normal rake angle to the cutting lip was determined by grinding sections along plan B-B at right angles to the lip at increments of 0.89 mm to coincide with the equivalent intersections of A-A. The normal rake angle was measured in plane BB.

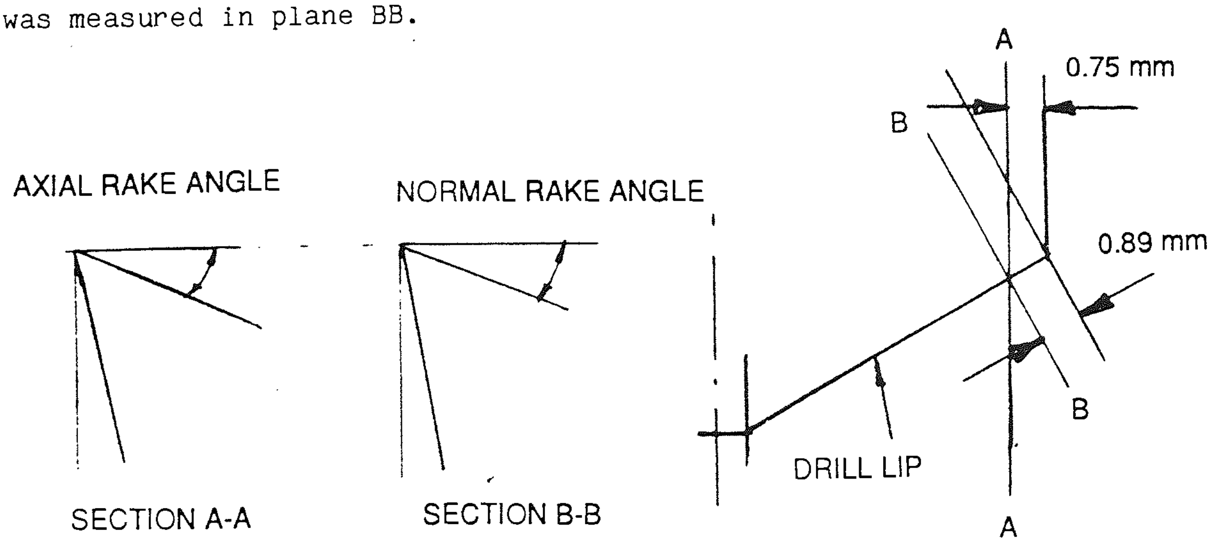



FIG VI-1 AXIAL AND ORTHOGONAL RAKE ANGLES

APPENDIX VII

## PREDICTIVE EQUATIONS

1. TORQUE PREDICTION (Fig.VII-1)

Lip Torque

$M_1 = F_{CL} \frac{d+dc}{2}$

Total Torque $M_P$

= Lip Torque + chisel and land torque

$= M_1 + M_2$

but from test results it was shown that

$M_2 = 0.1\ M_P$

therefore, $M_P = 1.11\ M_1$.

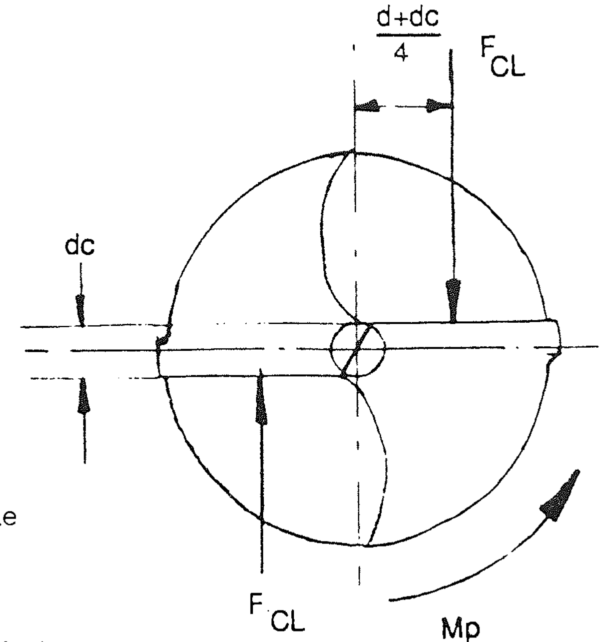



FIG VII-1
TORQUE PREDICTION MODEL

2. FEED FORCE PER LIP (Fig.VII-2)

By resolving normal Feed $F_{TL}$ the axial feed force per lip

$F_T' = F_{TL} \sin x$.

