THE INFLUENCE OF TWIST DRILL DESIGN ON RIGIDITY AND CHIP DISPOSAL

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by Rhona Elsbeth Leadbetter
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SUMMARY

The research work described in this report was carried out as part of the development of a CAD-CAM system for drills under a Teaching Company Scheme. A CAD drill modelling program with a force prediction module was already present. The main objective of this work was to add two sub-programs that could predict two other major performance criteria in drilling - chip disposal efficiency and drill rigidity and to develop the methodology for applying the programs to practical design environments. These are two conflicting requirements - an efficient chip disposal demands a large flute area, whereas sound drill rigidity needs a large drill cross-section. The fulfilment of these requirements must be a compromise.

An extensive literature search was carried out to determine theoretical and experimental methods of assessing these two performance criteria. There is little published on either topic. Using the theories found and my own practical experience, methods for predicting chip disposal efficiency and drill rigidity were added to the existing CAD system.

In the area of chip disposal, the flute area and the correct angle of chip transportation were calculated by computer. A best-fit circle placed within the flute area has previously been referred to as a relative indicator of the drill's chip disposal efficiency. Further work, reported here, has revealed other factors also have a critical influence on the chip disposal capability of the drill and these have been examined.

Drill rigidity has been examined using Finite Element Analysis, by means of which any type of drill can be modelled and analyzed for stress, strain and displacement. Experimental work has also been carried out using a purpose-built torsion rig to demonstrate the accuracy of the FEA predictions.

A CAE system now exists where the CAD program is linked to several performance prediction modules. A case study given in this thesis shows how the CAE system is used to create a new drill. This is the first documented piece of work known to discuss such a computerised approach to twist drill design.

KEY WORDS : Twist Drill Design, Rigidity, Finite Element Analysis, Chip Disposal, Deep Hole Drills

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NOMENCLATURE

	SYMBOL	UNITS
Up-Curling Curvature	$1/\rho_x$	(degrees)
Side-Curling Curvature	$1/\rho z$	(degrees)
Chip Flow Angle	η	(degrees)
Resultant Angular Velocity	ω	(m/s)
Cutting Speed along Lip	ω_z	(m/s)
Cutting Speed resulting from Up-Curl	ω_x	(m/s)
Chip Pitch	P	(mm)
Chip Diameter	D	(mm)
Chip Angle	θ	(degrees)
Torque	T	(Nm)
Thrust	Th	(kN)
Angular Twist	φ	(degrees)
Polar Second Moment of Inertia	J	(mm^4)
Outer Drill Radius	r	(mm)
Drill Radius	p	(mm)
Area of Drill Cross-section	A	(mm^2)
Maximum Displacement	y	(mm)
Degree of Freedom Matrix	{d}	(mm)
Action Vector Matrix	{A}	(N)
Stiffness Matrix	[K]	(N/mm)
Displacement Vector	{u}	(mm)
Force Vector	{F}	(N)
Modulus of Rigidity	G	(N/mm^2)

CHAPTER 1. INTRODUCTION

The twist drill is the most common tool used in manufacturing processes. Drilling operations represent over half of all chip producing processes and have a major impact on product quality and performance. As the number of drilling operations is so vast, it is apparent that even slight improvements to the drilling process would be of great commercial value to industry. These improvements are presently being sought in the areas of more rapid material removal rates and long periods of unmanned operation. An increase in drill life of for example 10%, would give an annual saving of 30 million dollars to the American market in tool cost alone [1]. But above and beyond that, the savings in labour cost, machine cost, scrap reduction and improved productivity are estimated to be far greater.

As drilling conditions become more demanding, a higher degree of reliability is required in the drilling process. Good chip control becomes essential to prevent problems such as "choking", where chips fold back on themselves, become locked in the flutes and then prevent other chips from escaping. In extreme cases, this causes fracturing in the drills themselves. As well as good chip control the tool must have an acceptable and reliable life-span, minimising tool changes and allowing tool wear-out to be reasonably predictable. The drill therefore must have the rigidity and strength to endure the most demanding of cutting conditions.

The demands for chip control on the one hand and drill rigidity on the other are in conflict, as one requires large flutes and the other requires a large drill cross-section. The search to find a suitable compromise is at the centre of this thesis, which examines the influence of the drill's geometric design on these performance criteria, using both experimental and numerical methods.

A Teaching Company Scheme has been operated between Aston University and SKF & Dormer Tools Ltd. The main objective was to establish a CAD-CAM system which would produce commercially successful drill designs using the principles of simultaneous engineering to reduce design-to-product times and costs. A CAD program has been written, based on mathematical equations that define the complex three-dimensional drill shape [2]. The work described here is part of the next phase of the project where the CAD program becomes a platform for a more extensive CAE system. This involved the creation of program modules to make accurate performance predictions in terms of various aspects of a drill's performance.

The aim was to use the predicted performance data, collected about the drill model from each module, for the creation of a design methodology. This would introduce a more logical and consistent approach to drill design, as well as present information about the design previously available only with more extensive prototype production and testing than is now necessary. With the tools developed during the project, the time scale from defined need to prototype manufacture has been reduced from 1 to 2 years to about 6 months.

The work reported here has resulted in four papers, two of which were presented at two DTI Teaching Company Seminars [3,4], one was presented at the 1993 MATADOR Conference [5] and another which is to be published by the IMECHE in November of this year [6]. These are presented in this thesis as supporting material.

CHAPTER 2. BACKGROUND OF DRILLS AND DRILLING

Although drills originally date back many centuries, the modern day drill is based on the design patented in 1863 by Stephen A. Morse in the United States of America [2]. The general appearance of drills has altered little since then, but considerable improvements have been made in manufacturing methods and materials. There is also a current trend to move away from the conventional geometry to more radical shapes.

2.1 DRILL DESIGN

Drills are typically of a two-fluted, right-hand helix form made of high speed steel or cobalt steel. Figures 1(a) & 1(b) show a typical standard drill and the nomenclature of the various parts and dimensions. The Appendix contains a definition of terms for the drill elements, linear measurements and angles. A conventional twist drill consists of a shank, body and point [3].

* DRILL SHANK

The shank is that part of the drill which is held and driven by the machine tool. Straight shanks are held in a drill chuck (or a collet in CNC machinery), whereas tapered shanks have a tang which fits into a slot in the drill holder or the spindle socket and is for ejection purposes. Generally, drills up to 13 mm diameter are produced with straight shanks, with larger drills having tapered shanks. A drill often consists of two bars that are electrically friction welded together by rotating them in opposite directions. This means it is

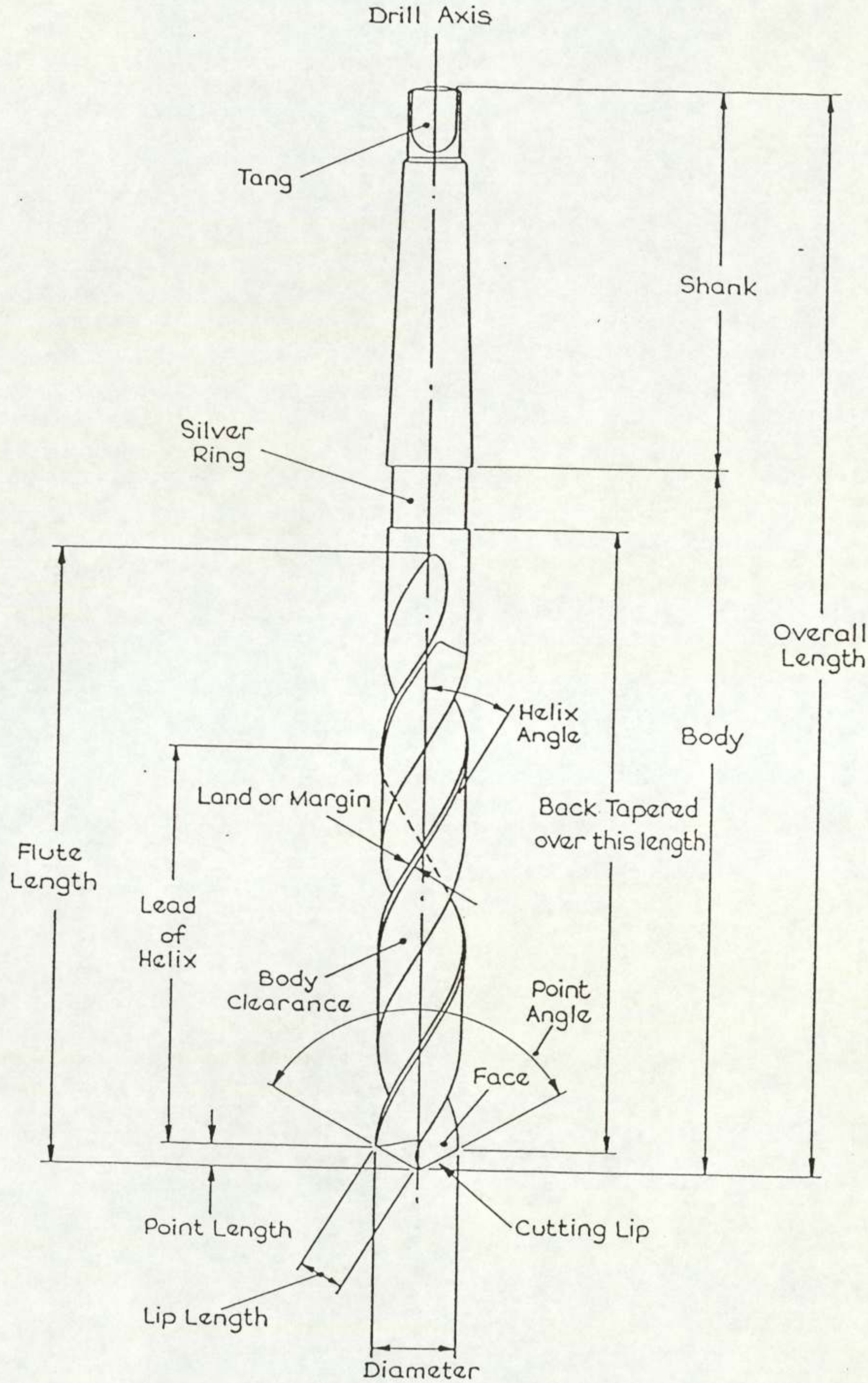


Figure 1a - Drill Nomenclature

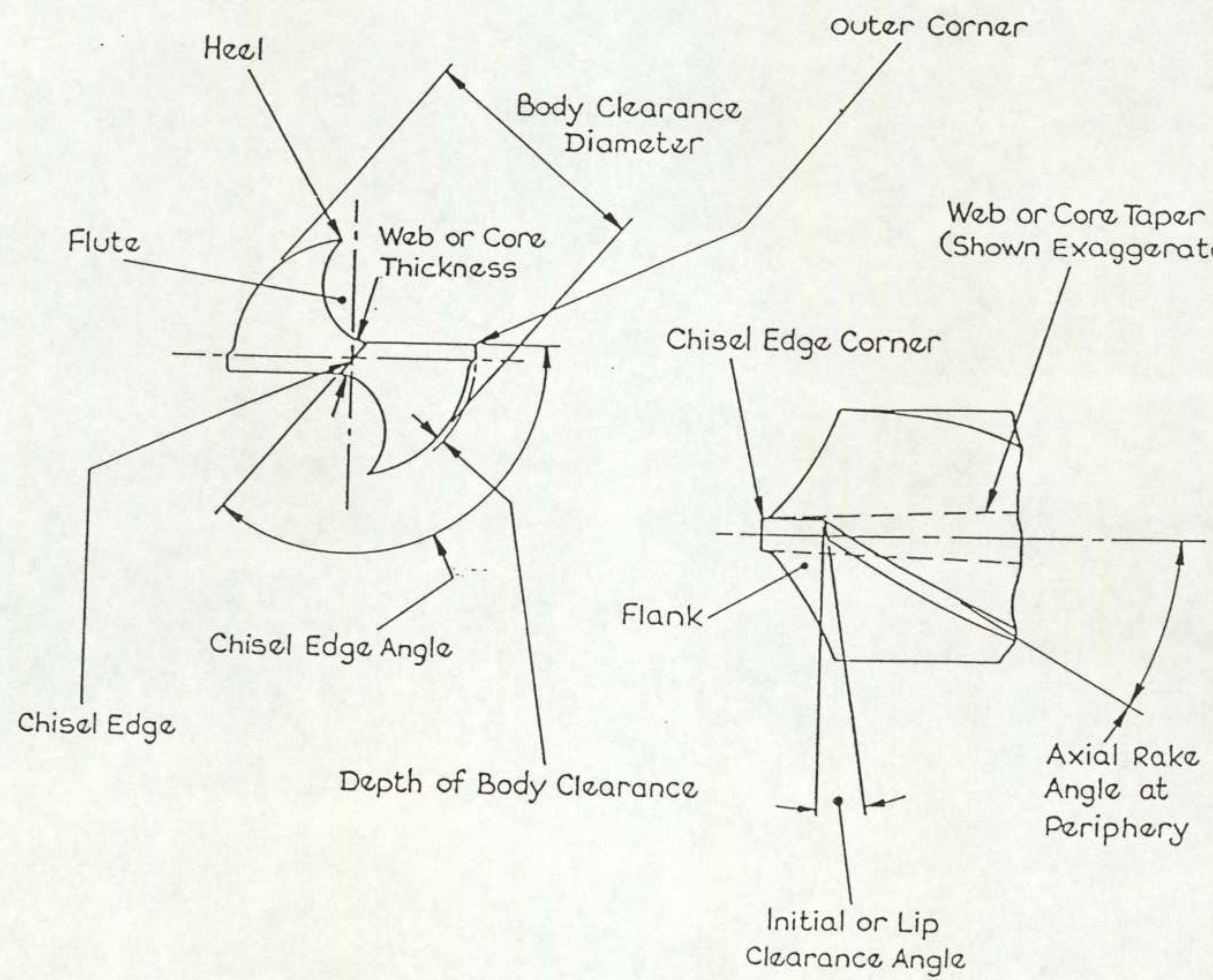


Figure 1b - Drill Nomenclature

possible to manufacture a drill consisting of two different materials and/or parts that have undergone different preparatory treatments. It is therefore possible to have a relatively soft shank (improves grip) and a relatively hard body (reduces wear). This can also be achieved by heat treatment wherein the body is heated and quenched in a salt bath.

The shank is often used to display the manufacturer's trademark, as well as the material and diameter of the drill. This information can also be displayed on the "neck" of the drill - indicated in Figure 1(a) as the silver ring. This ensures the markings are not damaged by the chuck teeth and remain legible.

* DRILL BODY

The drill body runs from the shank to the drill point. There are two helical grooves, called flutes, cut in the body that provide cutting edges, chip ejection channels and coolant flow to the point. The remaining helical part of the body that is not cut away is known as the land. Part of this is removed (body clearance diameter) to prevent rubbing against the hole wall, reducing friction. The land that is left (the margin) has the full diameter of the drill and stabilizes the drill in the hole. The central portion of the body that joins the lands is the web, which provides drill rigidity and sometimes tapers towards the drill point. This increases the stability of the tool. The drill body tapers very slightly in the opposite direction, towards the shank, to give clearance and reduce friction (maximum taper equals 0.08% of body length). It is possible to have channels running through the body of the drill which supply coolant to the drill point to reduce heat generation at the cutting lips.

* DRILL POINT

The point has a chisel edge at the end of the web, which is often thinned or faceted to reduce the thrust force on the tool and improve the drill's centring capability [1]. The lips are the cutting edges of the drill that run from the chisel edge corner to the outer corner, and can be straight or curved. They are created by the rake face (the flute) meeting the flank face (the point surface). The standard point angle, as is noted in the British Standards definition of a drill form, is 118 degrees. This angle has been established by drill manufacturers as the most suitable for general purpose work. Angles greater than this are normally used for a brittle material, such as Cast Iron, and a smaller angle is used for a ductile material such as Aluminium. The rake angle normally ranges from highly negative (around -55 degrees) at the chisel corner to positive at the outer corner, where it is equal to the helix angle - typically around 30 degrees. And finally, the lip clearance angle is a measure of the flank face clearance from the work-piece.

The drill design has a critical influence on its performance [4]. Different combinations of design features are recommended by manufacturers for the cutting of different materials. These recommendations are often based on a tried-and-tested basis, rather than a detailed scientific understanding of the relationship between design and performance. It is intended that the performance prediction modules, as described in the introduction, can help clarify this complex relationship and therefore assist in the successful selection of drill designs for different material groups.

2.2 DRILL PERFORMANCE

Users place a variety of demands on drills, depending on the required result. The main objectives of the drill users have been identified and are used as the main criteria for rating drill performance [4]. They are:

1) Maximum Rate of Penetration
2) Long Drill Life
3) High Efficiency of Material Removal
4) Hole Accuracy
5) Hole Surface Finish

1) Rate of Penetration can be expressed as depth of hole drilled per revolution, and is dependant on the feed and speed selected [4]. An increase in the rate of penetration results in a direct reduction in cutting time and costs.

2) Drill life is usually expressed as the number of holes drilled between re-grinds. Alternatively it can be the number of holes drilled before a drill fails - either through accumulated wear or fracture. In both cases the drill is considered by the user to be worn out and therefore discarded.

3) Drilling Efficiency may be expressed in terms of volume of material removed per kilo Watt minute or as power required for a given rate of drilling. It is a reflection of the mechanical efficiency of the machine used. Due to the complexity of the drilling process the efficiency of material removal is considerably less than that of simpler operations such as rough turning on a lathe.

4) Different applications demand different degrees of accuracy of a drilled hole regarding specified size and position. When drilling is used as a rough machining operation, the highest rate of material removal is required and accuracy is sacrificed. A high degree of accuracy, i.e. dimensionally correct with a low run-out, can also be money-saving by reducing scrap or re-work or the need for a finishing operation.

5) After drilling a hole, a finishing operation such as reaming or boring is often required to remove burrs and improve accuracy and surface finish. Time can be saved by producing a good quality hole with only one operation.

The five main criteria described above are affected by numerous factors, the most important of which are shown in Figure 2 [4]. The influence of these variables on drill performance, and their inter-dependence, has been researched over the last 130 years. The vast majority of currently available empirical data is supplied by drill manufacturers, as obtained from extensive experimentation spanning many years.

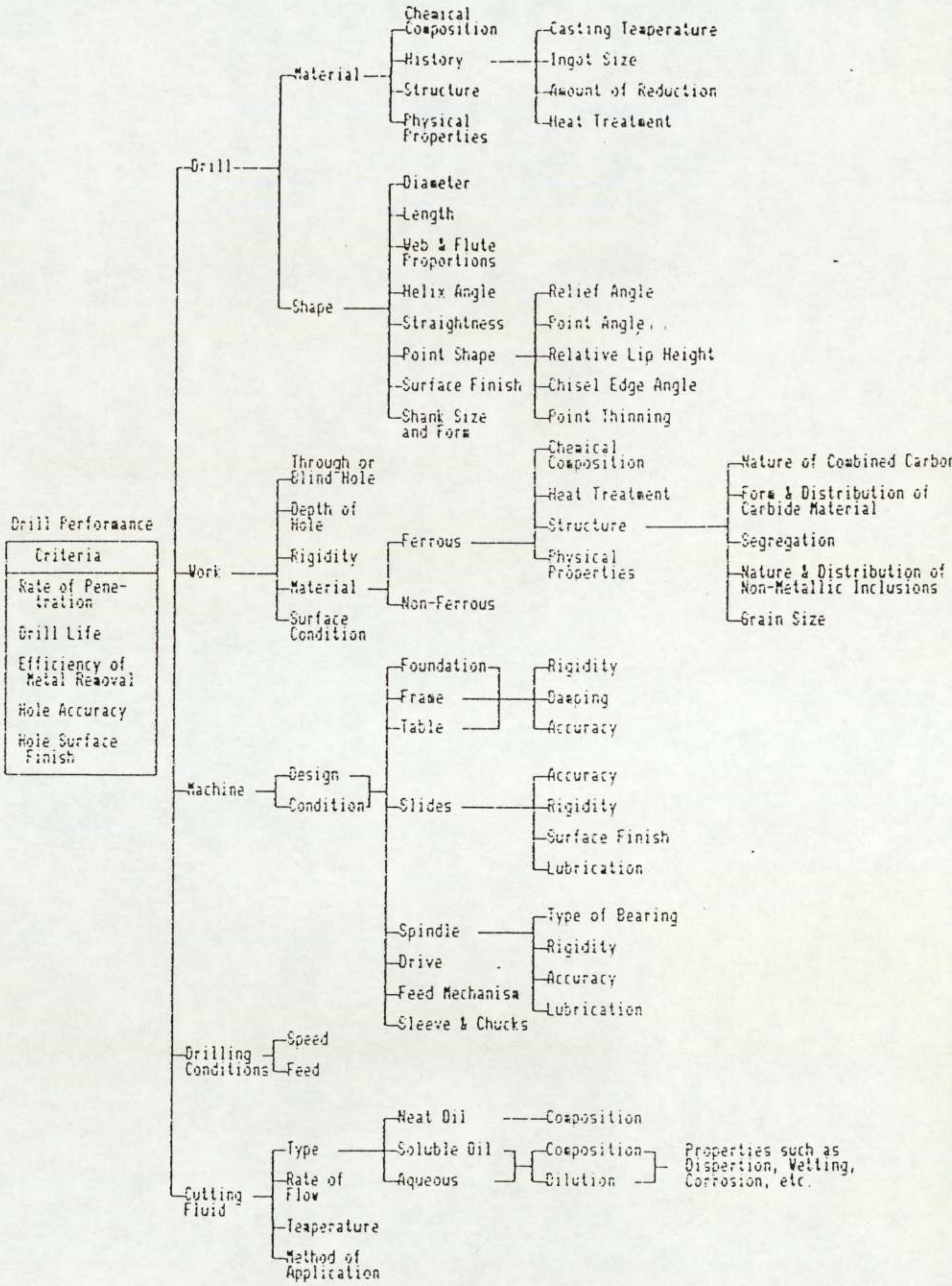


Figure 2 - Table of Performance Criteria [4]

More recently research has taken a different approach, aimed at analysing drills theoretically rather than empirically. Galloway's work [4] reported mathematical equations that describe drill geometry for conical points. These equations form the basis of the CAD system mentioned earlier, and several other computer programs that model conical points [5]. Further development was done by Tsai and Wu [6] to describe hyperbolical and ellipsoidal drill points, in such a way as to facilitate computer analysis.