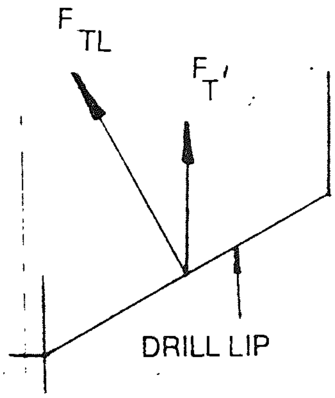



FIG VII-2
FEED FORCE PER LIP MODEL

APPENDIX VIII

## COATING PROCESSES FOR TITANIUM NITRIDE

Two processes are used for the deposition of hard coating materials on various substrates, they are:

1. Chemical Vapour Deposition (CVD)
2. Physical Vapour Deposition (PVD)

### 1. CHEMICAL VAPOUR DEPOSITION (CVD)

In this process, introduced in 1969, the coating is formed chemically by the reaction of the gases Titanium techrachloride, Hydrogen and Nitrogen at a termperature between 800°C and 1000°C.

$$2TiCl_4 + 4H_2 + N_2 \text{ ---> } 2TiN + 8HCL$$

Although successfully used for the application of TiN coatings to carbide tools, this process is not suitable for coating High Speed Steel tools, because at temperatures above 550°C the H.S.S. may temper back and loose its edge hardness. Distortion of the tool may also occur.

Post-coating rehardening and retempering of the H.S.S. is possible, but this complicates the process, introducing addition cost, and may produce further distortion of the tool. A further disadvantage of the CVD process is the toxic and corrosive nature of the waste gases, including hydrogen chloride.

## 2. PHYSICAL VAPOUR DEPOSITION (PVD)

The essential differences of PVD from CVD are that metallic Titanium is used instead of a gaseous reaction medium, and the operating temperature is much lower, between 200°C and 500°C, which has no adverse effect on High Speed Steel.

Various methods can be used to convert metallic Titanium to a plasma which contains ionised Titanium together with Nitrogen and Argon at low pressure, and from which deposition can be induced on to the H.S.S. tool which is the workpiece in the process.

These methods can be classified according to the means by which the metal vapour is produced, i.e. "Sputtering" or "Evaporation". Both methods are carried out in vacuum chambers and require strict cleanliness of the workpiece and achieve good deposition and adhesion of the coating.

### 2.1 Sputtering

This involves the application of a high voltage between the workpiece (anode) and the solid Titanium metal (cathode), which is bombarded by excited ions from the low pressure atmosphere of Argon and Nitrogen. Titanium molecules thus liberated are ionised in the plasma and react with Nitrogen to form TiN ("reactive sputtering") which is attracted to the workpiece and forms a coating. The process is rather slow, requiring 20-30 hours to produce a useful thickness of coating (about 5 microns), although it can be accelerated by the application of a magnetic field in a variation of the process termed "magnetron sputtering".

A Sputter Ion Plating process has been developed by the U.K.A.E.A. at their Harwell laboratories, and is being commercially exploited by T.I. Abar at Tyseley, Birmingham.

## 2.2 Evaporation

Evaporation techniques are used in the majority of present commercial coating processes, with two main methods, "electron-beam evaporation" and "arc evaporation".

2.2.1 Electron-beam Evaporation, also called Reactive Ion Plating, uses an electron beam directed on to a crucible of molten Titanium metal, which is thus evaporated at low pressure in an atmosphere containing Nitrogen, with an electric potential applied to accelerate ions towards the workpiece to be coated, which is negatively charged. A limitation of the process is that the workpiece must be suspended above the molten pool of Titanium, making uniformity of coating rather difficult to achieve.

This is the basis of the process used by the Tecvac Company of Cambridge, and a similar process has been developed by Balzers A.G. of Liechtenstein, who are soon to introduce their process to the United Kingdom.