Theoretical analysis of drill performance has also been carried out in order to be able to calculate the forces experienced by the drill [7,8]. The metal cutting process during drilling is highly complex, and the theoretical determination of the torque and thrust is far from straightforward. Articles which attempt to describe the action taking place across the drill's cutting lips and chisel edge therefore incorporate a variety of models. The Teaching Company drill modelling system currently contains a torque and thrust prediction module. This is based on basic metal cutting theories and results in a numerical estimation of the torque and thrust across the cutting lip and the chisel edge. The predictions are known to lack accuracy as a result of the many influential variables that have not been taken into account (tool hardness, coatings, etc). The intention is therefore that the prediction will constantly be upper-bound, but by less than 20%. These numerical estimations are output from the program for numerous points along the cutting lip and chisel edge, and also summated as total torque and thrust. The user is therefore able to examine how the torque and thrust differ at various points along the cutting lip and chisel edge. This provides information on the torque and thrust distribution in terms of radial position.

As demonstrated by the above pieces of work, this current trend to analyse drill geometry and the relationship to the performance of the tool has been facilitated by the accessibility of cheaper, faster and more powerful computers. It is now possible to carry out analyses using computers that would previously have been too complex and/or time-consuming to undertake. Traditional experimental methods are still equally valid and can indeed be used to verify those predictions made numerically. In light of such advances, this study aims to analyze two specific drill performance criteria both theoretically and experimentally, the intention being to use computerized methods to obtain predictions as accurately as possible, when compared to reliable experimental results.

The original CAE system only provided predictions of torque and thrust. Two equally important aspects of the life and performance of a drill during cutting are drill rigidity and chip control. As will be shown, it is impossible to consider one without the other. It is therefore a natural progression for the project to investigate both these performance criteria and this provided the need for the work reported in this thesis.

CHAPTER 3. CHIP CONTROL IN DRILLING

Recent progress in the development of metal cutting tools and machine tools has greatly increased the productivity of cutting operations. Chip control has therefore become one of the most serious problems in machining, especially when considering implementing unmanned operation. In order to be able to make any predictions about the chip disposal ability of a drill, it is necessary to examine chip formation in the drill flute. Using this information a numerical approach to chip disposal efficiency can then be formulated.

There are two basic stages in chip control:

1) the formation of the chip and

2) the conveyance of the chip.

The first stage, the chip formation at the cutting edge, is fundamentally the same for all metal cutting processes including drilling. The second stage, the chip flow, is however considerably more complex for drills than for other cutting tools, due to the three dimensional cutting process that occurs within a confined space when drilling. It is therefore necessary to look specifically at the chip flow in drilling.

3.1 CHIP FORMATION IN METAL CUTTING

All chip-forming, metal-cutting, processes share the same basic principles. These are based on the concept of the tool's hard cutting edge, with a rake face and a flank face, passing through a softer material and shearing off the upper layer.

The conditions under which this shearing occurs and the material properties of the work-piece, determine whether the chip is continuous or discontinuous.

When a continuous chip is formed, a quasi-static plastic deformation occurs in the zone linking the chip to the work-piece. This zone is called the shear-zone because the plastic deformation in this zone is a simple shear [9]. Theoretically, this is often simplified to allow the shear to occur in one plane only, known as the shear plane (Figure 3). Additional shear takes place in the area adjacent to the tool face as a result of tool friction, and is known as secondary shear. The shear angle (the angle between the shear plane and the newly formed surface) is considered to be an extremely important parameter in cutting theory, as a result of its influence on chip thickness. Many studies have concentrated on its theoretical determination [10] in a plane situation, and it is generally stated that the magnitude of the shear angle is mainly determined by the cutting speed, depth of cut and the work-piece material. Empirically it has been confirmed that a larger shear angle gives a thinner chip and a shorter chip-tool contact length which has the positive effect of reducing tool surface friction. However, the situation in practical metal cutting is so complex that it is very difficult to accurately predict the value of the shear angle and therefore the chip form.

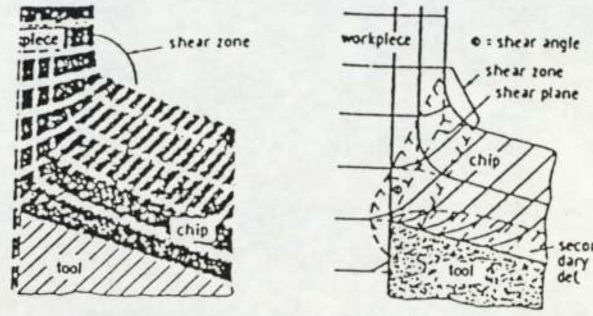


Figure 3 Shear zone, shear plane and secondary deformation [9]

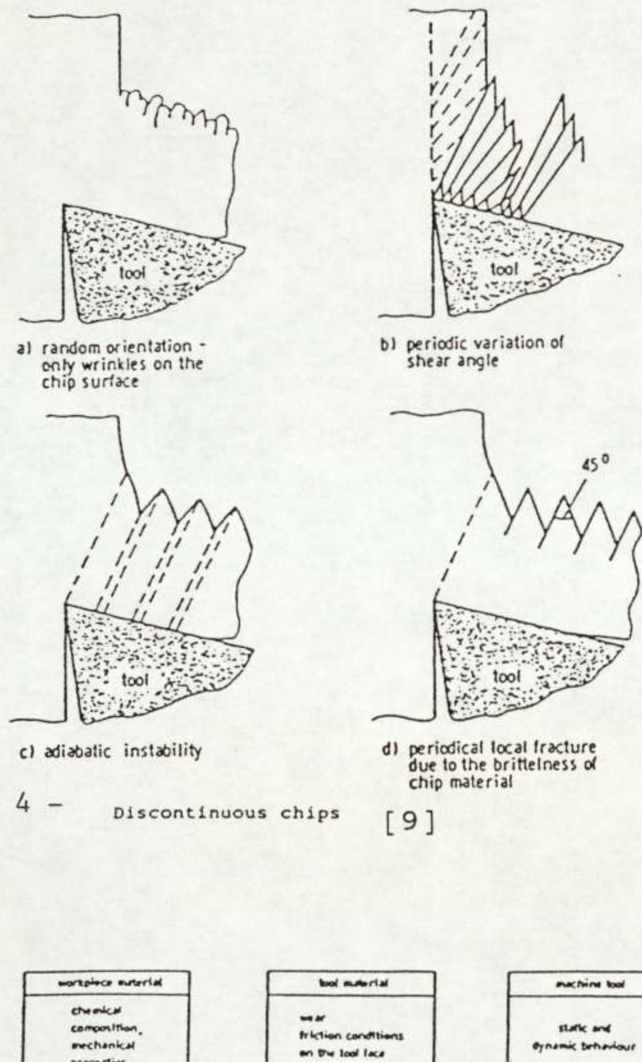


Figure 4 - Discontinuous chips [9]

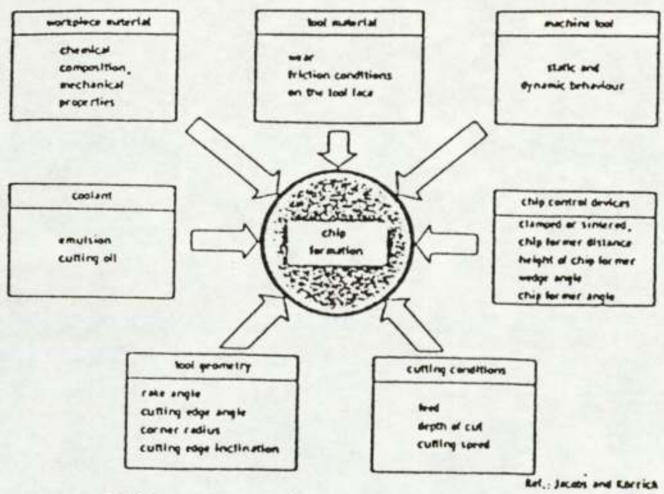


Figure 5 - Influences on the type of chip formation [9]

When a discontinuous chip is formed, the cutting forces on the tool fluctuate which can result in a wavy surface finish and tool failure if the system has poor rigidity. The quasi-static plastic deformation in the shear zone is disturbed and produces a discontinuous chip, for various reasons extensively discussed in [11]:

- the polycrystalline structure of the material has a random orientation and a non-uniform nature which causes wrinkles on the surface (Figure 4a);

- periodic change of the shear angle (Figure 4b) due to tool-chip friction or tool/work-piece/machine tool dynamic characteristics;

- periodic variation of size and shape of the built-up edge (see footnote);

- strain concentration due to internal heat in the high-speed cutting of poor heat-conducting materials (e.g. stainless steel), Figure 4c;

Footnote:
"Built-up" edge (BUE) is often encountered when machining ductile materials. The local high temperature and extreme pressure in the cutting zone cause the work-piece material to stick to the cutting edge of the tool, forming the BUE.

- local fracture due to the brittleness of the material (Figure 4d) resulting from environmental effects (e.g. coolant), or the composition and pre-treatment of the work-piece and the strain-hardening during cutting;

- any combination of the above.

It is not yet possible to theoretically predict whether discontinuous or continuous chips will be produced in a certain case. Figure 5 shows the many factors that influence the type of chip formations under the headings: work-piece material, tool material, machine tool, chip control devices, cutting conditions, tool geometry and coolant. These headings cover numerous factors and variables, illustrating the difficulty involved when attempting to predict the chip form.

It is, however, possible to predict the angle of chip flow as the material leaves the cutting lip. This is often referred to as Stabler's Law [12], which states that the inclination angle of the approaching work-piece material is equal to the inclination angle of the chip material as it moves away from the cutting edge. A computer module was created by Webb [2] as part of the drill CAE system that calculates the chip flow angles across the cutting lip of a drill based on Stabler's Law.

As the chip leaves the cutting edge it starts to curl. There are two theories about the nature of this chip curl formation [9,11] - one states the chip curls after it has been sheared and as a result of travelling up the tool face, whilst the other states that the chip is "born" curled. Generally a combination of the two theories is presented where non-uniformity in shearing is seen as the main cause of chip curl with the contact force produced between the chip and the rake face influencing this shear deformation.

Geometrically, the chip form is indicated by the combination of the "up-curling curvature" $1/\rho_x$, the "side-curling" curvature $1/\rho_z$ and the chip flow angle η [9,13,14]. This can be seen in Figures 6(a) & 6(b), where θ is the angle between the chip axis and the x-axis. Together with the width, thickness and length of the chip, these factors can be used to describe the form of the chip. "Up-curling" has been seen to increase as a result of obstacles in the way of the chip flow (such as chip breakers), the built-up edge and the secondary shear. There is a range of views on the cause of "side-curling" and the direction of chip flow [9,14], together with an indication of a lack of knowledge in this area. However, the major influence is given as the variation of chip velocity. This is a product of the cutting velocity and the chip thickness ratio, and therefore a variation in one or both of these will produce side-curling. This is influenced by the change in rake angle, shear angle and chip length ratio.

3.2 CHIP FLOW IN DRILLING

Most research into chip flow has been carried out for machining processes such as turning where the flow is undisturbed, and the unconstrained path from the tool tip to the machine bed is a relatively easy one. Less attention has

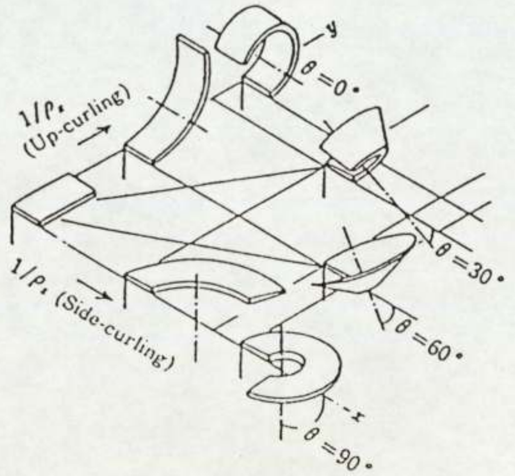


Figure 6a Variation of chip form by up-curling and side-curling when $\eta=0$ [11]

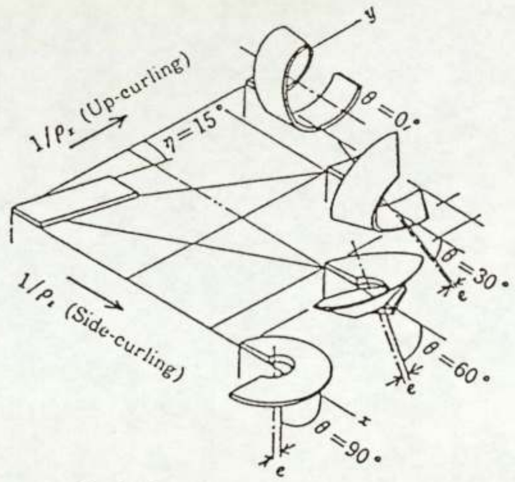


Figure 6b Variation of chip form by up-curling and side-curling when $\eta=15$ [11]

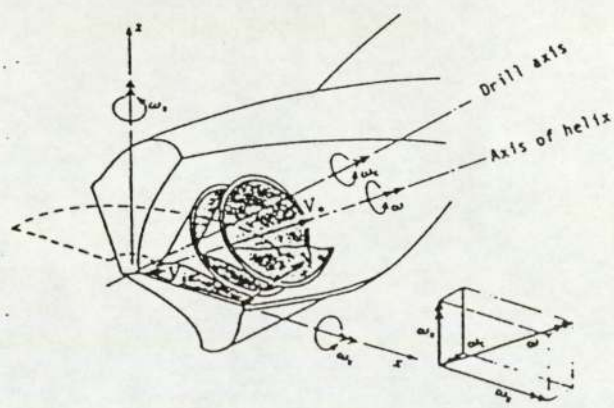


Figure 7 - Conical helical chip produced by twist drill [16]

been paid to those processes where the chips are not free-flowing, such as drilling, where the chip is deformed in a narrow area between the work-piece and the tool.

Some papers, found in the field of drilling [13,15,16], emphasize the need for chips that are readily ejected. As the flute area is only about 50% of the total drill cross-sectional area, the chips must be removed at twice the speed they are created. As a result of these space restrictions, it is desirable to have chips that are discontinuous, as these are more easily removed by the conveyor action of the helical flutes, gravity, coolant pressure and/or the withdrawal of the drill.

Continuous chips, on the other hand, occupy a space that is greater than the actual volume of the material removed due to of their conical shape, see Figure 7, which can complicate their removal. These chips have a tendency to "bird-nest" (wrap around the drill shank) and are therefore a known hazard to tool life, operating personnel and the surface finish of the work-piece [9]. There is also a greater tendency for continuous chips to clog in the drill flute which causes higher drilling torque, higher cutting temperature, lower quality of hole produced, accelerated tool wear and even catastrophic failure.

By considering the principles of chip formation and chip curl the chip form produced in drilling can be understood. The rake face of a drill is not flat but twisted, also the rake angle increases along the cutting lip from the inner (chisel) corner to the outer corner. Figure 7 shows that the twisted rake face has the effect of rotating the chip around the axis of the drill (with the angular velocity ω_c). Side-curling is induced by the varying cutting speed along the cutting lip (ω_z), with the obstruction of the web causing the chip to curl up (ω_x). The chip is therefore given three components of angular velocity ω_c , ω_z and ω_x , which result in the helical motion of angular velocity ω . A collection of typical chip forms produced in drilling is shown in Figure 8.

The general classification of chips [13] can be seen in Figure 9, where nine types of chip are basically defined according to their length. More detailed classification symbols can be used to indicate the mode of chip curl (upward, oblique, sideward), the radius of curvature (relative to the width of chip) and the pitch of coil (Figure 10). From a practical point of view, the chip form is more conveniently expressed in terms that can be readily measured, i.e. the pitch P, the diameter D, and the angle between the chip face and the coil axis, .

When drilling most engineering materials, the initial chip form will be unconstrained producing a basic conical chip shape. The chip formation across the chisel edge is different and resembles an extrusion process more than cutting (Figure 11). Separate chips are produced which are transported and deposited together with the main chips. As the hole deepens, the initial chip motion is prevented by the hole wall. Depending on the ratio of feed/drill diameter, the drill geometry and the brittleness of the material, one of the following will occur:

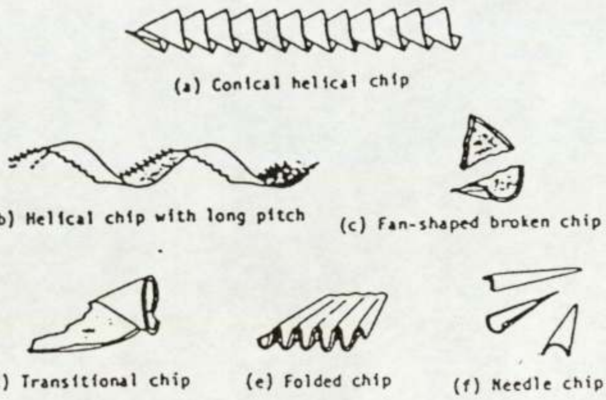


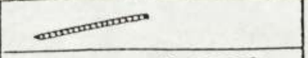
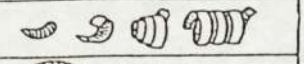
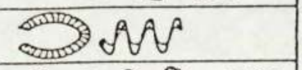
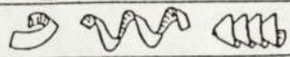
Figure 8 - Various forms of drill chip [16]

General classification

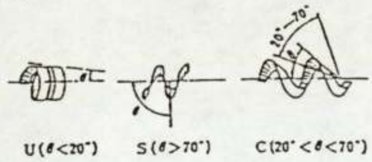
type	symbol	form	example: turning	example: drilling
type 1	1 (•)	powder or elemental	[1] [1] [1]	
type 2	2 (▯)	rectangular	[2]	
type 3	3 (ɔ)	broken 1/2 turn	[3] U50	[3] C10
type 4 (C type)	4 (C)	broken, about one turn (C shaped)	[4] U20 [4] C40 [4] S3S	[4] C2S
type 5 (E type)	5 (ε)	broken, 2to 10 turns	[5] U2S [5] U3M	[5] U2S [5] C1S [5] C2S
type 6	6 (6)	broken, irregular form	[6] [6]	
type 7	7 (γ)	continuous, constant form	[7] U3M [7] C3L [7] U2S	[7] U3L [7] C1S [7] U1L [7] N
type 8	8 (∞)	continuous, irregular form	[8] R5Z	[8] [8] C9L
type 9	9 (×)	other than the above types		
	0	unknown (no information)		

Figure 9 - Classification of chip form by Subcommittee "Chip Disposal", Sectional Committee on Machinability in JSPE [11]

(1) Mode of curling

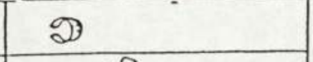
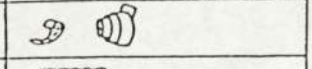
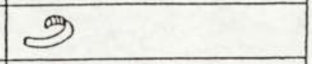
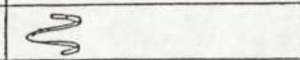
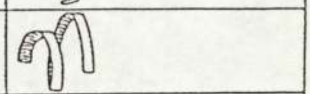
type	symbol	example
no-curl	N	
up-curl	U	
side-curl	S	
conical-curl	C	
random-curl	R	
miscellaneous	Z	
unknown (no information)	0	

(Note)

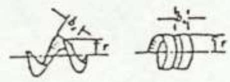


θ: the angle between the coil axis and the tangential plane to the chip surface

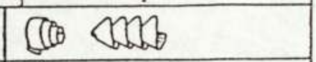
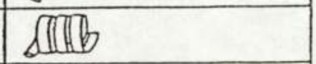
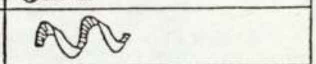
(2) Radius of curvature

type	symbol	example
small radius	1	
increase from small radius	2	
medium radius	3	
increase from medium radius	4	
large radius	5	
increase from large radius	6	
miscellaneous	9	
unknown (no information)	0	

(Note) small radius: $r/b_c < 1$
medium radius: $1 < r/b_c < 2$
large radius: $r/b_c > 2$



(3) Pitch of coil

type	symbol	example
short pitch	S	
medium pitch	M	
long pitch	L	
miscellaneous	Z	
unknown (no information)	0	

(Note) short pitch (S): $p/b_c < 1$ (overlapped)
medium pitch (M): $1 < p/b_c < 2$ (close)
long pitch (L): $p/b_c > 2$ (open)

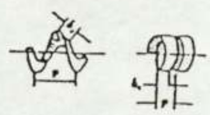


Figure 10 - Classification of chip form by Subcommittee "Chip Disposal", Sectional Committee on Machinability in JSPE [11]

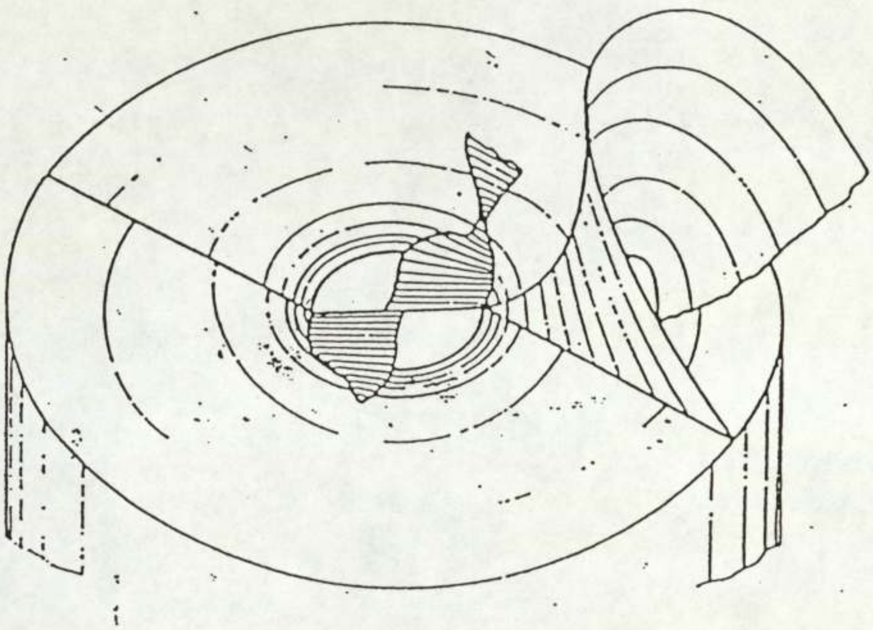


Figure 1/ - - Chip Formation from Chisel and Cutting Lip

a) the chip is thin enough to deflect elastically and passes through the narrow flute space between the drill and the work-piece, maintaining the basic conical and now helical shape (Figure 8a);

b) the chip is not so thin and undergoes a constraining force which decreases the side-curl and increases the chip flow angle. This results in a helical chip with a long pitch, Figure 8b. For a brittle material with insufficient ductility a jagged inside edge is produced;

c) the material lacks ductility to withstand the severe deformation and short fan-shaped broken chips of uniform thickness are produced (Figure 8c);

d) the material has a medium ductility and a cross between a) and b) is produced where the initial conical form is followed by a long pitch helical chip. The constraining force from the hole wall and insufficient ductility eventually results in the chip being broken (Figure 8d).

The above case is also true for a curved cutting lip (convex and concave), although there are some differences such as the direction of chip flow across the lip. As part of the development of a new hi-tech Titanium Nitride coated drill at Dormers, known as the ADX drill, work was carried out to determine the benefits of a curved cutting lip in terms of chip disposal. From experimental work carried out by the author the curved cutting lip was found to have the additional benefit of stretching the material as it cuts. Together with the added design feature of a curved flute surface (a result of the drill having a "rolled heel" - see Figures 12(a) and (b)) the chip bends back on itself, while being stretched and is encouraged to tear. This process is drawn in five stages in Figure 13, where the computer's chip flow prediction module was used to provide the chip flow lines from the cutting lip. In contrast, Figure 14 shows, also in five stages, how material passes up the flute of a straight lipped drill. The chip is not stretched as it passes over the cutting lip, nor does it undergo a forced curvature on the relatively flat flute surface, the chip is therefore able to curl up into a continuous conical form. The joint presence of a curved cutting lip and a rolled heel has been found by the author to be an extremely effective way of producing discontinuous chips, particularly when cutting tough, ductile materials such as titanium or stainless steel. This information has been used by Dormers in their technical sales leaflet (see Figure 15).

Discontinuous chips are associated with efficient chip disposal as a result of the ease of transportation. If continuous chips are being produced, however, there are still ways of promoting efficient chip disposal:

* A chip can be encouraged to break by using a chip former or breaker [17,18]. By placing an obstacle in the way of the chip flow, the chip undergoes a forced curvature and subsequently breaks when it hits either the work-piece or the tool surface. Such an effect can successfully be achieved by grinding nicks in the cutting lip [19] or by grinding a groove along the web in the flute [15].

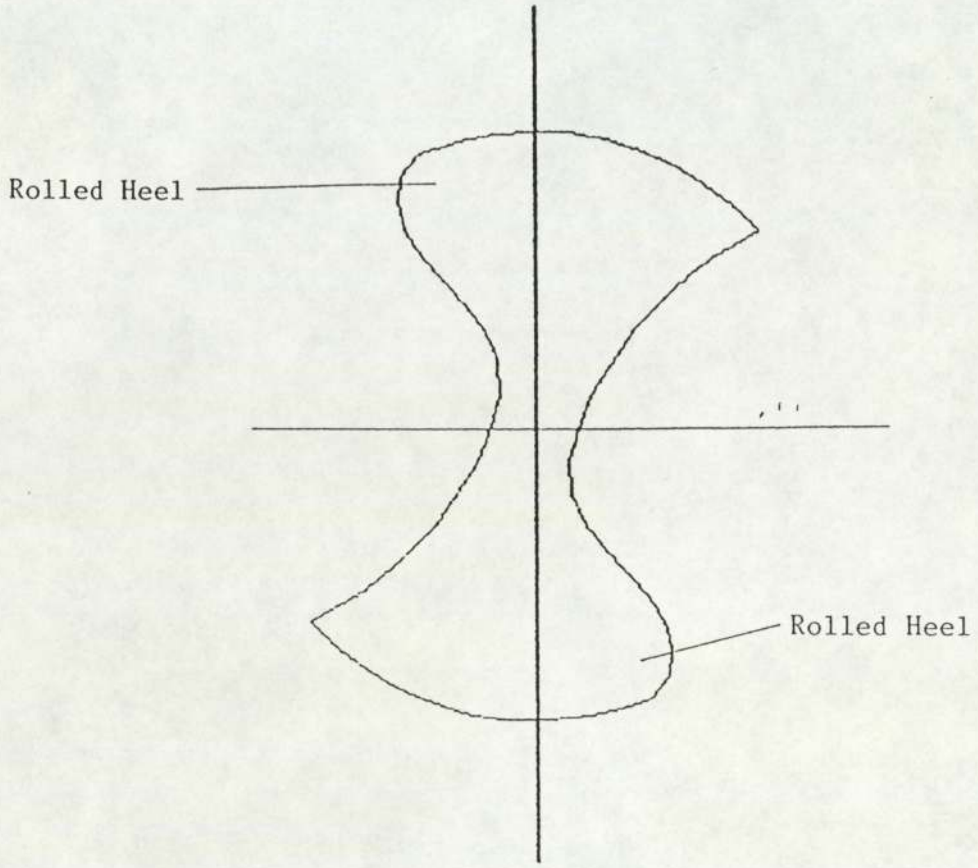


Figure 12 a - Cross-section with Rolled Heel

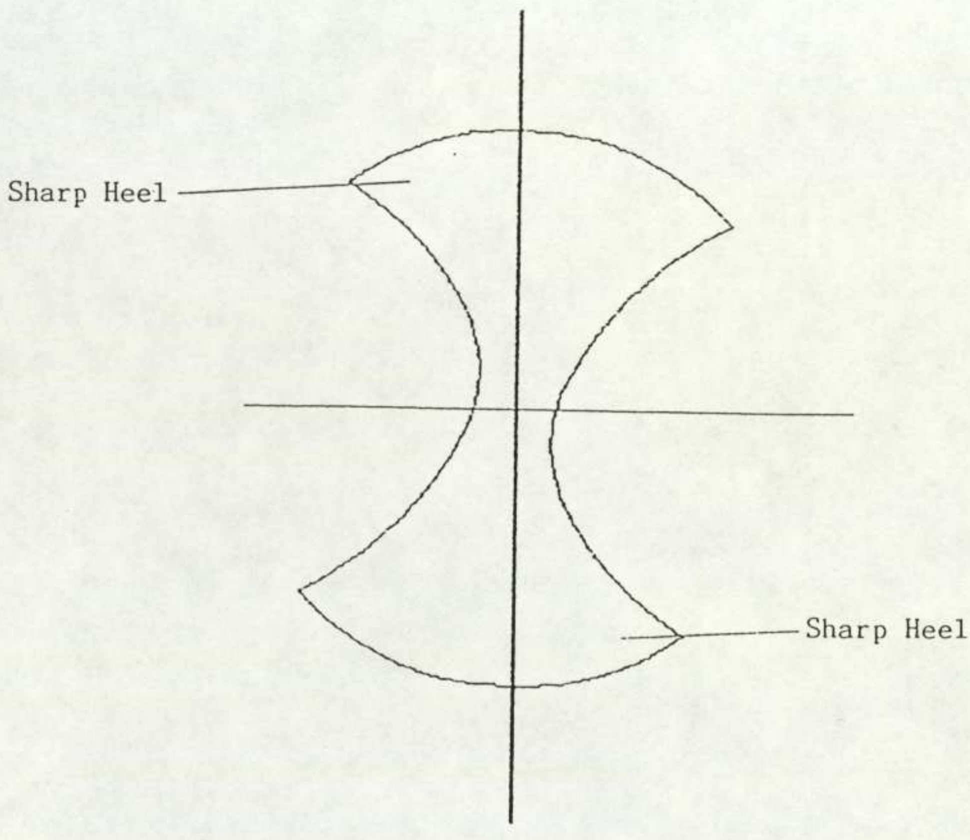


Figure 12 b - Cross-section with Conventional Sharp Heel

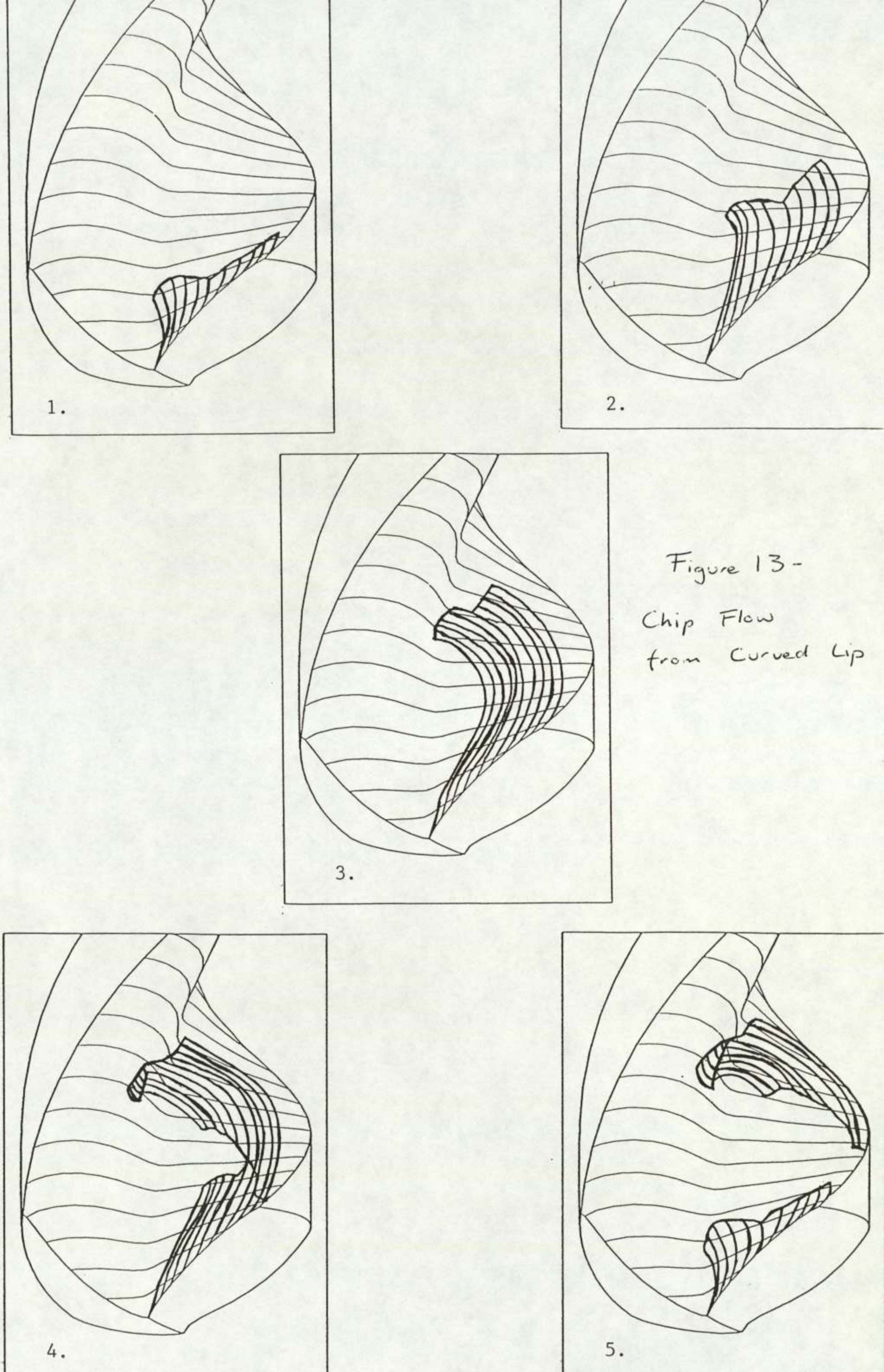


Figure 13 - Chip Flow from Curved Lip

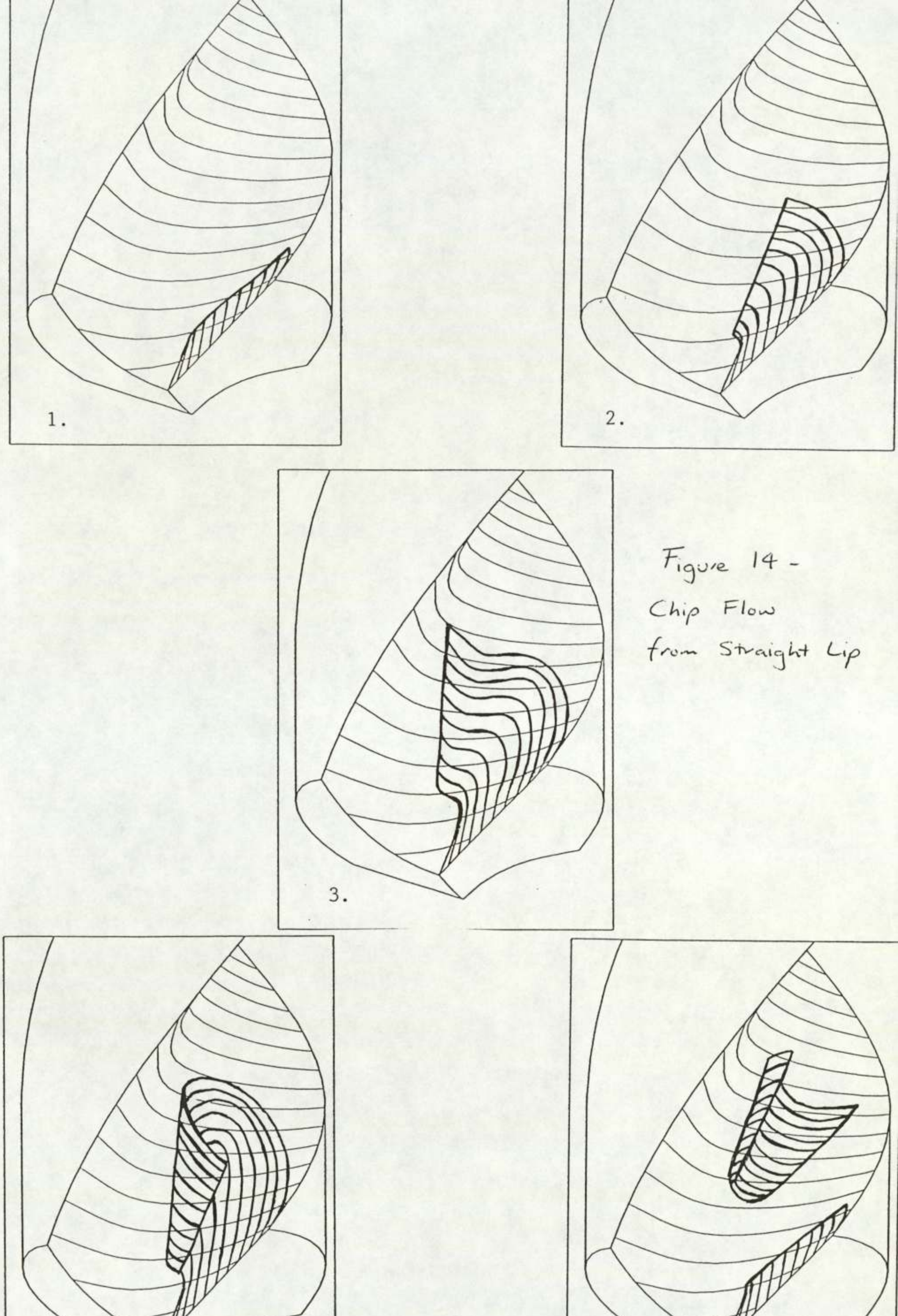


Figure 14 -
Chip Flow
from Straight Lip

ADX SWARF BREAKING

The unique design of the ADX drill contains a chip control feature which breaks the swarf by stretching. This re-thinking on chip control gives small chips which are easily transported along the drill flute in a smooth controlled manner.

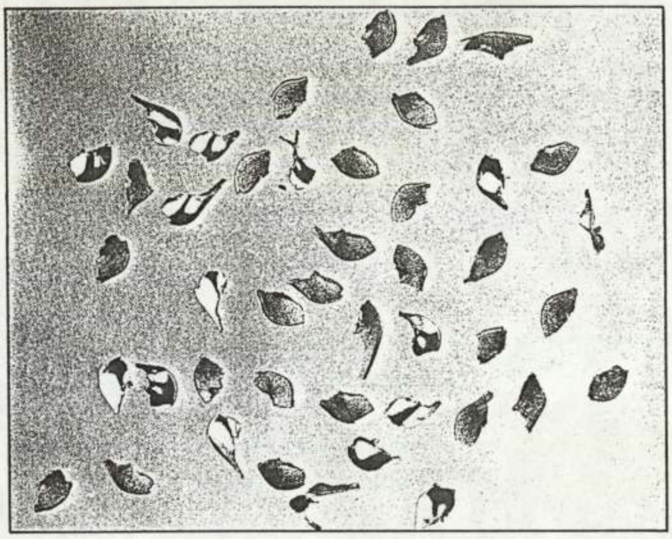


Figure 15 - Technical Sales Promotion

* A tapered collar on a twist drill has the effect of forcing the chips outwards, preventing them from clinging to the drill as they exit the flutes (prevents bird-nesting).

* Chip morphology is influenced by the rake angle and speed of the cutting tool and is highly dependent on the work-piece material. It has been shown how the transition rake angle (where for a given depth the chips become discontinuous) is a function of the material being cut [20]. It is possible to alter the rake angle by removing material along the cutting lip [3]. A larger positive rake angle across the lip, forces a greater degree of curvature on the chip, causing it to break. Increasing the helix angle or the point angle has a similar effect. A decrease in cutting speed has also been shown to promote discontinuous chips in a titanium-alloy and a steel [20].

* Similarly the feed rate and depth of hole used in drilling determine the chip form. At a critical hole depth [14] the constraint of the hole was found to change the chip form from conical helical to the transitional or long pitch helical. It was also apparent that the larger the feed and the smaller the drill diameter, the more the chip was encouraged to break [14,18].

Another method of obtaining discontinuous chips would be to replace a ductile work-piece material with a less ductile one, although a reduction in ductility often goes hand-in-hand with a reduction in strength which can perhaps lead to an unsatisfactory performance of the component. Free-machining steels have therefore been developed to give a longer tool-life and shorter chips without sacrificing strength. This normally involves the use of additives in the material (such as Manganese Sulphide or Lead) to reduce the ductility, provide lubricity and sometimes cause a small, but stable, built-up edge that can increase up-curl and therefore help break the chip.

3.3 CRITICAL REVIEW OF LITERATURE ON CHIP DISPOSAL IN DRILLING

All of the above papers focus on chip formation; none of them refer to the issue of chip disposal. Predicting chip form is currently a large area of research, but so far no work has been found that attempts to connect the formation of the chip to its subsequent disposal. This is, however, a very important and necessary link that must be made if metal cutting theory is to play a major role in the further development of commercial tool design.

Some design changes (as previously mentioned) have been found to have a beneficial effect on chip disposal in drilling, but theoretically little is known as to how drill design influences chip disposal. A literature search carried out at Aston University consulted both the Compendex (a computerized data-base of all engineering articles published since 1985) and the Engineering Index for previous years. Only one piece of work was found to examine this aspect of chip control. El-Wahab's thesis [21] describes the chip disposal efficiency in terms of drill parameters by pre-supposing that most chips are typically of a basic conical helical shape. This results in

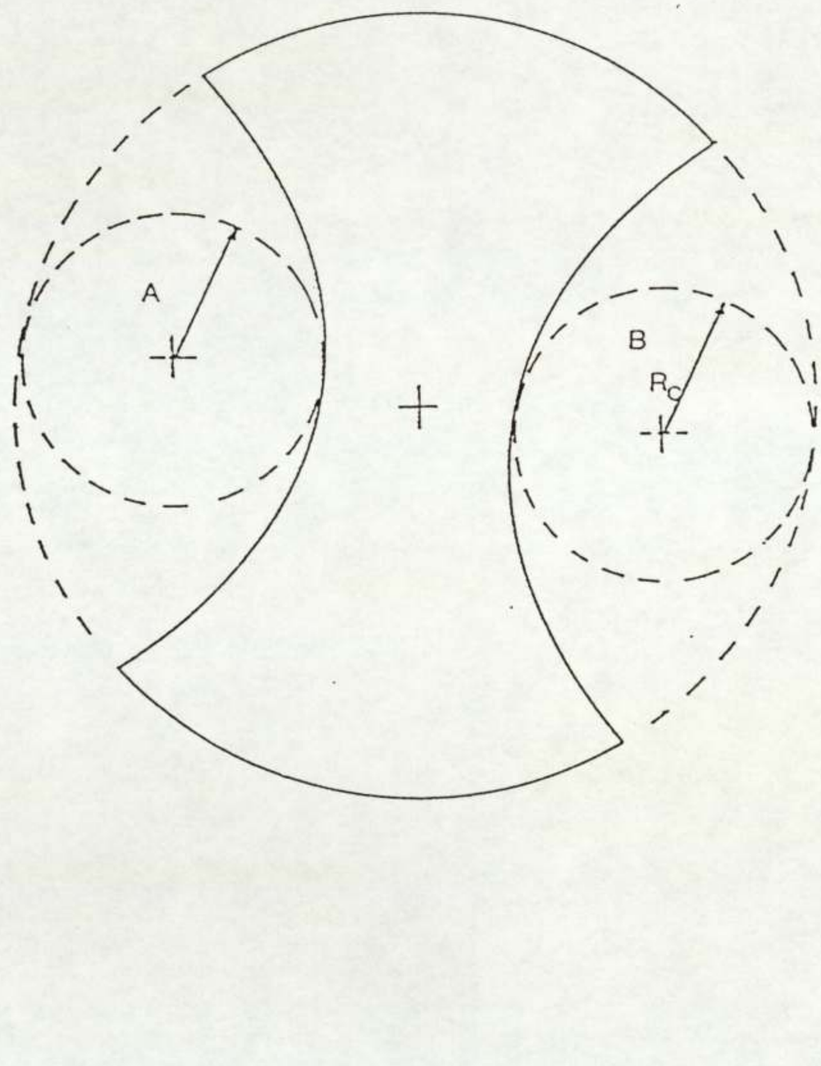


Figure 16 - Inscribed circle in the flute space [18]

the area occupied by the chips in the flute having a circular cross-section (Figure 16). It is therefore not the total area of the flute space that is considered to be the significant factor by El-Wahab, but the inscribed critical diameter which is subsequently described in terms of the drill's geometric parameters. The theory is supported by work previously carried out by Waller [22], where one drill with a larger critical diameter drills a greater number of holes than another drill before choking, with a smaller critical diameter but a larger total flute area.