2.2.2 Arc Evaporation required electric arcs which are struck and maintained between solid blocks of Titanium metal and the walls of the vacuum chamber. The arcs are controlled to move over the metal surface, generating minute sources of vapour with a high content of Titanium ions. Nitrogen gas present at low pressure is also ionised and reacts to form TiN as an electrical potential accelerates ions towards the workpiece to be coated, the kinetic energy of deposition being much higher than with other PVD processes.

A high coating rate is achieved, with good adhesion to the substrate surface, which can be maintained at a temperature well below the tempering temperature of High Speed Steel. As the source of Titanium ions is solid metal, (not molten as in the Electron-beam evaporation method), there is greater freedom in locating the items to be coated, and the process is easily controlled to give uniform coatings.

This is the process first patented in America then taken up and refined in Russia, and later licensed to the firm of Multi-Arc Inc. of Minnesota, U.S.A. The process is now available in the United Kingdom from the firm of Multi-Arc (Europe) Ltd., at Consett, Co.Durham and also from the company J.J. Casting Investments of Caerphilly.

In the Aston University Research, drills coated by both the "Sputtering" and "Evaporation" processes were evaluated. The coatings were produced by the five companies listed in this Appendix.

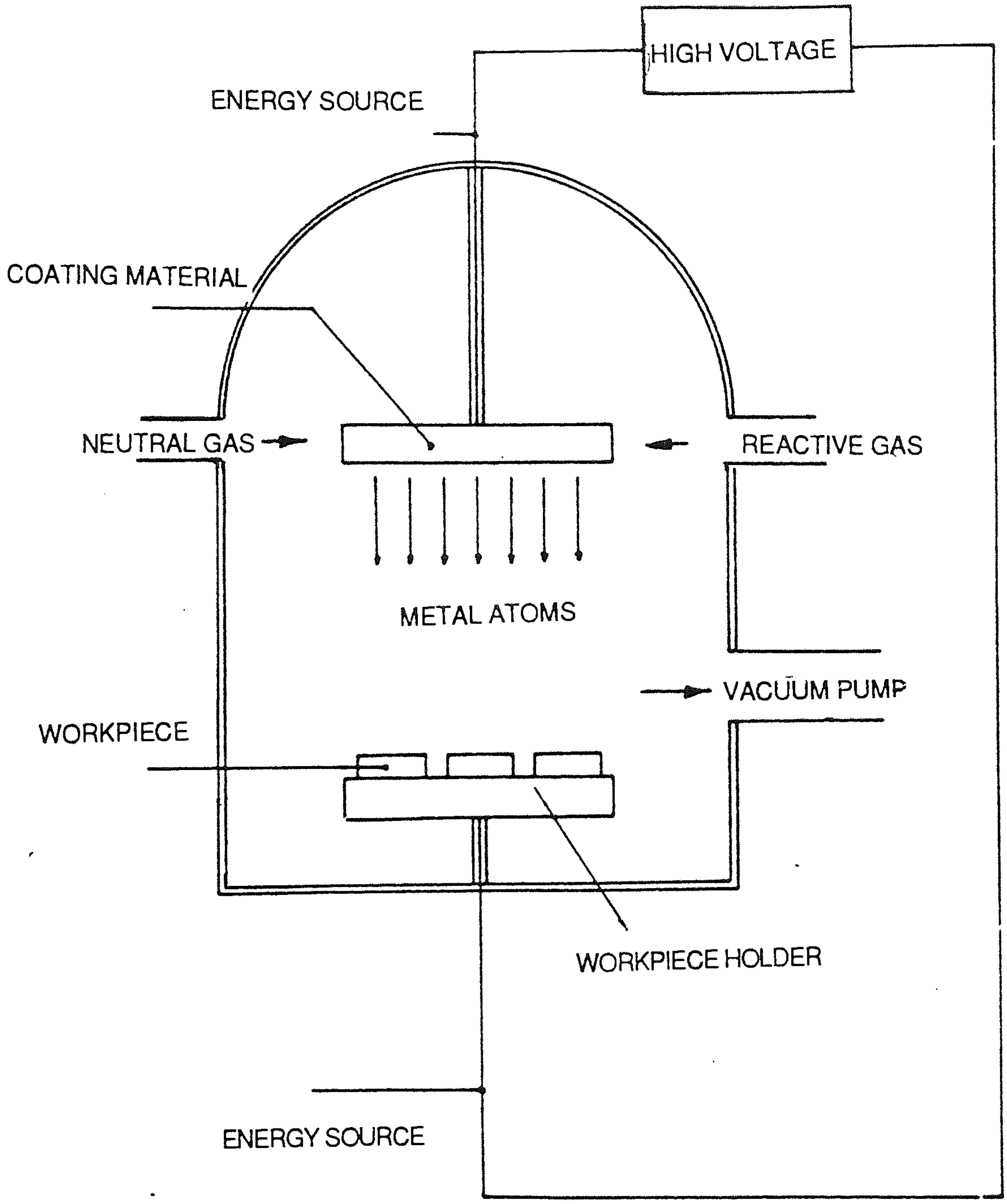



FIG. VIII-1 THE "PVD" PROCESS -REACTIVE SPUTTERING

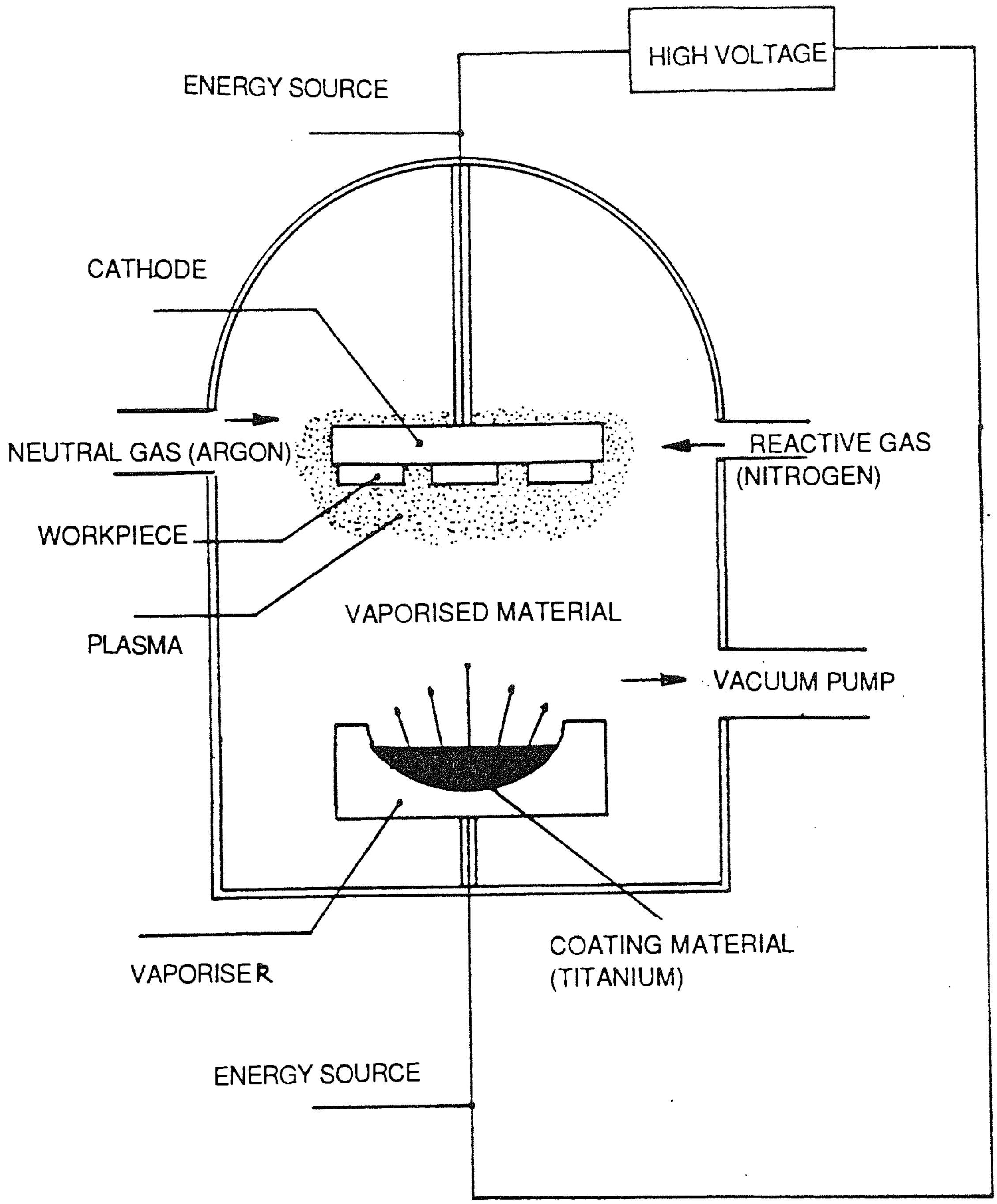



FIG. VIII-2 THE "PVD" PROCESS -REACTIVE ION PLATING

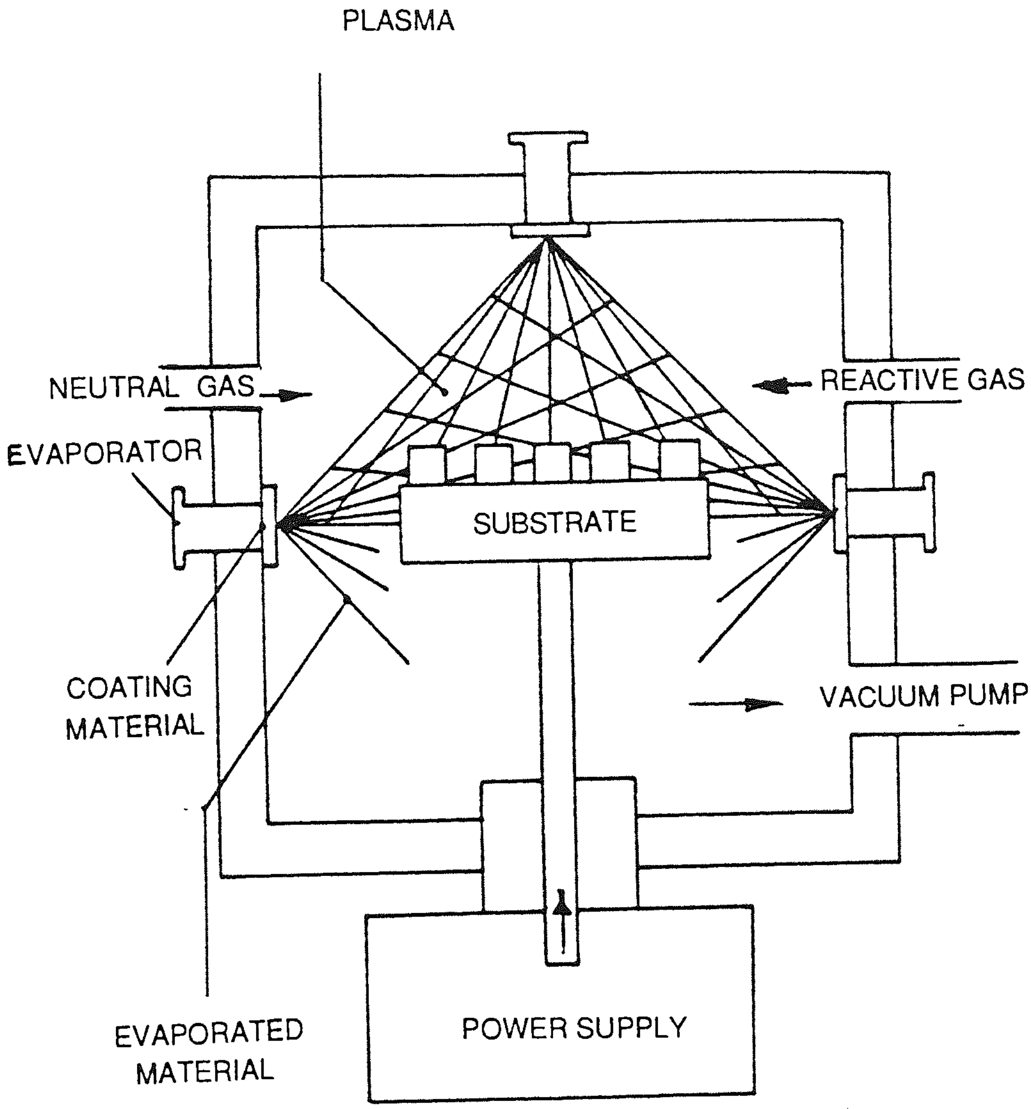



FIG. VIII-3 THE "PVD" PROCESS -ARC EVAPORATION

APPENDIX IX

## EXAMPLE OF CALCULATION UNDERTAKEN TO OPTIMISE THE PROTOTYPE DRILL FLUTE PROFILE

1. General Method of Determining the Flute Cross Sectional Area for Drills with Equal Flute Forms. (Fig. IX-1)

Each flute was assumed to be equal, and each flute area was divided into two parts to form a segment and a parabola, for ease of calculating the areas.

1.1 Area of Segment ($A_{SEG}$)

The area of the segment formed from the intersection of the line A-B with the outside diameter of the drill body, radius 'a', and the end of the flute was determined as follows:

$BCO = \theta$

and $OC = a \cos\theta$

$CB = a \sin\theta$

Area of Sector A C B = $\frac{\theta}{\pi} \pi a^2$

$\Delta$ Area of Segment = Area of Sector - 2 (Area triangle OCB)

$= \theta a^2 - a^2 \cos\theta \sin\theta$

$= a^2 [\theta - \cos\theta \sin\theta]$ - [i]

1.2 Area of Parabola ($A_P$)

For the parabola with origin O and base length A B, the general equation of the parabola was of the form $y = k - mx^2$ - [ii].

where k and m were constants, and the area under the parabola

$$= \int_{-x}^{+x} y \, dx \quad - \text{[iii]}$$

Example of flute area for Prototype No.5

A scale drawing (Fig.IX-1) was produced from a shadow graph trace taken from a section through the drill body. From the drawing the following parameters were determined:-

radius 'a' = 9.41 mm

angle $\theta$ = 39.8°

$\cos\theta$ = 0.7682

$\sin\theta$ = 0.6402

length OB = OA = 6 mm ($\pm x$)

length OD = 3.4 mm

From [i]

Area of Segment ($A_{SEG}$)

$$= 9.41^2 \, [0.6946 - 0.7682 \times 0.6402]$$

$$= 17.96 \text{ mm}^2$$

From [ii]

Equation of Parabola

$$y = k - mx^2$$