El-Wahab's assumption that the diameter of a conical chip inscribed in the cross-section of a drill is an estimation of the tool's chip disposal efficiency is considered to be inadequate on several accounts:

1) although the cross-section of a chip may be approximated by a circle, the chip would not be circular in the cross-section at right angles to the drill but elliptical. As shown in Figure 7 the chip has its own axis, at an angle to the drill axis. The inscribed critical circle would therefore be found in the section of the drill at right-angles to the chip axis, rather than the cross-section which is at right angles to the drill axis;

2) the theory is considered by the author to be severely limited in its validity by assuming that the critical aspect of the flute area is the size of the inscribed circle. It is proposed here that the size and shape of the entire flute area is of critical importance to chip disposal. This can be seen

in the success of the deep hole drills which have very shallow, wide flutes to encourage chip disposal, essential when drilling deep holes as choking is more likely due to the greater distance the chips must travel. The shape of the flutes encourages the chips to break by increasing the contact area with the hole wall, this increases the total area, but does not affect the critical circle diameter. Therefore, the larger the flute area, the better the chip removal, the lower the friction between upward moving chips and subsequently the lower the cutting forces [1,23]. This can be recognised in the current trend within drill manufacturing where "rolled heels" are being put onto drills instead of the traditional sharp heel (Figures 13 a & b);

3) not all work-piece materials form conical chips as assumed by El-Wahab. When drilling Cast Iron, for example, the chips produced are generally small and fragmented and will not merely occupy the inscribed circle, but are more likely randomly to travel throughout the flute area. Whether a work-piece material will produce continuous or discontinuous chips, as explained in 3.1 and [11], is also dependant on many other factors, such as drill geometry and the cutting conditions used (ie. selected feed and speed). It is therefore inaccurate to assume that all materials will produce conical chips when drilled;

4) the value of the inscribed chip circle diameter is measured for one specific cross-section. If the drill has a parallel web, this cross-section will remain constant, and will accurately represent the drill throughout. However, if the

drill has a tapered web, the drill cross-section will change in shape, with the flute area decreasing towards the shank. This has a detrimental effect on the chip disposal capacity of the drill, and must therefore be taken into consideration;

5) the chip disposal efficiency is analyzed by El-Wahab as being a purely two-dimensional geometric issue. As discussed earlier the helix angle and point angle influence the chip form and subsequently the disposal of the chips, which makes it a three-dimensional problem. The author's experience in drilling has shown that there are many other factors involved in the disposal of drill chips that are not of a geometric nature. Some of the main influences being the properties of the tool material and the work-piece material, the surface finish and chemistry (ie. coating) of the drill flutes. This is reflected in the current trend for drill manufacturer's to introduce more sophisticated tool materials (HSCo instead of HSS) and coatings (Titanium Nitride instead of nitriding).

Given the above criticisms El-Wahab's method of determining chip disposal efficiency is considered to be extremely limited when making any predictions about the chip disposal efficiency of drills in terms of practical applications. The theory can however be seen as a rough estimation of a drill's ability to dispose of chips when neat, continuous conical chips are produced, most usually from a ductile material. The analysis of a single cross-section is valid along the entire length of the drill in the case of parallel webs. When analysing drills with tapered webs, however, more care must be taken to examine the variation in cross-sectional properties of the drill. This can be done by determining the drill cross-section at several points along the drill length and assessing the influence of the declining flute area on the value of the inscribed chip circle diameter. El-Wahab's theory is also recommended only for certain material groups that display conical chip formation, such as Aluminium, Brass and most steels, depending on cutting conditions. When using this method as a performance predictor for examining drills, it is vital to ensure any comparative experimental work is carried out under the constant cutting conditions. Any variation in the experimental environment would invalidate the performance prediction of such a technique, which is based on certain assumptions.

It is one of the purposes of the work reported in this thesis to develop this basic method of assessing chip disposal efficiency into a more versatile and practical analysis technique, through the introduction of computers.

3.4 NUMERICAL ANALYSIS

A performance prediction module for the assessment of chip disposal efficiency was created to calculate El-Wahab's critical diameter in the flute area. The module is a result of combined work by the author and Webb. The theoretical concept of the module and the design of its format were carried out by the author, supported by Webb's programming skills and knowledge of the existing CAD Modeller. This was necessary to mount the module on the system which is now part of the geometric drill modeller as created by Webb [2] and described in the Introduction. This CAD system generates geometric models of twist drills and can produce three-dimensional surface models.

Once the CAD system has successfully created a model of the desired drill shape, the drill cross-section at the base of the point can be viewed, both graphically and numerically in terms of its two-dimensional co-ordinates. The chip disposal module uses a sub-routine to define the outline of the flute shape and the corresponding co-ordinates. This produces a graphic output of the curved outline of a single flute area (the other area being identical). The program then selects three equally spaced points from this outline and using the co-ordinate information, inserts a best-fit circle. This routine successfully computerises the El-Wahab technique.

As stated above, the first inadequacy in El-Wahab's theory (section 3.3) is that it considers the chip to be circular at right-angles to the drill axis. As demonstrated, using Figure 7, this is not actually the case, as the chip will be circular in cross-section at right-angles to the chip axis, not the drill axis. As the program has the ability to move the three-dimensional drill shape to be viewed from any specified angle, the cross-section of the drill at right angles to the chip axis can also be determined. Together with Webb, an iterative routine was created to determine the exact value of the chip axis angle, which is equal to the helix angle at the centre of the best-fit circle. Firstly the program obtains the co-ordinates of the outline of the flute area (this is done using the computer graphics output of the program to the screen). This outline is then considered to be a two-dimensional curve by eliminating the z co-ordinate value, see Figure 17. The program then selects two reference points on either side of the curve and one point on the straight line representing the drill hole wall. Once the equidistant centre point of these three points is found using the iterative program, a circle is drawn which connects the three points.

The final output on screen is an image of the circle within the flute area at right angles to the chip axis, the numerical value of the angle of this view (in relation to the drill axis), the size of the circle diameter as well as the total flute area (Figure 18).

The program can thus calculate El-Wahab's circle as well as the more accurate chip-axis circle. A few comparative tests showed the circular area in the drill cross-section to be larger than that in the orthogonal section to the chip axis. El-Wahab's critical diameter therefore consistently overestimates the area of the chip, although the ranking order in terms of size of circle and flute area are the same.

3.5 CORRELATION OF RESULTS

The CAD system has the capability of calculating the chip disposal efficiency of any drill model created. It can be used for drill cross-sections of parallel webbed drills, as well as used to examine the influence of tapered webs on the changing drill cross-section along a drill's length. El-Wahab's circle diameter remains constant for a range of helix angles, as long as the drill cross-section is the same. In contrast - by using

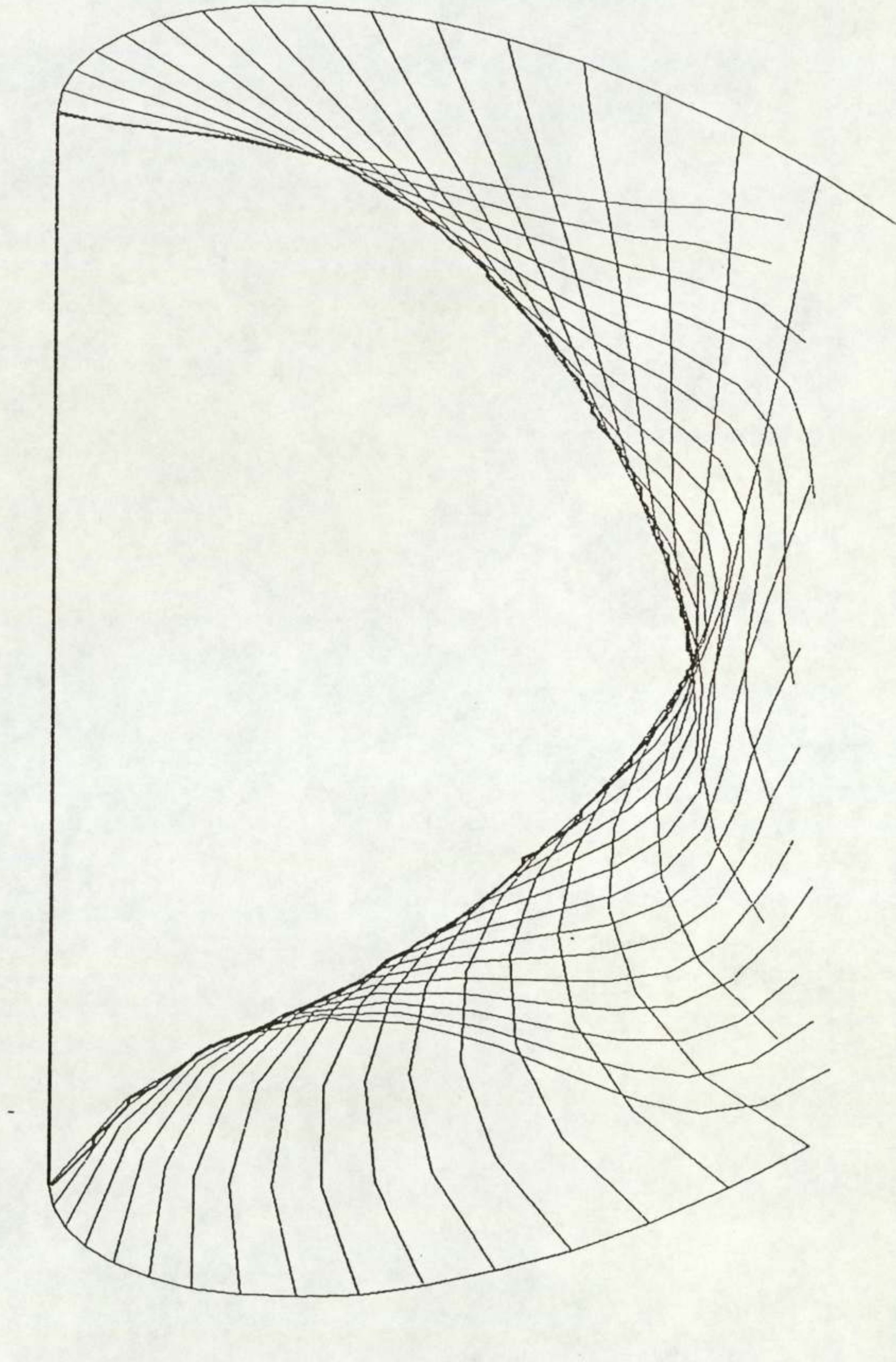


Figure 17 - View of Flute from Chip Axis Angle

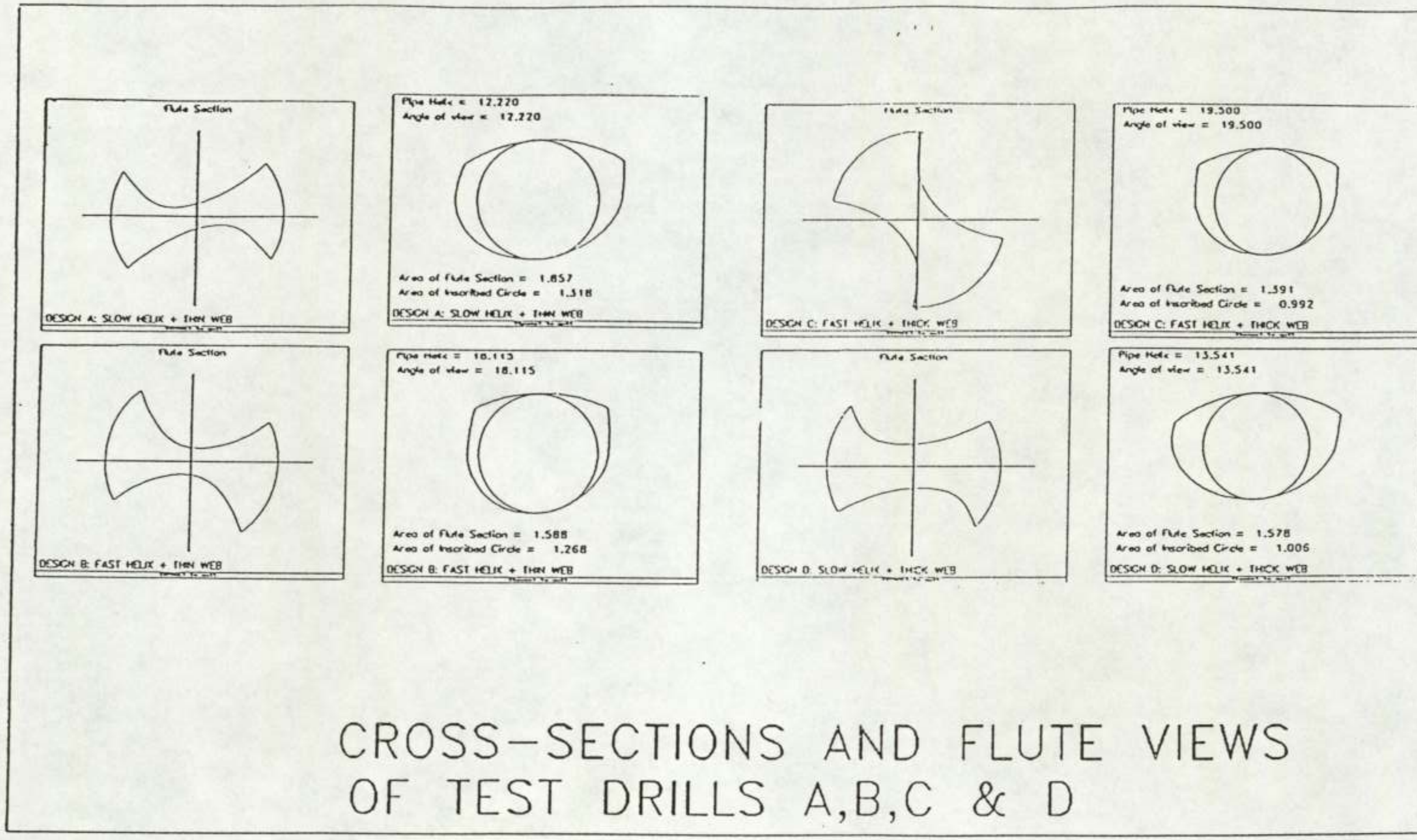


Figure 18 - Cross-sectional Views and Chip Disposal Circles

the program, the drill section is viewed from an angle, so the calculation of the circle diameter at the chip axis angle includes the effect of the helix. The program also calculates the total flute area at right angles to the chip axis, or at which ever view is selected by the program user and displayed on the screen. This numerical value would be appropriate when considering discontinuous chips which are known to travel throughout the flute space. This module subsequently removes many of the restrictions inherent in the El-Wahab theory.

It is, however, extremely difficult to justify the accuracy of such predictions using experimental methods. There is no adequate experimental method of assessing the chip disposal efficiency of a drill, in contrast to the measurement of drilling forces, for example. Waller [22] considered the number of holes drilled before choking occurred to be a measure of the drill's ability to dispose of chips. In the drilling field, this is generally referred to as the "life" of a drill (as described in 2.2), and is known to be a result of the interaction of many performance criteria [4], not just the chip disposal efficiency. It is currently not possible to single out chip disposal efficiency using experimental methods. As drilling takes place inside the work-piece there is little visual information about the formation of the chips, save the chips themselves. Currently the best experimental method of assessing the ability of a drill to dispose of chips is by watching and listening to the drill when cutting, and examining the chips produced. From experience one is able to assess whether or not a drill is efficiently disposing of the chips, although no objective numerical value, as such, can be given to the performance of the tool.

Although the numerical value of the chip disposal circle cannot be directly compared to an experimentally determined factor, the ranking in which they are predicted to perform can be used when considering running comparative experimental tests, where drills have been tested under identical conditions. The drills can be modelled and the values of the critical circle diameters compared, to give, at the very least, a relative indication of the potential ability of each model to dispose of chips. For example, such an experiment was carried out by the author using four drills called A, B, C and D. Each drill's geometry was accurately measured and using this data, modelled on the CAD modelling system. The drills are fundamentally of the same type, but are a unique combination of a fast or slow helix and a thick or thin web. Figure 18 shows the cross-section of each drill, the critical circle diameter of each design and the total flute area. The drills are ranked according to the critical circle diameter in Figure 19 together with the order of performance from the life tests. Here the drills have been life-tested drilling Mild Steel under accelerated cutting conditions.

It can be seen from these results that the ranking order of the life tests and the chip disposal efficiency predictions are not the same. As explained above life is a result of many inter-acting performance criteria, and as suggested, no direct comparison can therefore be made between chip disposal efficiency and drill life, although the size and shape of the flute area is certain to be a major influence.

RANKINGS - 3 mm DRILLS

LIFE	CHIP DISPOSAL		RIGIDITY	
NO. HOLES DRILLED	CIRCLE	FLUTE AREA	ANSYS	RIG
C	A	A	C	C
B	B	B	D	D
D	D	D	B	B
A	C	C	A	A

LEGEND: Helix/Web

A - Slow/Thin
B - Fast/Thin
C - Fast/Thick
D - Slow/Thick

Figure 19 - Actual and Predicted Rankings

The life of a drill is recorded as the point where the drill is considered to have ceased to perform, which is usually determined by the operator. The criteria used can vary from extreme wear, audibly determined by the "screeching" of the drill, to spontaneous catastrophic fracture. Electronic condition monitoring systems are becoming more common, which can detect the level of vibration of a tool which indicates the point at which a tool needs to be replaced. These systems have the benefits of being objective and consistent in use, and are ideal for unmanned machining.

A set of tests was carried out by the author to verify that the values given for the flute and circle areas are correct. This was done by ensuring that the drills being modelled were geometrically correct, and that the flute areas calculated matched those measured experimentally. After having modelled drills A, B, C and D, they were physically sectioned by grinding off the drill point to reveal the drill cross-section. The cross-sectional areas of the drills are magnified and an outline can be traced using a shadowgraph machine. Squared graph paper is then used to calculate the size of the areas. These tests verified the accuracy of the program for numerous drills, with the two sets of areas (predicted and measured) corresponding satisfactorily to within 5% of each other. This error margin was considered to adequately reflect the numerical accuracy of the ideal computerised world and the dimensional tolerances of the real manufacturing world.

CHAPTER 4. STRUCTURAL INTEGRITY OF DRILLS

The cross-section of a drill is totally determined by the manufacturer, in contrast to the point profile which can be altered by the user. In selecting the appropriate cross-sectional shape, the drill designer must ensure that on the one hand the flute space is large enough to allow good chip disposal, but on the other hand the cross-sectional area of the drill must be large enough to withstand the cutting forces. These are two conflicting demands, the partial satisfaction of each requires a compromise.

The previous chapter examined the effect of drill geometry on chip disposal. In this chapter the effect of drill geometry on the rigidity of the drills will be considered. Drill rigidity, both in torsion and bending, has a major effect on the life of a drill, a small increase in drill rigidity can yield a large increase in life [18]. The size and straightness of the holes is also largely dependant on the rigidity of the tool, especially when drilling deep holes or high strength materials. All of these requirements are fundamental performance criteria stated in 2.2, and directly affected by the drill rigidity.

To understand the importance of torsional rigidity of the drill, it is necessary to consider the state of the drill whilst cutting. As the drill penetrates the work-piece, the torque on the tool has the effect of unwinding its helical structure, and subsequently lengthening the tool [2]. If the drill were then to cut into a cavity in the material or drill a "through" hole, the drill will quickly spring back to its original length. This contraction has been known to cause spontaneous failure in drills. The extent to which a drill will unwind, or how rigid the drill is in torsion, is therefore an important consideration. Less essential to the drill's life is its bending stiffness, as each drill is likely to undergo some amount of radial displacement when cutting. This has an effect on the positional accuracy of the hole, and results in an undesirable poor quality of hole. Radial displacement, however, is not generally considered to be "life-threatening" and, in that context, is therefore considered to be of less immediate importance than the angular displacement. It is for this reason that the work described in this chapter has focused on the torsional rigidity of drills.

The necessity to be able to assess the torsional rigidity of a drill is therefore clear. Before a suitable analytical tool could be selected for the investigation of drill rigidity, previous work in this field was examined.

4.1 CRITICAL REVIEW OF LITERATURE ON DRILL RIGIDITY

Torsional analysis of a prismatic bar of circular cross-section shows the central role of the polar second moment of its cross-sectional area [23]. This is explained in the brief resume of torsion theory included in the Appendix. A similar approach has been taken by several articles that have reported on research into torsional rigidity of drills by examination of its cross-sectional geometry. A popular method given by Oxford [18] involves taking an outline of the cross-section of the drill, obtained from cutting the drill normal to its axis. It is claimed that the diameters of the circles that could be inscribed in these cross-sections is a good index of the torsional rigidity of the section (see Figure 20). By plotting the ratio of the inscribed circle diameter over the drill diameter versus the relative torsional stiffness (seen as a percentage of the rigidity of a solid rod), the rigidity of the section is stated to be proportional to the fourth power of the inscribed circle diameter. It is stated that a drill section commonly has only one tenth to one fifth of the rigidity of a plain round rod. Using computer methods (see Finite Element Analysis as covered in section 4.3) this was confirmed by the author to be valid.

Although it is stated that the results are valid for "any feasible drill section", the study examines traditional drill shapes only, and the inscribed circles theory cannot, for example, determine the difference in torsional rigidity between drills with rolled heels and traditional heels (see Figure 12). This results in an analysis technique that is not sensitive enough to changes in the cross-sectional shape, essential to the more radical modern drill designs. The paper also claims that the results are independent of the flute helix angle. Work carried out by the author, described in chapter 6, shows that the helix angle certainly does influence that drill's rigidity and can therefore not be ignored. It is difficult to critically review this work in more depth as the material presented in [18] is based on a report not available for general distribution.