when $x = 0$ $y = 3.4$, $= k$

when $y = 0$ $x = \pm 6$, therefore $m = 0.094$.

(intermediate points checked for fit from scale drawings)

therefore $\underline{y = 3.4 - 0.094x^2}$.

Area of Parabola ($A_p$)

$$= \int_{-6}^{6} (3.4 - .094x^2)dx$$

$$\left[3.4x - \frac{.094x^3}{3} + C\right]_{-6}^{6}$$

where C was a constant.

$$= \underline{27.3 \text{ mm}^2}$$

Therefore,

Total Flute Area

= Area of Circle - Area of 2 Segments

- Area of 2 Parabolas - Coolant Hole Area. $= \underline{179.7 \text{ mm}^2}$

and % ratio

$$\frac{\text{Total Flute Area}}{\text{Total Area of Cross Section}} = 32.5\%$$

## 2. Method of Determining Polar Second Moment of Area (J)

The basic method of determining the polar second moment of area was to calculate the second moment for the complete circular section and then deduct the values for two segements and two parabolas.

It was first necessary to determine the centroids as follows:-

### 2.1 Centroid of a Segment ($\bar{y}_s$)

Consider an element of segment width $\delta x$ .

Moment about CE = area x distance of centre of gravity from C.

Area of Element = $(y - a \cos\theta)\ \delta x$.