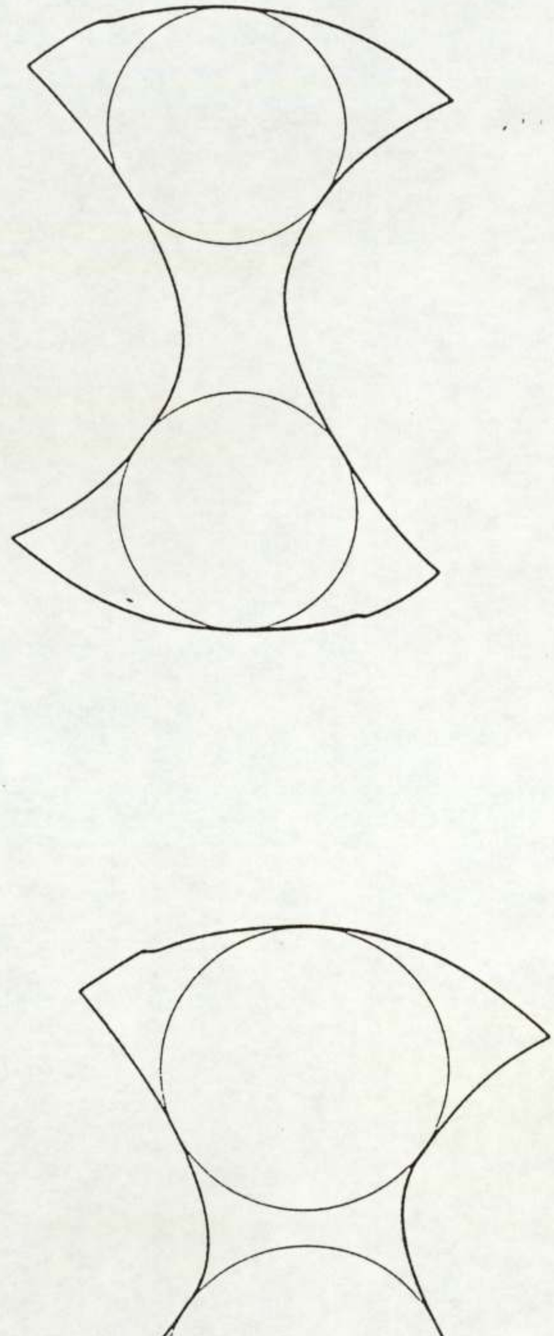


Figure 20 - Inscribed Circles in Drill Cross-sections

[21]

El-Wahab [21] states the polar second moment of area of a drill cross-section to be proportional to drill rigidity. He then goes on to say that the value of the inscribed circle diameter as used by Oxford [18] is not consistent with the ranking of the polar second moment of area, and is therefore not accurate. In contradiction to [21] Saint Venant is quoted by Webb [2] as stating the drill rigidity decreases as the polar second moment of area increases. In Webb's work [2], the drill cross-section is also erroneously treated as being elliptical in shape. Spur and Masuha [24] deduce that due to the role the polar second moment of area plays in the torsional stiffness of drills, it is not only the area of the cross-section that must be considered, but also the manner in which the area is distributed along the radius. It is concluded that torsional rigidity of the drill will be increased by maximising the total area of the drill cross-section and/or re-distributing the area away from the drill central axis. The effect of having a larger web thickness therefore appears to have little beneficial effect on the stiffness of the drill, as well as producing a detrimental increase in thrust force.

From the above conflicting theories, it can be concluded that there is some considerable confusion in the determination of the torsional rigidity of a drill. Calculating the second polar moment of area of an irregular shape such as a drill cross-section is complex. However, its relationship to the drill's rigidity cannot be considered to be valid when it is clear that the drill is not a prismatic bar due to the presence of its helical flutes. Particularly when considering that the helix angle is known to have a profound influence on the drill rigidity. Apart from the obvious contradictions within the above pieces of work, it is apparent none of them achieve the goal of establishing an accurate method for the determination of the torsional rigidity of a drill. A possible reason, and further criticism of all these papers, is that they attempt to analyze the drill cross-section in two dimensions only, and not the three-dimensional drill body.

There are some papers that do recognise the torsion of a drill as a three-dimensional situation. Lorenz [25] reports that the helix angle increases the torsional rigidity when a drill is compared to an untwisted bar of the same profile. This results from the "unwinding" of the twisted profile when the drill is loaded in torsion. He investigates the relationship between drill life and helix angle and believes that an increase in helix angle to 40 degrees will treble the life of the drill. Work carried out by the author in chapter 6, demonstrates that the rigidity of the tool will increase as the helix angle increases, and although this may be detrimental to chip disposal, it will have a substantial influence on the drill life. It is not possible to state quantatively how much the life would improve by, without sophisticated experimentation.

Another piece of research reported in [26], states the maximum torsional stiffness of a drill as being experimentally determined at a helix angle of 28 degrees. Theoretical work reported in this thesis shows no existence of such an optimum value, although no experimental work was carried out in this area. The reason for this being the inability to access a set of drills, with the same profile, but a varying helix angle. There is a contradiction in the two statements made about optimum helix angle. One [25] implies that by maximising the helix angle (realistically within the boundaries of commonplace drill manufacturing to about 40 degrees) the life of the drill will be trebled. The other [26] states there is a optimum helix angle, after which the torsional stiffness will decrease. This piece of work will demonstrate numerically its agreement with the first statement, although no direct reference can be made to life, without experimentation. It will also demonstrate that [26] inaccurately assumes an optimum helix angle for maximum torsional stiffness. The paper is also incorrect in assuming that such a statement is valid across-the-board for all drill types and sizes. Each drill must be evaluated individually, as there is no linear relationship between the changes in dimensions for different sizes, nor any tangible connection between drill types. Kirilenko [27] presents equations containing complicated factors to assess the influence of the helix angle on the stiffness of drills. These are further developed in [21] to include the effect of both helix and point angle, but again the method is approximate and highly complex, and relies on the determination of the polar second moment of area. Both studies claim good correlation with experimental data, with integration of a computer establishing good correlation between these two pieces of work. As with the work done by Oxford [18], only traditional drill shapes are examined.

In terms of extensive investigation into the wide variety of commercial drill shapes currently available, these methods are considered by the author to be complicated, laborious and insufficiently accurate. All analyses rely on the traditional cross-sectional drill shape, which is a simplistic and very restrictive approach. Further more, none of the above analyses include the web taper, which has a decided effect on the torsional stiffness. Nor is the length of the body taken into consideration, which is also known to be of critical importance. These design variables are often used by drill manufacturers as direct ways of influencing the strength of their tools.

The above methods are not suitable as analytical tools for investigation into the relationship between drill rigidity and drill design. To be of any practical use in the design of drills, an analytical tool must be developed that is accurate and relatively quick and easy to use. The new work reported in this thesis aims to develop such a tool, facilitating the process with the implementation of computers.

With the drill presenting such a complex problem in structural mechanics, it lends itself well to numerical analysis. Successful examples of this have been demonstrated using the membrane analogy method [2,28] experimentally for the determination of stress distributions for various drill cross-sections. A suitable mathematical approach using a numerical analysis technique is the finite element method, which is particularly effective in cases of complex three-dimensional problems. As a result of the advance in computer technology FEA has become the most sophisticated computerised numerical analysis method, the principles of which are briefly described in the Appendix. Once the author had carried out some bench-mark research into the possibilities of FEA computer packages, it was decided that FEA was the most appropriate route for structural analysis, within the CAE system.

4.2 FINITE ELEMENT ANALYSIS OF DRILLS

The possibility of applying FEA to drills has been recognized by a few researchers [2,29-31]. Before the development of the powerful, user-friendly packages that are available on the market today, attempts were made to write such analysis programs. In one paper [29], for example, a computerised surface model is used as a pre-processing unit for the finite element method. The model is rather primitive, using only a single layer of elements to form the model of the drill point. This consequently ignores the complex three-dimensional behaviour of a drill. The output only displays the displacement of the model under load. An even more courageous (and possibly foolhardy) piece of work [30] takes the simplest possible form of three dimensional model, i.e. a three-dimensional drill comprising of two elements only. Using only one element for each drill-half severely restricts the drill shapes that can be modelled, especially when considering some of the more recent, radical designs. It also limits the degrees of freedom at each node of the model and prohibits accurate deformation analysis and the likely accuracy of the results. The manner in which the drill can be loaded is similarly restricted by the number of nodes present, which makes this a simple, but highly inaccurate model. The model requires a subdivision into more elements, to provide more nodes. A criticism can also be made of the assumption that the results for one diameter of drill will generally hold for all drill sizes due to dimensional similarity throughout the range. Any drill manufacturer's handbook shows considerable discrepancies between the relationships of the geometric dimensions for different drill sizes.

A two-dimensional approximation of a three-dimensional problem was made by Webb [2], although the output is somewhat primitive and unclear. The determination of stress seems particulary user-unfriendly and complicated. A much more visually pleasing analysis and comprehensible analysis of a three-dimensional drill model is given by Niu and Chen [31]. Here a commercial FEA package was used to examine a drill under bending, where good agreement with experimental methods was found and the weakest region of a drill could be determined. The appendix explains how such a three-dimensional model is created.

This last piece of work is the only one found to have carried out a successful analysis using commercially available FEA. However, no real cutting conditions were simulated (the drill being loaded in a static state), nor was any work carried out into the torsional rigidity of the drill. It can therefore be seen that the new work described in this thesis has a substantial amount of originality.

4.3 NUMERICAL ANALYSIS

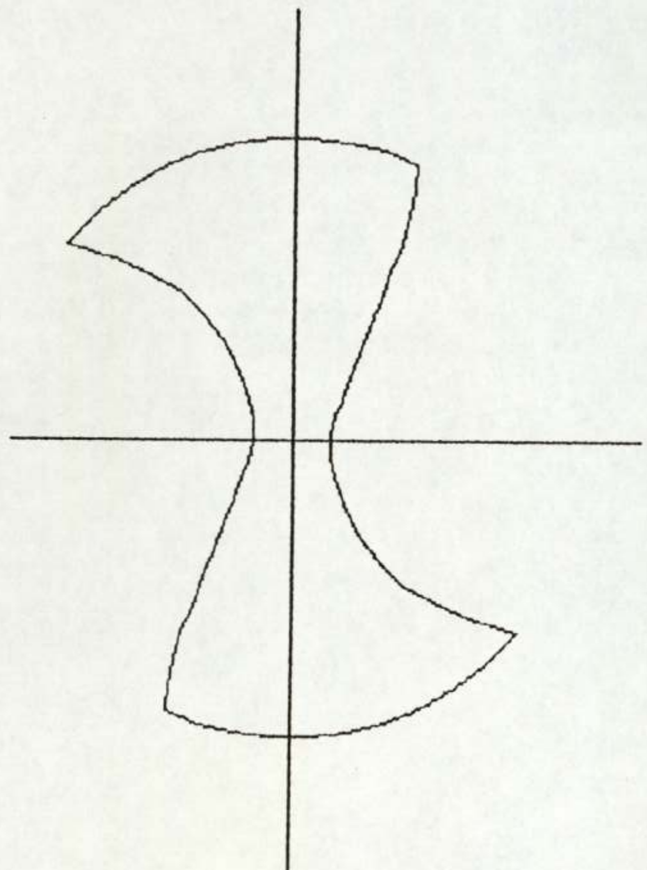
To enable the prediction of the torsional rigidity of various drill designs using a computer, a commercial Finite Element Analysis (FEA) package, ANSYS version 4.4a, was acquired. The basic principles of the Finite Element Method are given in the Appendix. The input data required by ANSYS to create a drill model was provided in the form of cross-sectional co-ordinates by the CAD Drill Modeller (see Figure 21). The x and y coordinates are manually transferred to the FEA pre-processor, Figure 22. It is anticipated that this link will be automated in the future using data on disc to transfer the co-ordinates. This data is then manipulated to create a three-dimensional model of a drill, by using extrusion and rotation graphic techniques available on ANSYS. This produces a model without a point or flute run-out.

The manner in which this manipulation occurs depends on the class of drill to be modelled, either with or without a web taper. A parallel webbed drill is the easier and therefore quicker to model. The two-dimensional co-ordinates are simply rotated and simultaneously extruded to give a three-dimensional shape with a constant cross-section. To create the model, firstly an outline is created using lines to join up the key-points (co-ordinates), Figure 23. The lines are then joined up to create two areas (Figure 24), which are divided into elements, by meshing the cross-section with two-dimensional elements (Figure 25). This is done using a macro program (Quad.mac - see Supporting Material) written by the author especially for this application. The existing nodes are

Ansys In-put

DRILL DATA

Drill Diameter	=	20.000
Cutting	=	Right Hand Thread
Helix Angle	=	38.500
Web Thickness	=	2.570
Lead	=	78.990



FLUTE COORDINATES

'X'	'Y'	'X'	'Y'	'X'	'Y'
-0.782	1.436	-9.085	4.180	-6.454	-7.638
-1.344	1.686	-9.529	3.034	-5.983	-6.107
-2.046	1.964	-9.831	1.833	-5.468	-4.828
-2.852	2.271	-9.982	0.595	-4.850	-3.787
-3.728	2.605	-9.978	-0.665	-4.122	-2.958
-4.644	2.959	-9.812	-1.929	-3.304	-2.317
-5.575	3.317	-9.481	-3.178	-2.428	-1.838
-6.499	3.652	-8.982	-4.396	-1.533	-1.508
-7.399	3.934	-8.312	-5.560	-0.666	-1.323
-8.264	4.124	-7.469	-6.649	0.124	-1.292
-9.085	4.180	-6.454	-7.638	0.782	-1.436