Distance to centre of gravity from C = $(a \cos\theta + \frac{y - a \cos\theta}{2})$

therefore, Total Moment

$$= \int_{-a \sin\theta}^{a \sin\theta} (y - a \cos\theta)\ \delta x\ (a \cos\theta + y - \frac{a \cos\theta}{2})$$

$$= \tfrac{1}{2} \int_{-a \sin\theta}^{a \sin\theta} y^2 - a^2 \cos^2\theta . \delta x$$

for a circle $y^2 = a^2 - x^2$

therefore $$= \tfrac{1}{2} \int_{-a \sin\theta}^{a \sin\theta} a^2 - x^2 - a^2\cos^2\theta . \delta x$$

$$= \tfrac{1}{2} \left[a^2 x - \frac{x^3}{3} - a^2 x \cos^2\theta . \delta x\right]_{-a \sin\theta}^{a \sin\theta}$$

Total Moment = $[\frac{2a^3 \sin^3\theta}{3}]$ - [iv]

therefore, for Segment:

$\bar{y}_s$ x Area = Moment About CE.

therefore, From [i] and [iv]

$$\bar{y}_s = \frac{2a \sin^3\theta}{3(\theta - \cos\theta \sin\theta)} \qquad - [v]$$

## 2.2 Centroid of the Parabola $(\bar{y}_p)$

Moment about AB = Area x $\bar{y}_p$

therefore, Moment About (AB) = $\int y\ \delta x\ \frac{y}{2} = \tfrac{1}{2} \int_{-x}^{+x} y^2\ \delta x$ - [vi]

From [vi] and [iii]

$$\bar{y}_p = \frac{\tfrac{1}{2} \int_{-x}^{+x} y^2\ \delta x}{\int_{-x}^{+x} y\ \delta x}$$

Centre of Gravity for Prototype 5

For Segment

from [v] $\bar{y}_s = \underline{8.11\text{ mm}}$

For Parabola

$\bar{y}_p = 1.36$ mm From AB

therefore, From Origin C

$= a\cos\theta - 1.36$

$= 7.2 - 1.36 = \underline{5.84\text{ mm}}$

Polar second moment of area (J)

The general expression for $J = \sqrt{(A\bar{x}^2)^2 + (A\bar{y}^2)^2}$ was applicable to the Segment and the Parabola.

Since both the Segment and the Parabola were symmetrical about OC $\bar{x} = 0$

therefore, $J = \sqrt{(A\bar{y}^2)^2}$

Polar second moment for area for Prototype No.5

$$= \frac{\pi(2a)^4}{32} - 2\sqrt{(A_{SEG}\bar{y}_s{}^2)^2} - 2\sqrt{(Ap\bar{y}p^2)^2} - \frac{\pi b^4}{32}$$

where b = coolant hole diameter

Hence, $\underline{J = 8032\text{ mm}^4}$

Comparison of Torsional Stiffness per Unit Length

From the theory of Torsion $\frac{T}{J} = \frac{G\theta_1}{\ell}$ for circular sections and the torsional stiffness per unit length.

$$\frac{T}{\theta_1} = JG$$

where $T$ = applied torque

$\theta_1$ = angle of twist

$J$ = polar second moment of area

$G$ = modulus of rigidity

$\ell$ = length in torsion

This equation does not strictly apply to circular sections that have keyways or flutes cut into them. A good approximation for Torsional Stiffness for sqatt section, prismatic bars due to St Venant[96] was therefore used i.e.

$$\frac{T}{\theta_1} = \frac{GA^4}{40J\ell}$$ where $A$ = cross sectional area.

The torsional stiffness per unit length was therefore proportional to:

$$\frac{A^4}{40J}$$ (see Table 10.2)

This expression was used as a torsional stiffness comparison figure which provided an indication of the relative stiffnesses of the drills considered.

No allowance was made for the effect that the helix angle had on the stiffness. Where a taper web was used on the Mitsubishi and Prototype No.6 this would tend to increase the overal stiffness, but all calculations were based upon the minimum web thickness and maximum flute space at the drill tip.