20mm ADX STANDARD HEEL

<SPACE> to quit

Figure 21- ANSYS DATA FROM CAD MODELLER

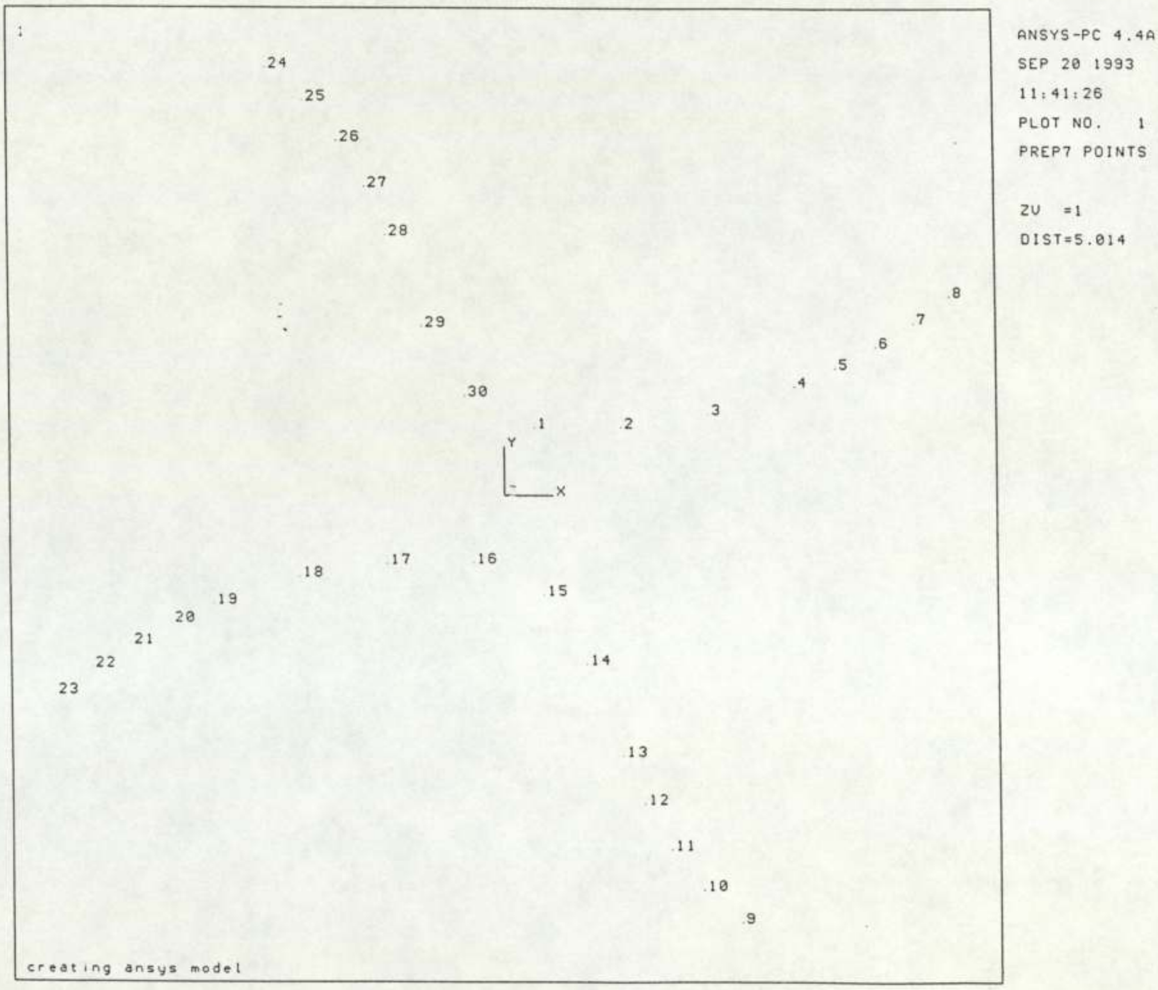


Figure 22 - ANSYS KEYPOINTS

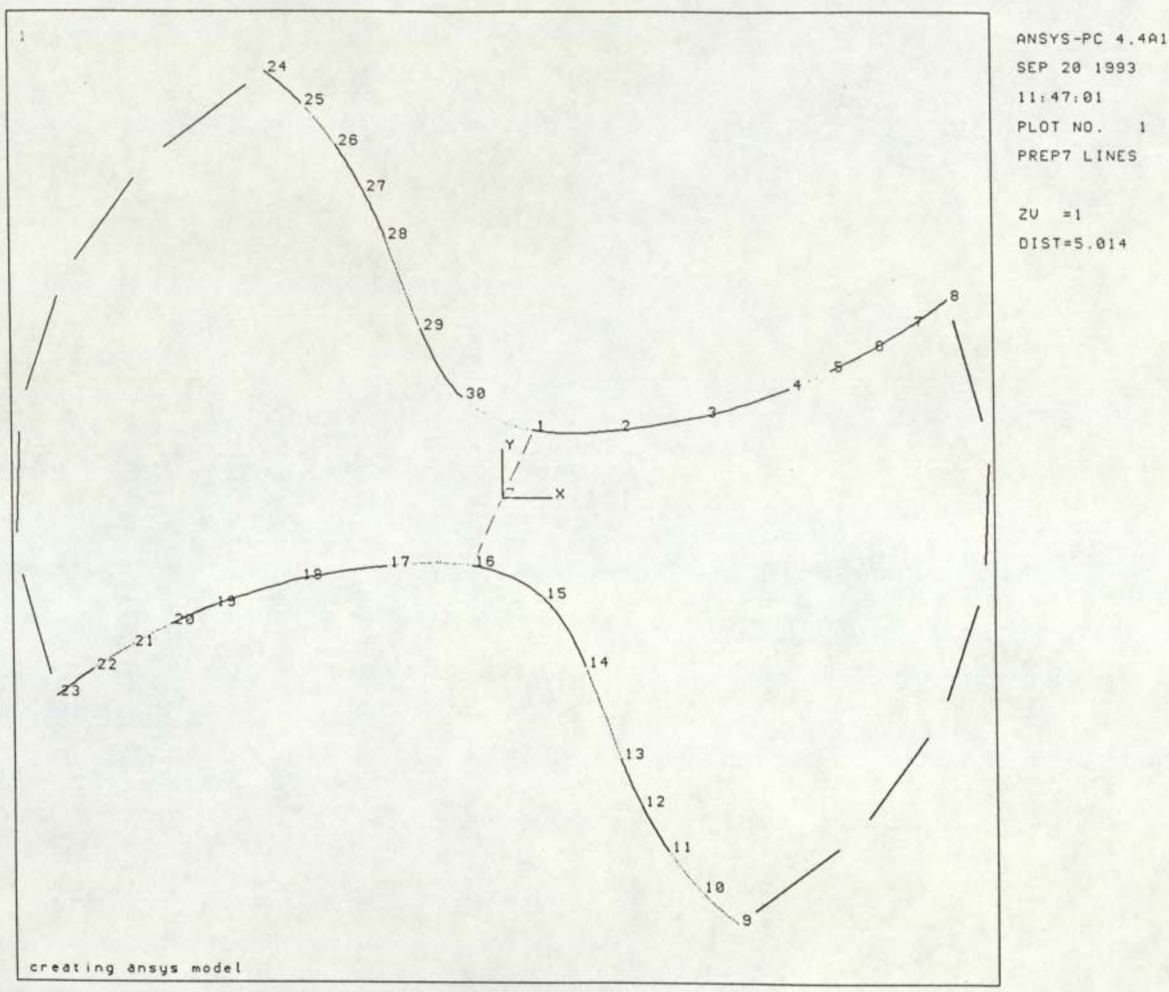


Figure 23 - ANSYS LINES

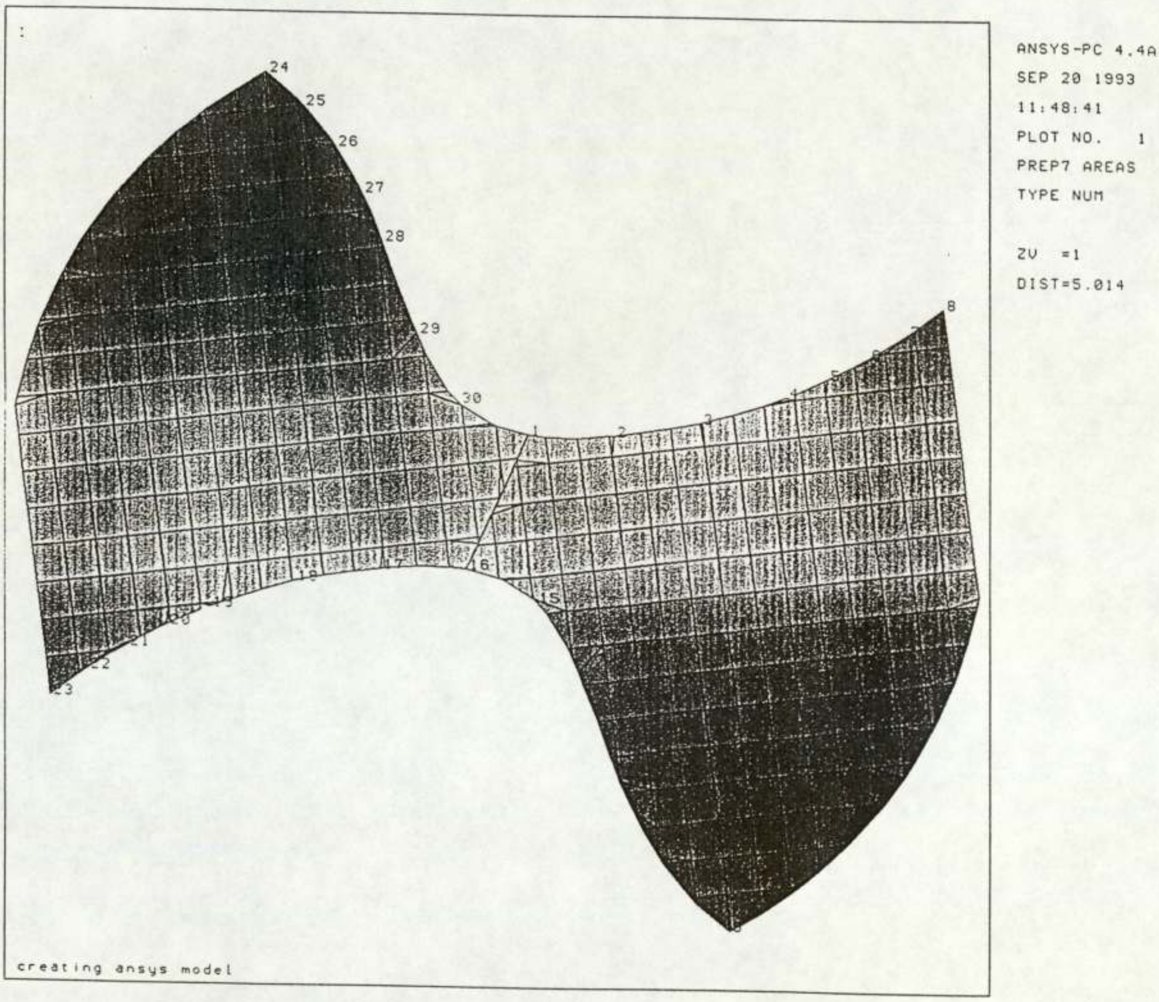


Figure 24 - ANSYS AREAS

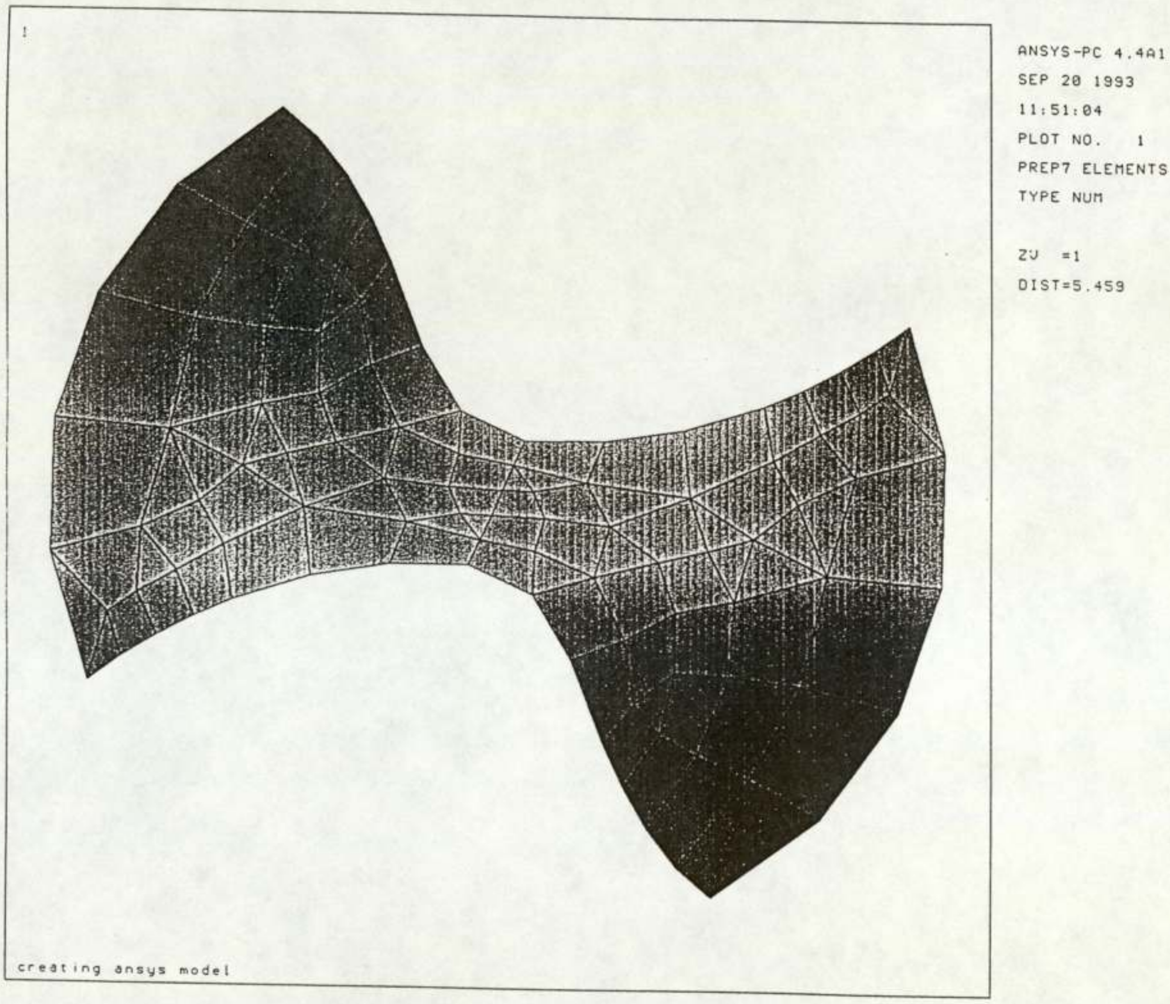


FIGURE 25 - ANSYS MESH WITH ELEMENTS

then re-generated for 36 layers (of a 10 degree twist to give a model of one full unit-of-twist) along the drill axis to create a three-dimensional model (see Figure 26). The two-dimensional elements are deleted and replaced by three-dimensional elements, as the program automatically meshes the model and connects the existing nodes.

A drill model with web taper is, however, more difficult to construct considering the constantly changing cross-section. The outer diameter of the drill remains constant, while the inner dimensions of the flute change as a result of the incremental increase in web thickness. Figure 27 shows how the cross-sectional shape alters when the web thickness is doubled. Geometrically this amounts to a taper inside a cylinder, which is very hard to model on a computer without a solid modelling capability (which the ANSYS pre-processing unit does not have). The modelling of a drill with web taper is more time-consuming and has a rougher appearance than the parallel webbed model. Again the x and y co-ordinates are manipulated, but this time in separate groups (see Mesh.mac - Supporting Material). The co-ordinates along the flute are extended in the radial direction to incorporate web taper, while the outer diameter co-ordinates are kept constant, and solely rotated and extruded. The co-ordinates of each layer are joined to the following layer by the creation of volumes (again a macro program has been written to dramatically reduce the time this process takes). Each volume is then automatically meshed by the program, using the number of elements defined by the programmer. This allows the model to maximise its accuracy by using the maximum number of elements available on this

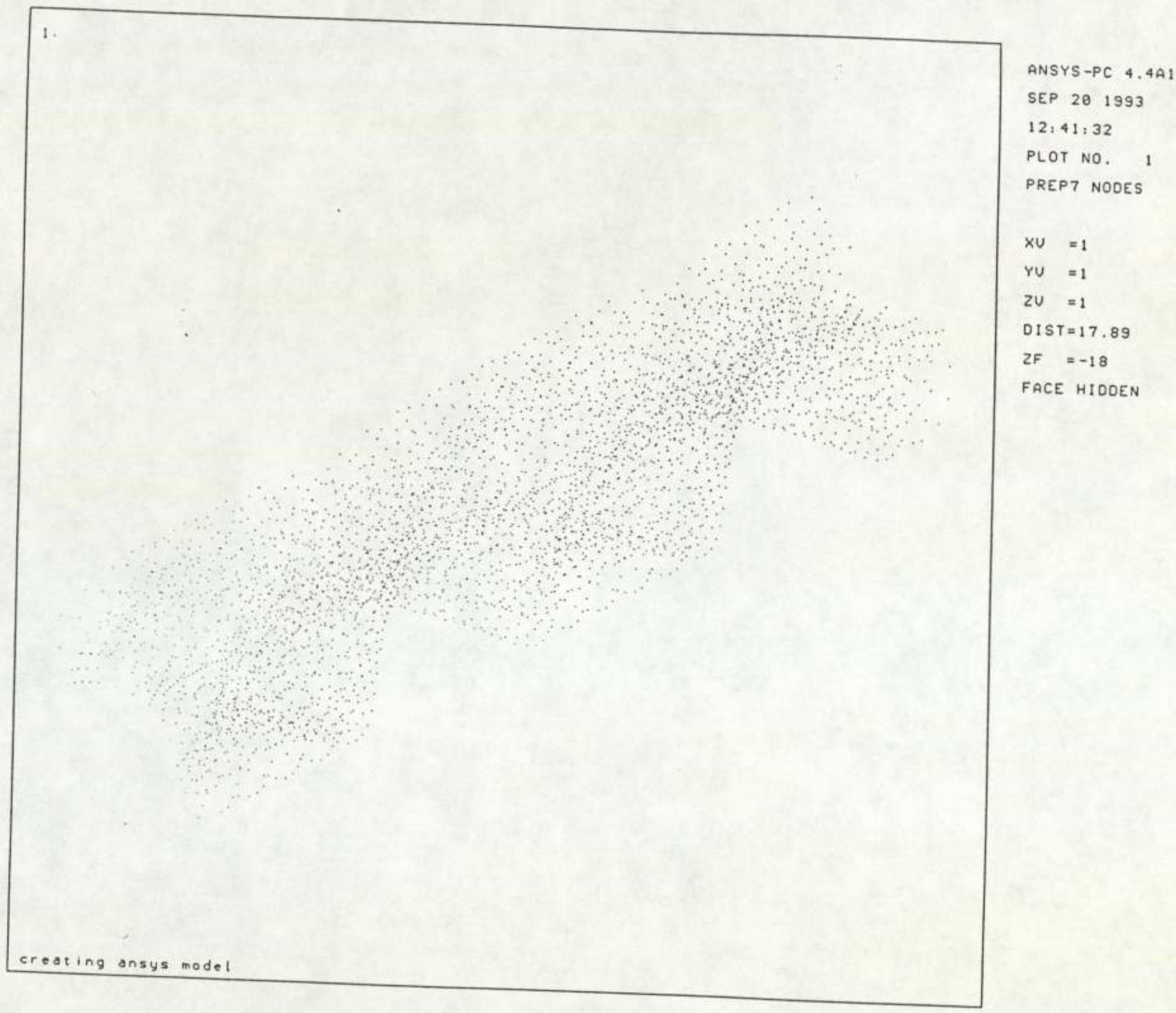
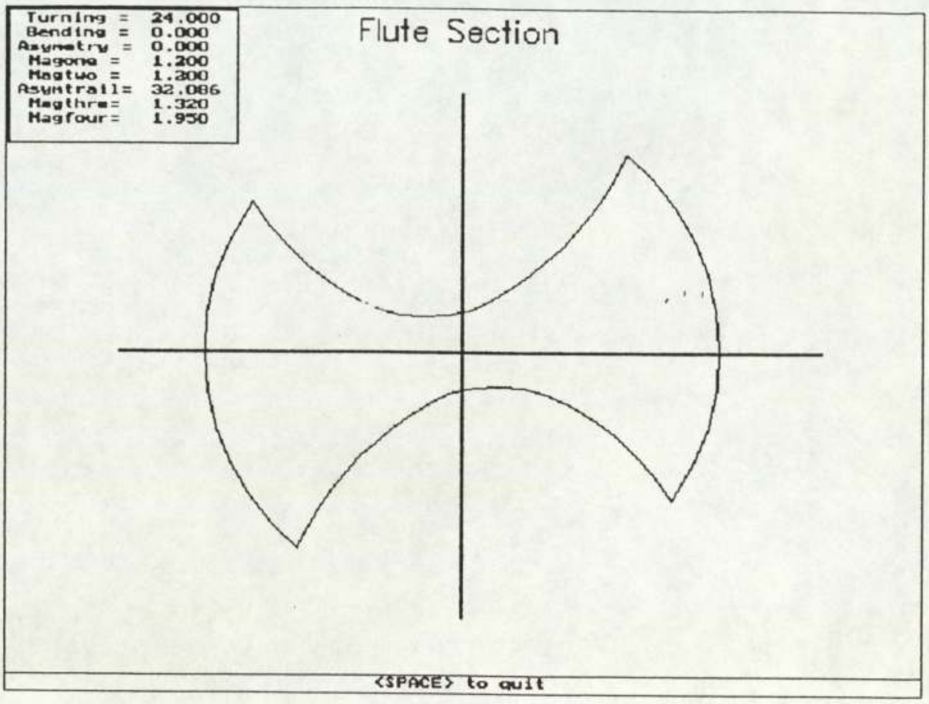


FIGURE 26 - 3-D NODAL MESH



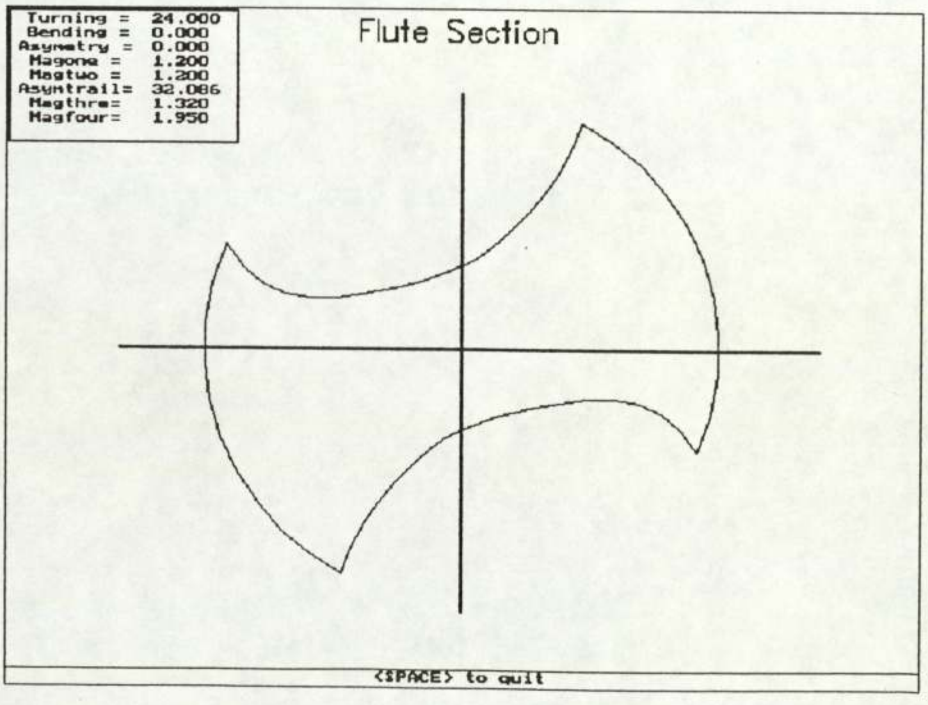


FIGURE 27 - CROSS-SECTIONS WITH VARYING WEB THICKNESS

particular version of ANSYS. The cross-section of the drill at the extruded end is different to the original cross-section, and can be verified using cross-sectional data from the CAD Modeller.

The element type used to mesh both types of model is a solid three-dimensional eight-node brick. Once the model has been created, the boundary conditions are then set, where the three-dimensional model is restricted at the extruded end (as if clamped in a chuck) by setting the x, y and z displacements of all nodes in that plane to zero. The other end is loaded, simulating a state of pure torsion, where forces are distributed along the nodes on the cutting lip. By applying a unit force at each node, a distribution of force similar to that predicted by the torque and thrust module on the CAD system is produced. Experiments were carried out with other types of loading (single point load, unevenly distributed load, etc), but none were closer to the actual situation during drilling, as described in cutting theory [2].

The model (Figure 28) is now ready to be analyzed, as the computer has sufficient information to solve the system equations (as explained in greater depth in the Appendix). With the given loads and zero displacements, numerical analysis can be applied to determine the unknown displacements at every node on the model. In the post-processing phase, the results are presented in terms of displacements which are further analyzed to give the stresses on the model (Figure 29). The torsional rigidity of the model is assessed using the maximum value of displacement of the model in the y-direction within a cylindrical system (equal to theta).

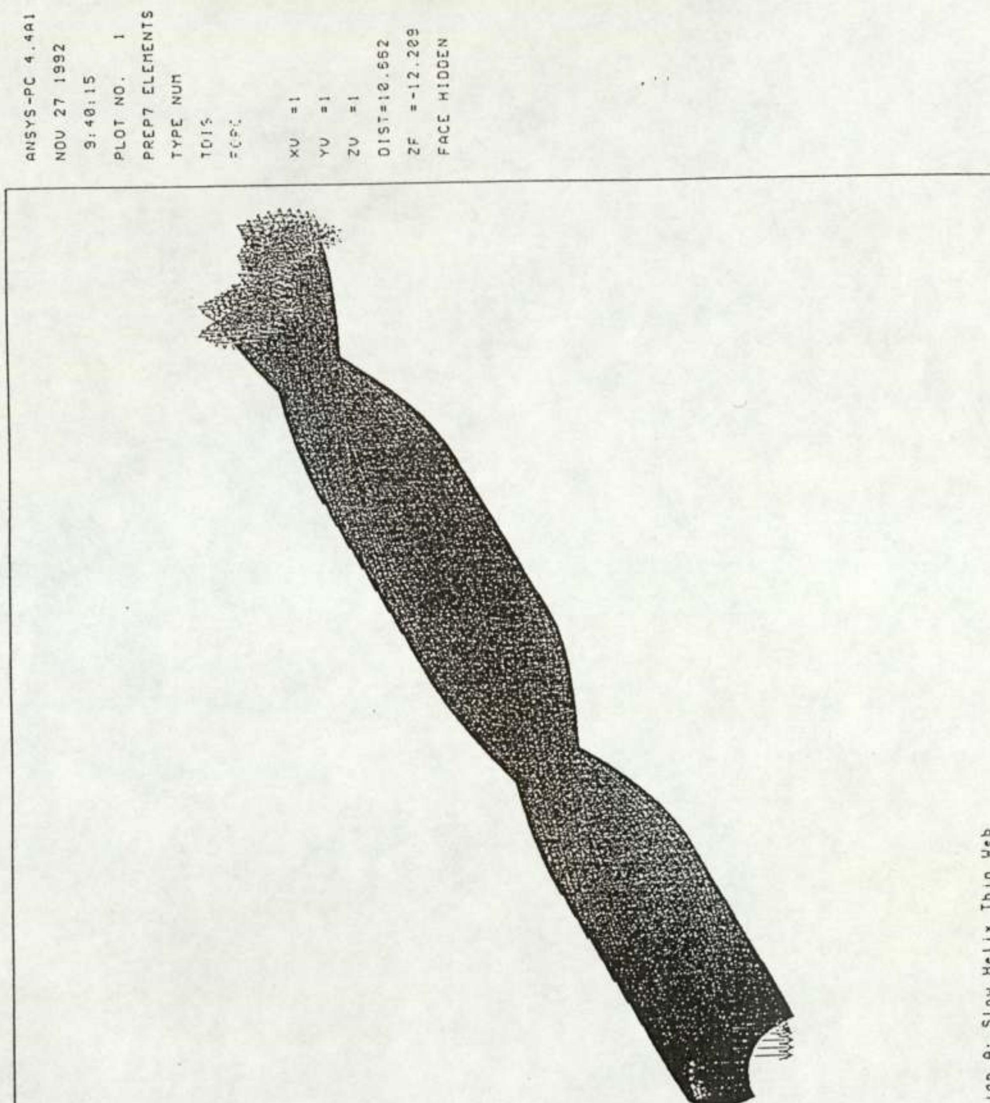


Figure 28 - Three-Dimensional Drill Model A with Applied Loads and Constraints

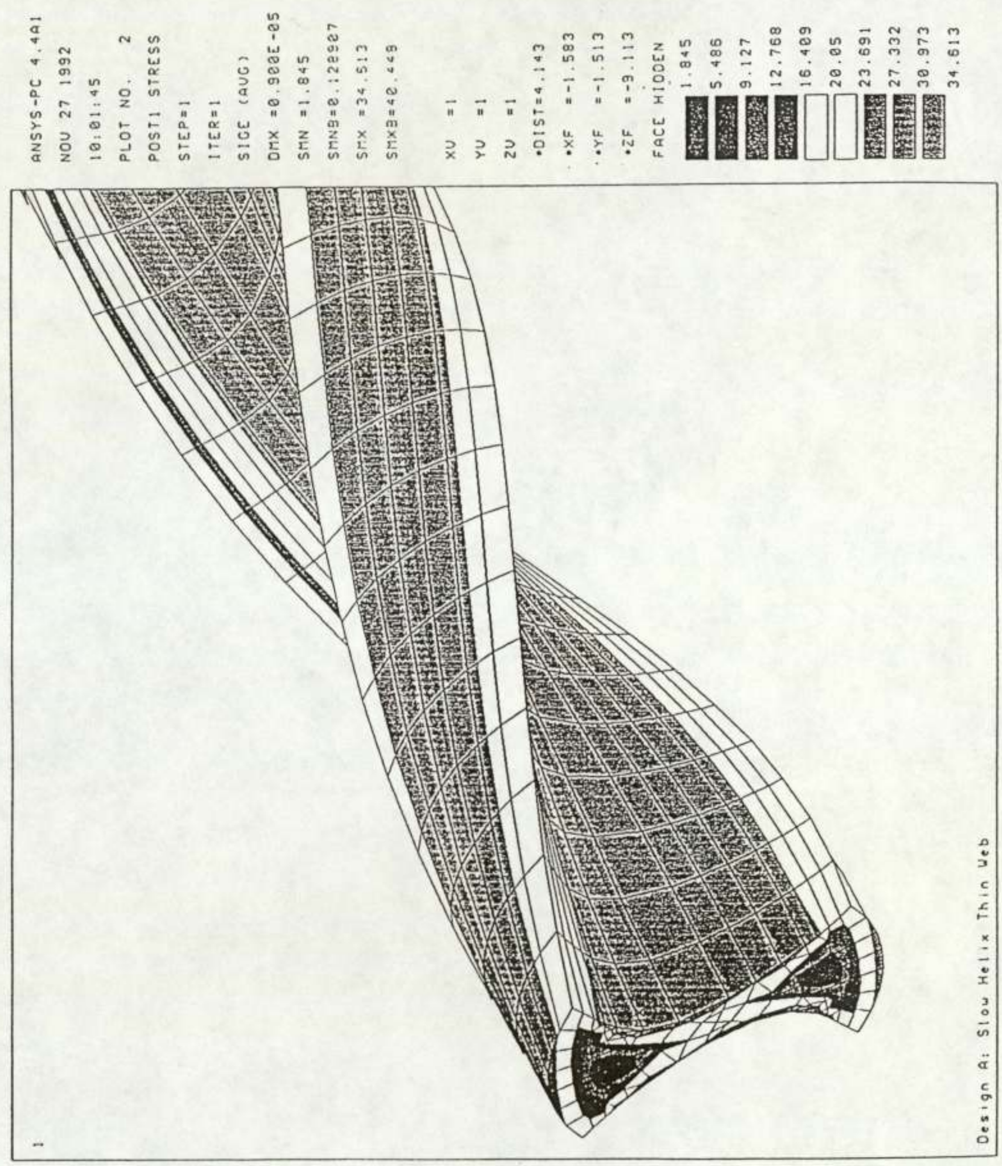


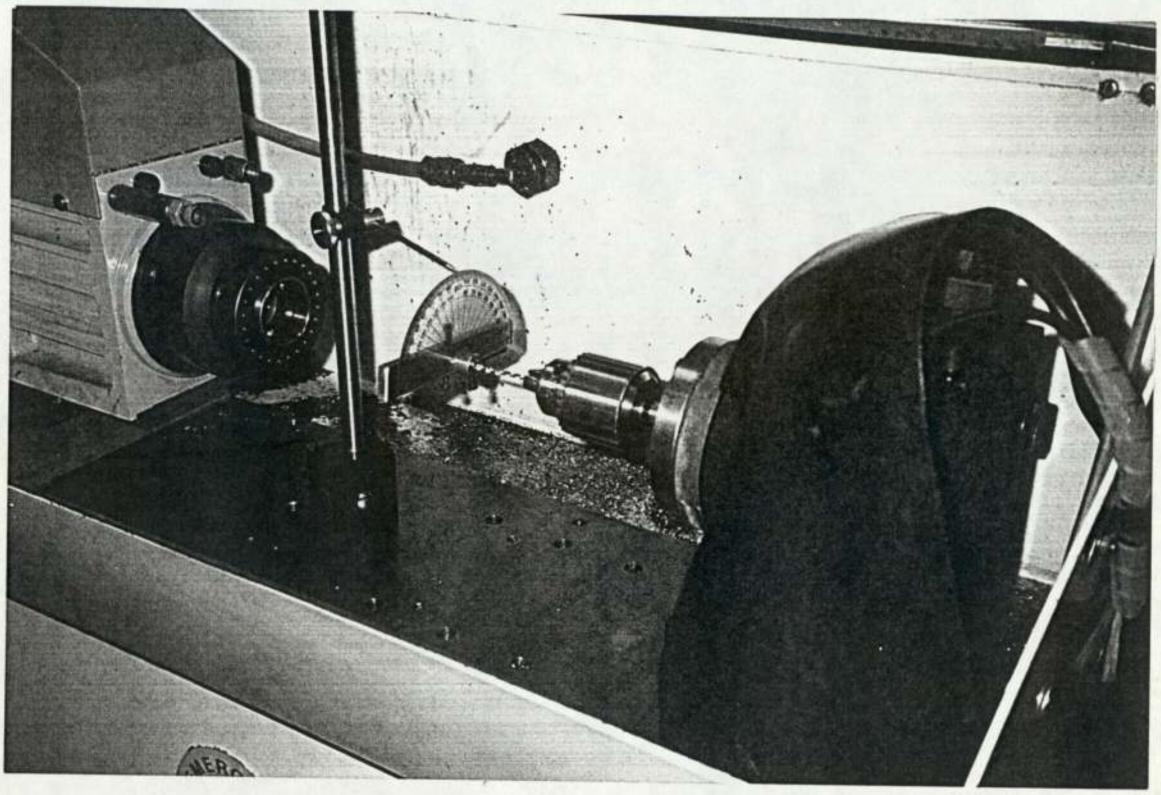
Figure 29 - Principal Stress Plot of Drill Model A

The versatility and high processing speed of the package makes it possible to model any type of drill, that has been modelled using the geometric drill modeller. It would be possible manually to determine cross-sectional co-ordinates in order to create models, but this would be extremely time consuming and laborious. As can be seen in Figures 28 and 29, the quality of the computer graphics is excellent.

4.4 EXPERIMENTAL RESULTS

In order to demonstrate that the numerical modelling is reliable, it is necessary to compare predicted results to those determined experimentally. A rig was constructed at Aston by the author and technicians for the specific purpose of testing drill rigidity. It was not necessary to purchase any new equipment, as use was made of what was already available in the workshop, to avoid any expensive investment.

This rig (Figure 30) is mounted on a horizontal drilling machine, with the drill clamped by a drill chuck placed in the tool-post. A thin bar is fixed to the drill point by two grub screws, with a protractor securely attached to indicate the angle of rotation. The metal pointer indicating zero degrees rotation is held in place by a stand with a magnetic-base clamped to the bed of the machine. The load cell, mounted inside the chuck, monitors the torque and a signal is transmitted to a computer for storage and subsequent processing. This is subsequently displayed on screen in the form of graphical output which can be analyzed by the computer to give an average torque reading over any period of time, to



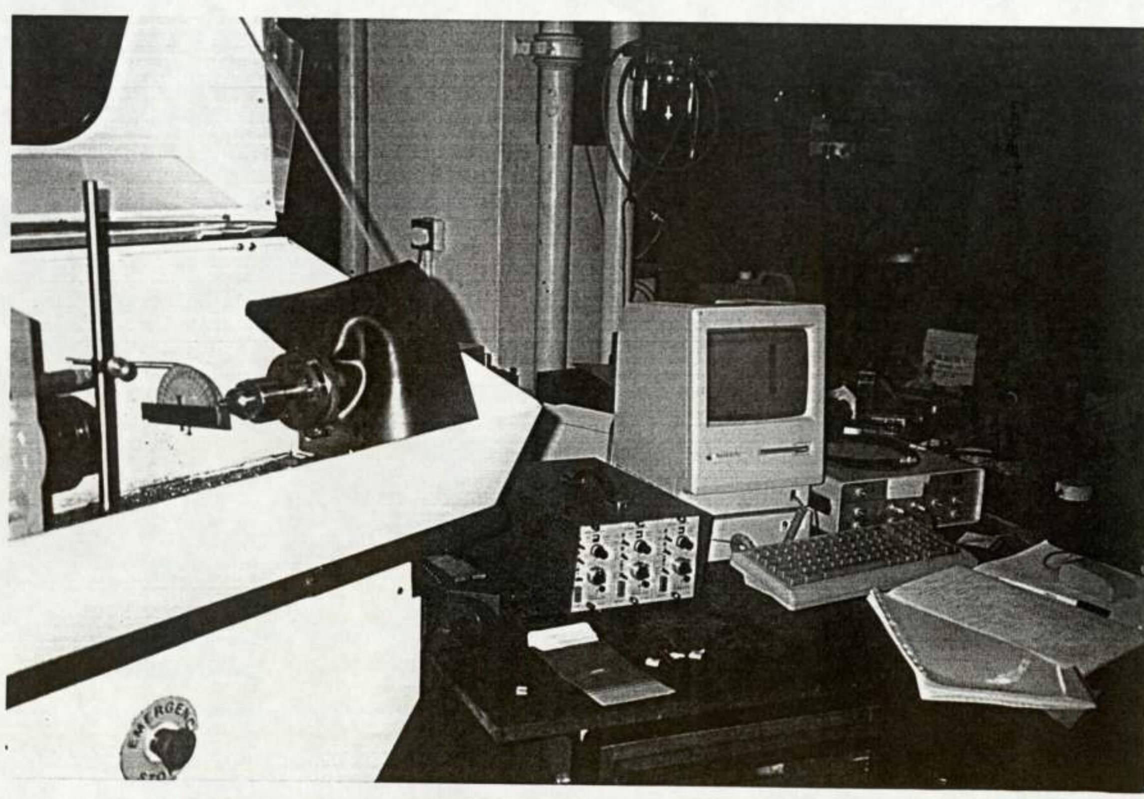
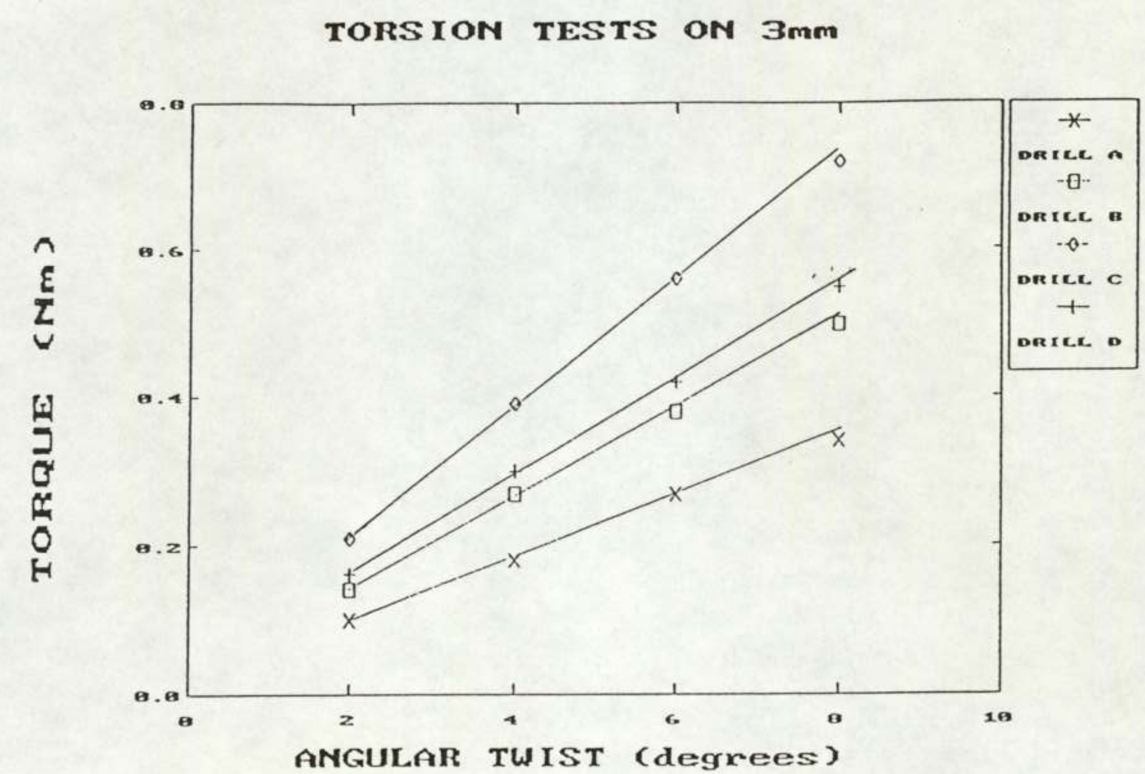


Figure 30 - Torsion Test Rig at Aston

the second decimal place. The torque increments required to produce two degree steps of angular twist is applied to the bar and is fed through to a computer screen giving a wave-form read-out of the applied load. A calculation can therefore be made of the average load required for each angle of twist, which will be linear given that all deformation taking place is elastic. This method has excellent repeatability, with the error of the whole set-up estimated from experience of the technicians to be around 5%.

To coincide with development work being carried out at Dormer Tools, a torsion experiment was set up for the four 3 mm drills described in Chapter 3.4. The test was to investigate the effect of helix angle and web thickness on drill rigidity. Each drill has a different combination of fast or slow helix and thin or thick web. The drills were prepared for the test by each one having its point removed and all four were ground down to be of an equal length. The drills were experimentally tested by the author on the above described rig for the angular displacements of 2, 4, 6 and 8 degrees. It was difficult to physically apply enough force to surpass an eight degree twist. The results from this experiment in the form of a graph plotting the torque versus angle of twist, is shown in Figure 31.

Numerical analysis was carried out by the author, by modelling and analysing all four drills using the ANSYS program. This was to establish the accuracy of FEA as a performance prediction tool. Firstly the four drills were measured for all the geometric information required by the drill modelling



TORSIONAL RIGIDITY EXPERIMENTAL RESULTS

Figure 31 - Torsion Tests Angular Twist vs Load

program. This was done using standard drill measuring equipment which consists mainly of a microscope with a gradated lens to measure angles (e.g. helix angle). Gauges and an electronic meter are used to measure distances (for example fluted land width) or simply a micrometer (for the web thickness). The drills were subsequently modelled (Figure 18) and their cross-sectional co-ordinates determined. From this information, the drill models were created and analyzed using the parallel webbed procedure on ANSYS. The maximum displacements of the models under load were subsequently recorded as a measure of their torsional stiffness and are presented in Figure 19. This displacement is presented by the computer as the largest single displacement of one node. All other nodal displacements are also presented, but in this case (when searching for the most rigid model) the maximum angular displacement is of the biggest importance.

4.5 CORRELATION OF RESULTS

The order in which the drills are ranked in Figure 31 is identical to the order of predicted results. Relatively, therefore, the ANSYS program is capable of predicting the order of performance of a group of drills in terms of torsional rigidity. Although the drills are ranked correctly, there is no direct numerical comparison possible between the tests. This is a result of the differences in the type of loading simulated by the program, and the actual applied load. The resultant displacements of the model are given in units of metres times 10^{-5}. This can then be calculated into an angular displacement, given the radius of the drill. The angle of of displacement is however not comparable to the angles applied on the rig, there is a large magnitude difference. It is possible, therefore to use the predicted results as a relative indication of the order in which the drills will perform in terms of rigidity tests. Chapter 6 gives a more in-depth account of how this module functions as part of the design methodology that accompanies the CAE system.

CHAPTER 5. A DESIGN METHODOLOGY FOR DRILLS

For over a century the development of twist drill design has been rather irregular. Designs have originated from the empirical results of many trial-and-error experiments, where the successful geometric characteristics are selected and given to the drills designed for that particular application. For example, a smaller helix angle for drills used to cut plastic and a larger helix angle for drills to cut steel. Similarly the point angle is altered according to the application, a larger point angle for the drilling of Cast Iron and a smaller angle for drilling Aluminium.

In Chapter 4 it was explained that the drill point may be altered by the user, but the body of the drill cannot and is solely determined by the manufacturer. It is essential, therefore, that the manufacturer selects an appropriate drill cross-sectional shape, with the correct balance between flute space and drill area, as well as the right helix angle for the given application. This selection procedure has always been carried out with little or no rigorous methodology or consistency. The introduction of computers to the process of drill design allows a scientific approach to design, and subsequently a logical and consistent method of analysing drill shapes. This approach permits an analysis of multiple drill designs with a dramatically reduced need for costly and laborious prototype manufacture. It is therefore possible to introduce a design methodology and progress the design of twist drills away from the 'Black Art' approach of the past. This chapter describes such a methodology, based on a purpose-built twist drill CAE system.

5.1 A LOGICAL APPROACH TO DRILL DESIGN

As described in section 2.2, the overall performance of a drill can be divided into several categories. As with many complex engineering components, the performance categories are inter-related and each design will be a compromise of those criteria that are deemed to be most important. Limited by either financial or physical reasons, one single design is not superior for all categories, resulting in a vast number of different designs of one product. Each of these designs is created as a result of numerous applications for which a product can be used and the demands made upon it by the consumer. The aim of the design process (see Figure 32) is to evaluate and respond to those needs, taking into consideration the limitations that apply in each particular case.

* The Design Specification

The beginning of the design process is the design specification, a preparatory step that is often given insufficient time or thought. All parties that are to be involved with the new product must be consulted from the very beginning, to prevent potential problems later on in the product development cycle. This concept is often referred to as "concurrent engineering" [32], where people from the design and manufacturing functions are involved with the product from the very beginning of the design process. The aim is to reduce development times and cut costs, consequently improving the flexibility and efficiency of the company, and thus its competitiveness.

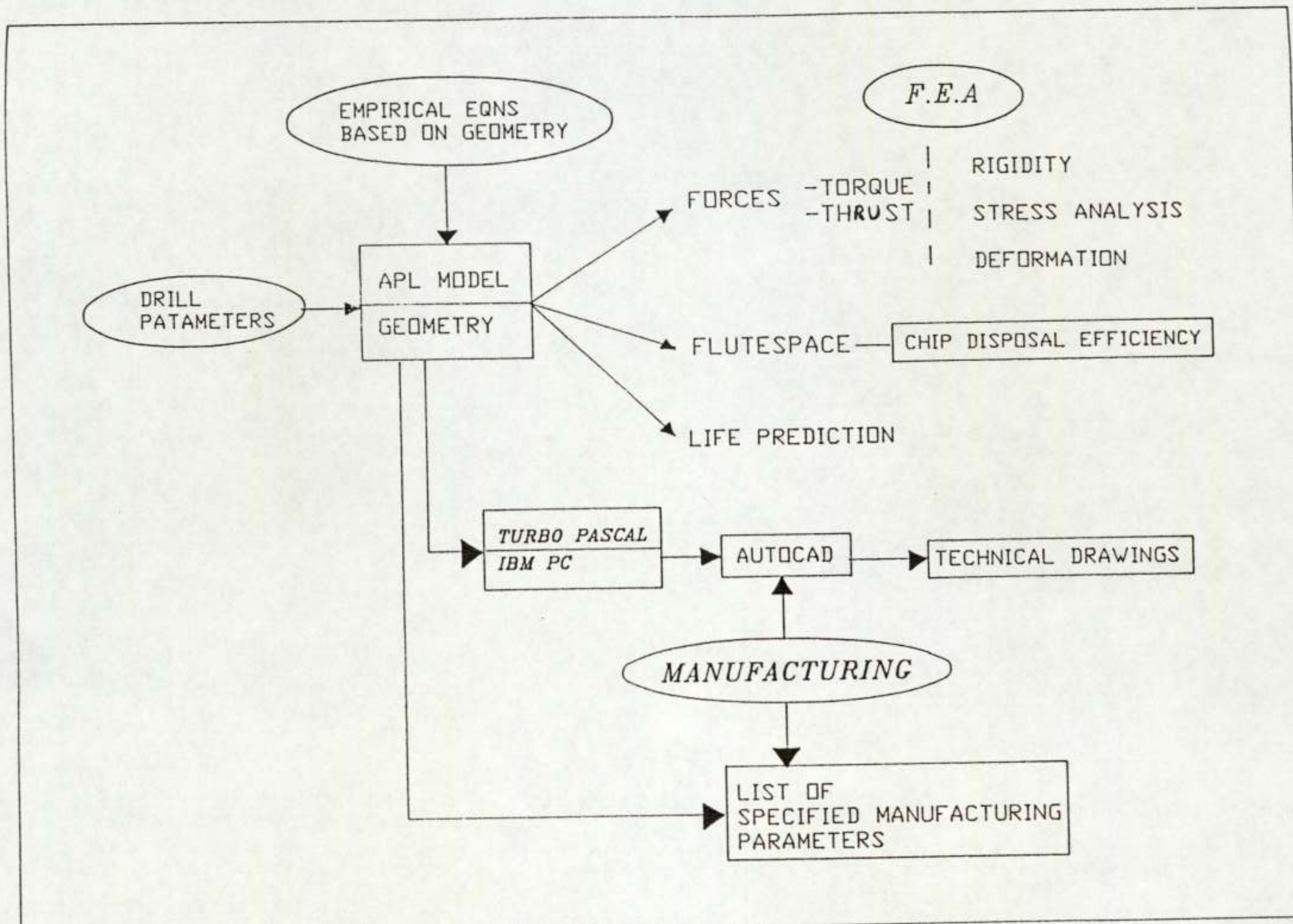


Figure 32 - Design Process

A design specification basically involves the identification of the critical requirements of the future product. A detailed list of those demands that must be fulfilled [33], should aim to:

- identify the requirements in terms of essential demands and less important desires
- determine the source of the requirement for clarification and relativity
- quantify the requirements wherever possible, into numerical values.

Once the product design specification is complete, it must be approved by the entire product design team before any other progress is made. One aim of concurrent engineering is to facilitate the process of reviewing and, if necessary, up-dating the specification at regular intervals after this point.

* Computer Aided Design

With the design specification complete, traditionally this is the point where the design engineers would work on producing a new product design by consulting the specification and referring to any previous designs of a similar type. Work would be carried out to introduce new ideas to solve any anticipated problems, normally those experienced in the past in a similar field. This part of the design process is demanding in terms of man-hours, as well as past experience and knowledge of the design team.

The introduction of Computer Aided Engineering has significantly altered the design process. In the past, systems were used as data-bases for the storage and retrieval of existing technical drawings and part lists and part programs for manufacture. However, as software and hardware become more affordable, faster and user-friendly, the design process has been enhanced by the skill of the computer operator and the quality of the systems available. CAD systems have almost completely replaced the drawing board, and all manufacturing systems (CAM) are quickly moving away from manually controlled machinery to CNC. Communication in the product development cycle has been much improved due to Computer Integrated Manufacture (CIM) systems, with CAD/CAM systems providing a direct link from design to manufacture.