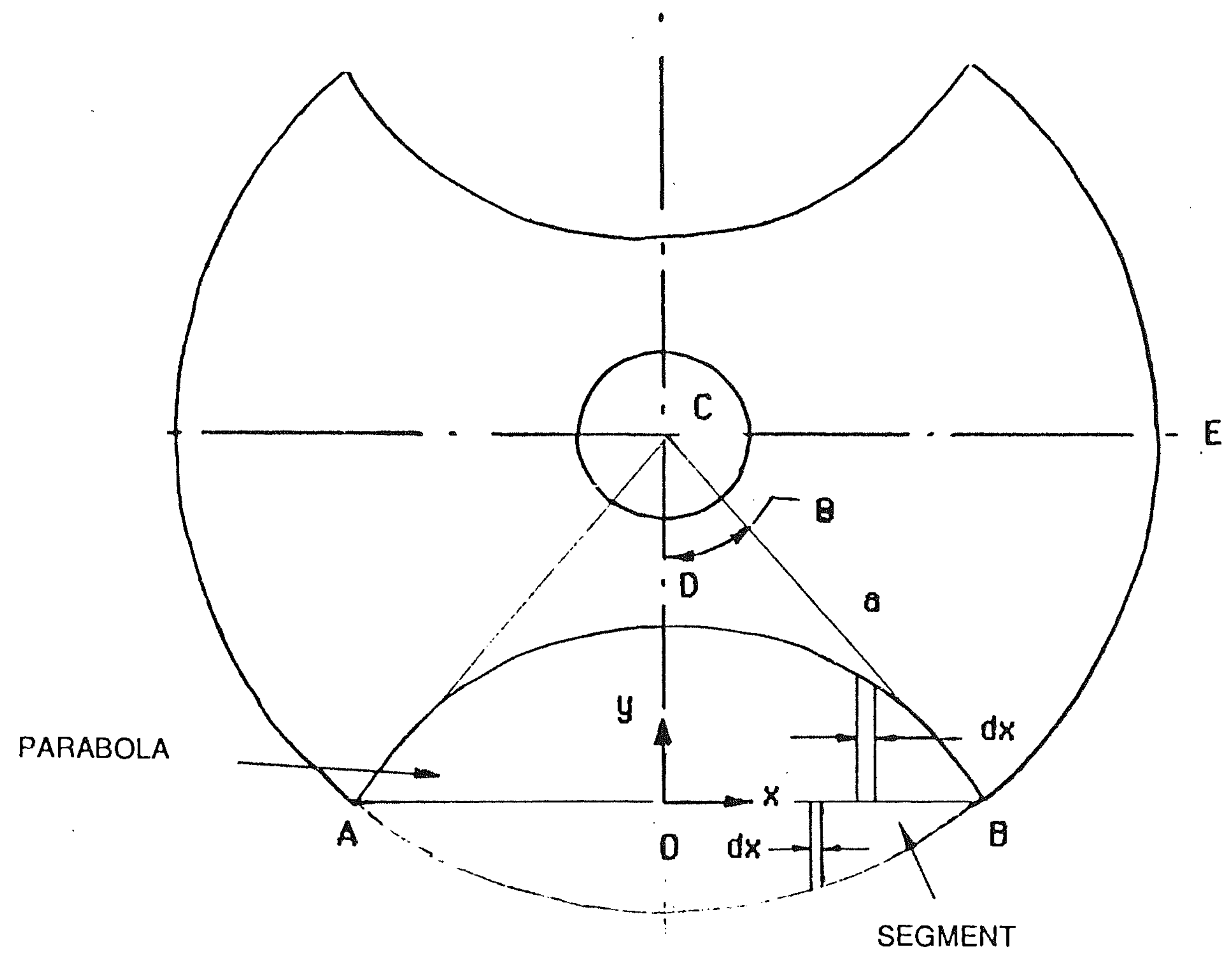



FIG . IX-1 DRILL CROSS SECTION -PROTOTYPE NO 5
CALCULATION OF FLUTE AREA
BY CONSIDERING A SEGMENT AND A PARABOLA
(7 TIMES MAGNIFICATION )

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