In order to adequately support concurrent engineering, a CAD/CAM system must move beyond simple geometric definition of a product. Concurrent engineering environments require sophisticated, unambiguous product information to be distributed to all engineering functions. Traditionally, CAD systems worked with entities such as lines, circles and surfaces that had to be altered appropriately to produce a given dimension on a product. When dealing with a complex geometrical shape (such as a twist drill) this is a near-impossible task. A new approach to CAD is currently growing in popularity which is known as Dimension Driven Geometry systems [34,35]. These systems offer modelling techniques that automatically translate dimensional changes into geometric changes, a much more direct and realistic method of creating drawings. The major difference between an ordinary CAD system and one based on variational geometry lies in the treatment of dimensions. In an ordinary CAD system, dimensions are subordinate to geometry, whereas in variational geometry this relationship is reversed. Hence the term Dimension Driven Geometry for systems based on variational geometry. It therefore becomes possible to change a dimension on a drawing and let the system automatically generate the new geometry of the entire drawing. Using conventional CAD, a change in a dimension would demand a complete re-build of the model, which is a cumbersome and costly process. The process of selecting new values for dimensions, and automatically creating a corresponding new model is known as re-dimensioning, an essential part of the design process. The CAD program developed to model drills has the advantage of being dimension driven.

An additional benefit of a CAD/CAM system is the availability of links to other design tools. This can be, for example, a draughting tool such as the commercial AUTOCAD, or a Finite Element Analysis tool, such as ANSYS. In the drive to reduce development times, and with more engineers carrying out their own product analyses, such tools can be vital assets, with the benefits outweighing the disadvantage of high initial investment costs.

5.2 DRILL DESIGN USING CAD

The design of a standard twist drill (see Chapter 2) still closely resembles the original design patented in 1863. Since then, however, many improvements have been made - some of the most important being the introduction of point modifications, oil-coolant holes, improved tool materials and coatings [36]. The main reason behind the 'Black Art' approach to drill design is the inherent complexity of the drill's design due to the numerous interdependent geometric features. When examining the performance of a drill it is impossible to vary one of these geometric parameters without affecting another. Without assistance from an advanced computer, it is an extremely difficult task to assess the direct influence of a drill design parameter on the performance of a drill, and subsequently make logical design improvements. This is the reason for the development of the TCS CAE system (Figure 33).

* Development of the TCS CAD Modeller

One of the major tasks achieved by the Teaching Company Scheme was to create a CAD system that was capable of designing the complex three dimensional drill shape [37]. Using the drill nomenclature used within the industry to describe the drill geometry it becomes clear that the CAD system must be one that uses Dimension Driven Geometry. It is an impossible task to accurately describe a drill shape in terms of lines and circles as used on the original CAD systems.

As far as the members of this TCS scheme and employees of Dormers are aware the CAD Modeller developed by the Teaching Company Scheme [37] is unique in its use of computers applied to drill design. The mathematical equations used to describe the drill shape are those developed by Galloway [4], which were subsequently computerised by Fujii et al [5] to produce

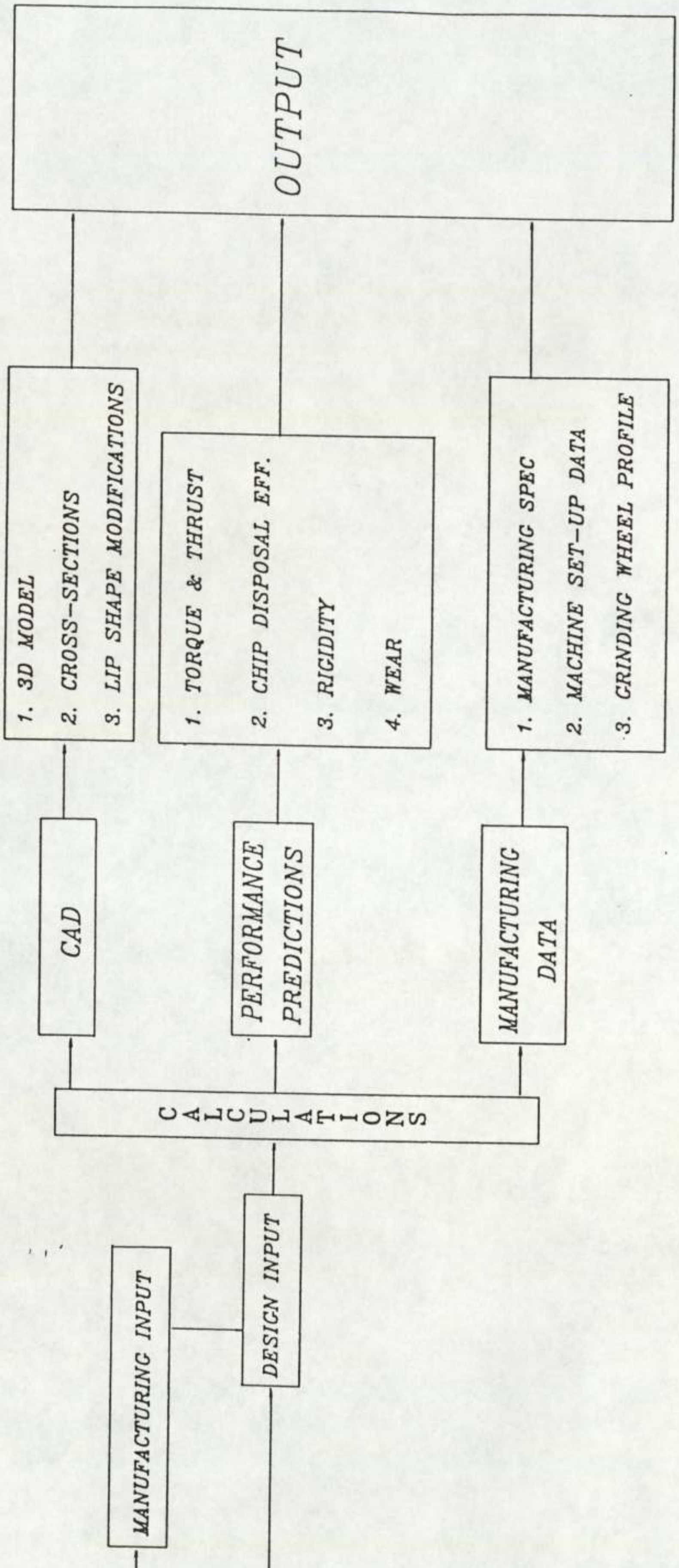


FIG 33: TWIST DRILL CAE SYSTEM

a visual representation of the drill shape. Several other authors offer a variety of approaches to the application of computer techniques to the drill modelling program [6]. However, the mathematical equations used in these papers to describe the geometry are based on the movements of the drill grinding process. The variables used in these equations are therefore not the same as the dimensions commonly used by industry to describe drill geometry. This is a major draw-back of all the computer programs as they actually model theoretical drill shapes rather then accurately model a 'real' drill.

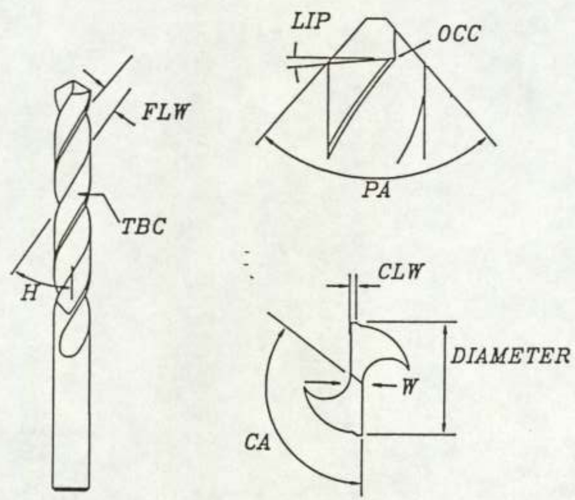
This discrepancy in drill geometry description has arisen from the fundamental difference in the approach to drill modelling from the manufacturing sequence. A drill is manufactured from a solid bar, by first having the flutes ground along its length, followed by the operation of point-grinding. The theoretical drill model, however, traditionally starts with the drill point and then uses the cross-sectional shape at the base of the point to create a three-dimensional drill body using extrusion and simultaneous rotation computer graphics techniques. This discrepancy has not only resulted in the creation of two different terminology groups to describe the drill shape, but it has also prohibited a link from theoretical drill design to actual drill manufacture.

The uniqueness of the Teaching Company CAD Modeller lies in its ability to bridge this gap between theory and reality. A program was created by Webb that contained two iteration procedures that allowed the numerical input to the program in drill design parameters, as well as standard drill nomenclature that would then iterate towards a solution in corresponding design parameters. This program was mounted on Webb's original computer model [2] providing a piece of software that permits the investigation into geometrical relationships that were previously far too complex to study. The author's contribution has been mainly in adding a module for the determination of chip disposal efficiency and linking up to ANSYS. Generally, however, team work with Webb, resulted in a user-friendly CAD program, that can be used by the personnel of the technical development department at Dormers.

* Features of the CAD Modeller

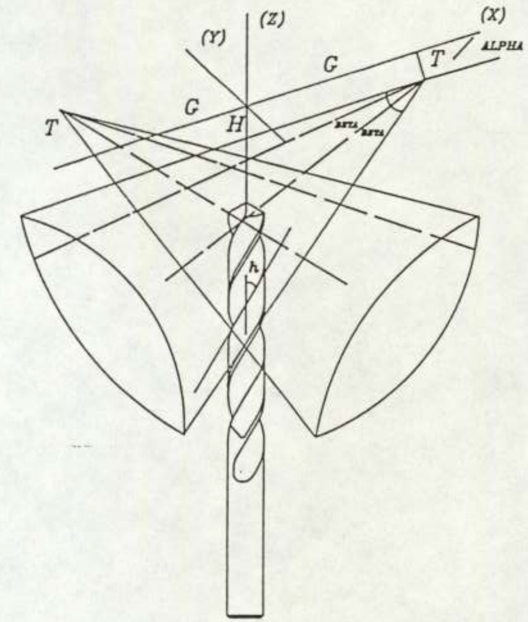
The drill design program is written in Turbo Pascal and has been implemented on an IBM compatible PC. A user-friendly interface was developed by the author to make the program more accessible to others. This involved writing a menu style interface, informing the user of the possibilities available and how to proceed with the program.

Two types of data entry are possible (Figure 33), either standard drill nomenclature as described by British Standard 328, or in terms of theoretical drill design parameters as developed by Galloway (Figure 34). This allows the program to be used by both drill theorists, and practical users. The program uses this information to create a three-dimensional model of the drill shape which it stores in terms of Cartesian X, Y and Z co-ordinates. The program user is then presented with the various possibilities of viewing the drill shape,



WEB THICKNESS	W
POINT ANGLE	PA
HELIX ANGLE	H
CHISEL EDGE ANGLE	CA
OUTER CORNER CLEARANCE	OCC
LIP CLEARANCE	LIP
FLUTE LAND WIDTH	FLW
CYCLINDRICAL LAND WIDTH	CLW
TOTAL BODY CLEARANCE	TBC

FIG 34 : DRILL NOMENCLATURE



The APEX CO-ORDINATES	G, H & T
The CONE INCLINATION	APLHA
The CONE SEMI-ANGLE	BETA
The FLUTE ANGLE	h
The WEB POINT PARAMETER	W
The FEED RATE PER REV	a

FIG 34: DRILL DESIGN PARAMETERS

such as the end or cross-sectional view (Figure 18) or as a three-dimensional wire-frame drill shape (Figure 35). These pictures have been used by the company for technical sales literature.

There is also a facility for the program user to alter the shape of the drill cross-section, by manipulating construction lines fixed to the outer corner and the chisel corner of the cutting lip. This also presents the opportunity to create drill models with straight or curved cutting lips. The relevant manufacturing information is automatically produced. Similarly it is possible to create drills with standard, parabolic or rolled heels as shown in Figure 12. The shape of the heel is known to have a decided effect of the chip disposal ability and rigidity of the tool, as described in Chapters 3 and 4.

5.3 CAE APPLIED TO TWIST DRILLS

The drill CAD Modeller has been used as a platform for a greater CAE system (Figure 33). By adding several performance prediction modules an analysis of various drill designs can be carried out. The program therefore enters the area of CAE, as a result of its ability to design and predict the performance of the model created. Four main performance criteria have been selected on the grounds that they are often seen as the most important in terms of customer requirements. These are - Torque and Thrust, Chip Removal Efficiency, Rigidity and Wear. By predicting the ability of each drill design within each category, a relative indication of how well and how long a drill is likely to perform can be made.

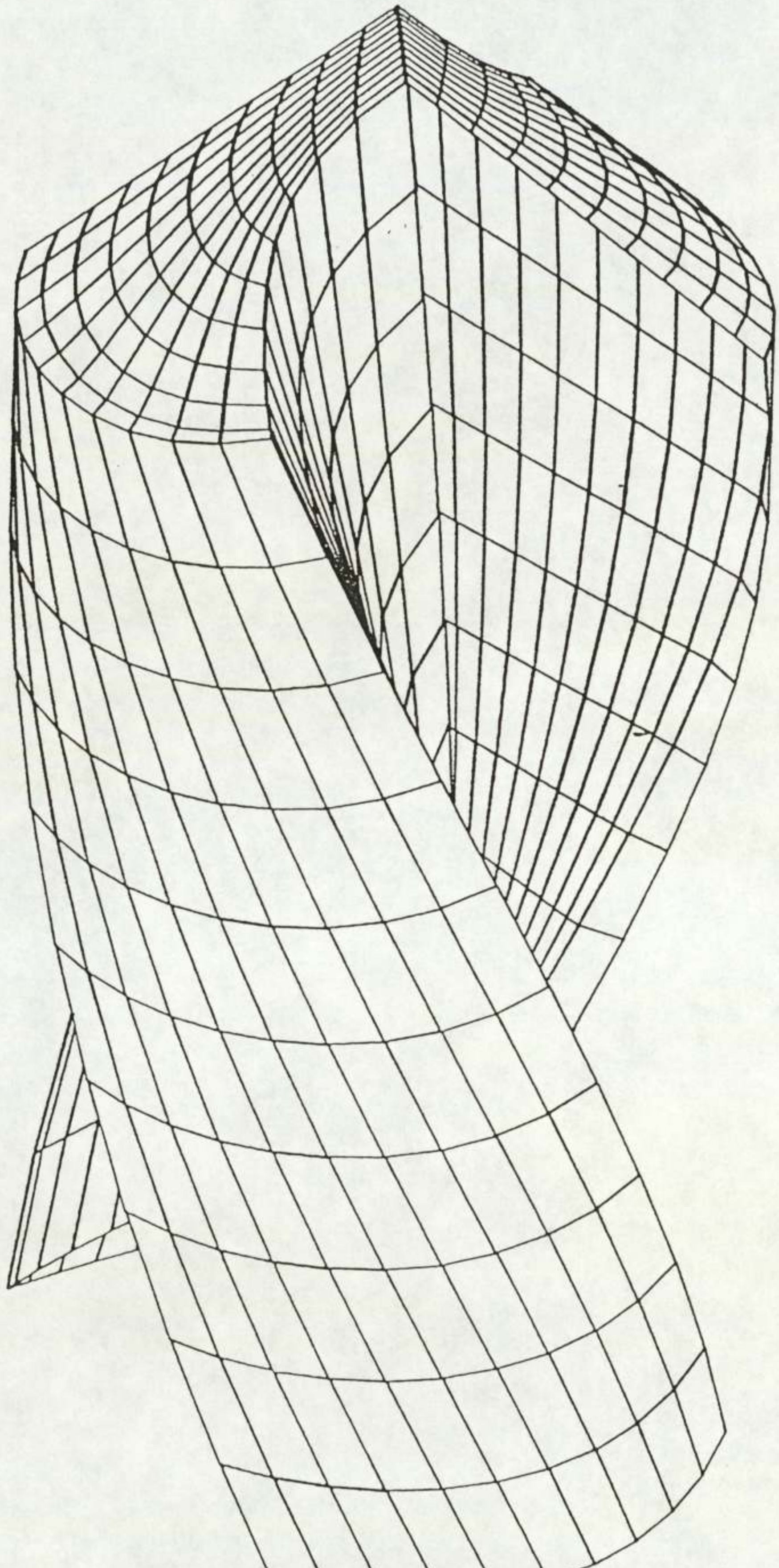


Figure 35 - Wire Frame CAD Drill Model

* Chip Disposal and Rigidity

In Chapter 3 it was described how the chip disposal efficiency prediction module was created and the theory behind this approach. Similarly, Chapter 4 described the implementation of Finite Element Analysis as a performance prediction module for drill rigidity.

* Torque and Thrust

A torque and thrust module was developed by Webb and is based on basic Merchant's cutting theory extended to include empirical findings of experimental work. The author does not consider it necessary to describe this module in depth, as it was developed by Webb, and has not been part of the work carried out for this thesis. The module has the ability to predict the torque and thrust across the cutting lip and chisel edge for a given feed and speed. The equation parameters used in the module are material dependant, and require a given amount of information about the work-piece material to be stored in a connected data-bank. To date, the data-bank contains four of the most common engineering materials which are drilled - Cast Iron (Grade 150), Mild Steel (080M46), Aluminium (LM5) and Stainless Steel (304515). Obviously there are many other factors that influence the forces undergone by the tool, but so far using this simplified approach, the module has been successful in predicting the correct order of performance of a range of drill, cutting under the same conditions. The magnitude of the predicted results is also within a satisfactory 20% error margin and, as required as a safety margin, consistently upper-bound. The module has been developed to include predictions for both uncoated and TiN coated drills, as well as drills with straight and curved lips. The force prediction field is known to be extremely complicated as a result of all the influential variables and instabilities in the cutting process. Any further improvement of this module would require an immense amount of work, and was deemed to be outside the scope of this Teaching Company Scheme.

* Wear

Wear most commonly occurs at the outer corners of the drill point and along the chisel edge. Over a period of time the drill will cease to function through actual breakage or accumulated wear. The prediction of wear is therefore an essential insight into the life and performance of a twist drill. Work is currently being carried out at Aston University and Dormer Tools to determine a wear index as a basis for a performance prediction module that will be linked to the CAD Modeller. The wear index will be based on the values of the clearance and rake angles as determined by the CAD system, and will take into account the cutting conditions, material properties of the tool and workpiece and the wear mechanisms present. Initially the aim is to assess the rate of wear at the outer corners of the drill lip as a result of the above variables. The effect on the torque and thrust due to the amount of wear will also be investigated, by combining the two modules within the CAE system. Eventually it is hoped to extend this study to include the wear rate across the cutting lip and chisel edge and gain a greater insight into the effect wear has on the life of the drill. Again, this work extends outside the limits of the Teaching Company Scheme.

CHAPTER 6. APPLICATION OF THE DESIGN METHODOLOGY

In the following chapter, a case-study will be used to demonstrate how the information from the performance prediction modules can be found to give the optimum geometric properties of the drill for a specific application. The example shows how the CAE system was applied to the design, development and manufacture of a Deep Hole Drill (DHD) as a new commercial product.

6.1 DEEP HOLE DRILLS (DHD)

Drilling any type of hole can present problems, such as chip removal, heat generation, hole finish and other performance criteria previously discussed. When drilling 'deep' holes (by definition, anything deeper than three times drill diameter) these problems become increasingly critical [38]. The main source of concern with deeper holes is the excavation of chips. If the chips are allowed to clog the flute, the drill will overheat and failure will follow. This problem can be overcome by changing the plane of drilling (e.g. from vertical to horizontal), or by 'pecking', which involves the regular removal of the drill from the hole to clear the chips. The design of the drill can also be altered to promote efficient chip disposal, consequently increasing the hole depth achievable in one single pass.

Some general design modifications for successful deep hole drilling are [3]:

- Fast helix angle (typically around 40 degrees) for swift removal of the chips from the cutting edge and increased rigidity, resulting in reduced vibration and consequently a straighter hole.

- Parallel web for a constant flute area along the length of the drill to prevent the clogging of chips.

- Point modification to increase positional accuracy and to reduce the thrust force caused by a greater web thickness.

- Parabolic flutes, obtained by rolling the heel on the cross-section (Figure 12), to increase the flute area which improves chip transport.

6.2 THE TCS DHD

One of the major objectives of the Teaching Company Scheme between Dormer Tools and Aston University was to develop the methodology to facilitate the launch of several new prototype drills for a variety of material application groups. Previous work had produced two Cast Iron jobber length drills, with a variety of coatings and point modifications. The next material group was Aluminium, and as a result of the capability of the CAE system to examine drill rigidity and chip disposal efficiency, it was subsequently decided to focus on the longer DHD.

* Design Specification

The objective of this project, assigned to the Teaching Company Scheme, was to demonstrate the ability of the CAE to successfully produce a Deep Hole Drill. The design specification, agreed upon by all parties involved, was to: **"design a deep hole drill to give the greatest straightness of hole at eleven times the diameter in an aluminium alloy in one single pass".**
The drill was specified as having parabolic flutes (a rolled heel), and to be manufactured using certain designated machines (for ease of manufacture) within a cycle time of six to eight weeks. The measure of the drill's success was to be assessed in comparison to the performance of other existing drills used for drilling deep holes.

Any restrictions on the drill's dimensions were determined in collaboration with the manufacturing division, by taking into consideration the mechanical limitations of the machines to be used. The following dimensions were selected for ease of manufacturing:

- The design of the point angle was limited by the point grinding machine to 133 degrees with a tolerance band of plus or minus three degrees;

- The flute shape of the new design was considered with regard to the point grinding machine, which required a shape in which the locating pegs of the machine could be accurately positioned within the flute;

- The overall length, flute run-out and cylindrical land were all set according to International Standards;

- A range of point modifications was selected to determine the most beneficial point type for DHD applications. Again, the mechanical restrictions of the point grinding machine were considered;

- A diameter size of 3.175 mm (1/8") was selected to correspond to a set of tests that had already been carried out at Aston University in the field of deep hole drilling. The aim of those tests was to evaluate the bending and torsion stiffness of four drills from a variety of manufacturers. This would allow a comparison to be made between previous and new results.

* CAE Applied to DHD

Using the information given above, the CAD drill modelling program was used to determine a suitable drill shape and the corresponding dimensional data. Within the boundaries of the specification, this drill shape was then altered to give a range of possible design solutions. This is carried out using computer graphics that allow cross-sectional changes to be made (see Figure 36). By manipulating construction lines and the position of set points on the model, a new shape can be created. The range of drill designs was analysed, using the CAD program and ANSYS, to establish the influence that varying certain drill dimensions (mainly changing the rolled heel and lip curvature) would have on the rigidity and chip disposal

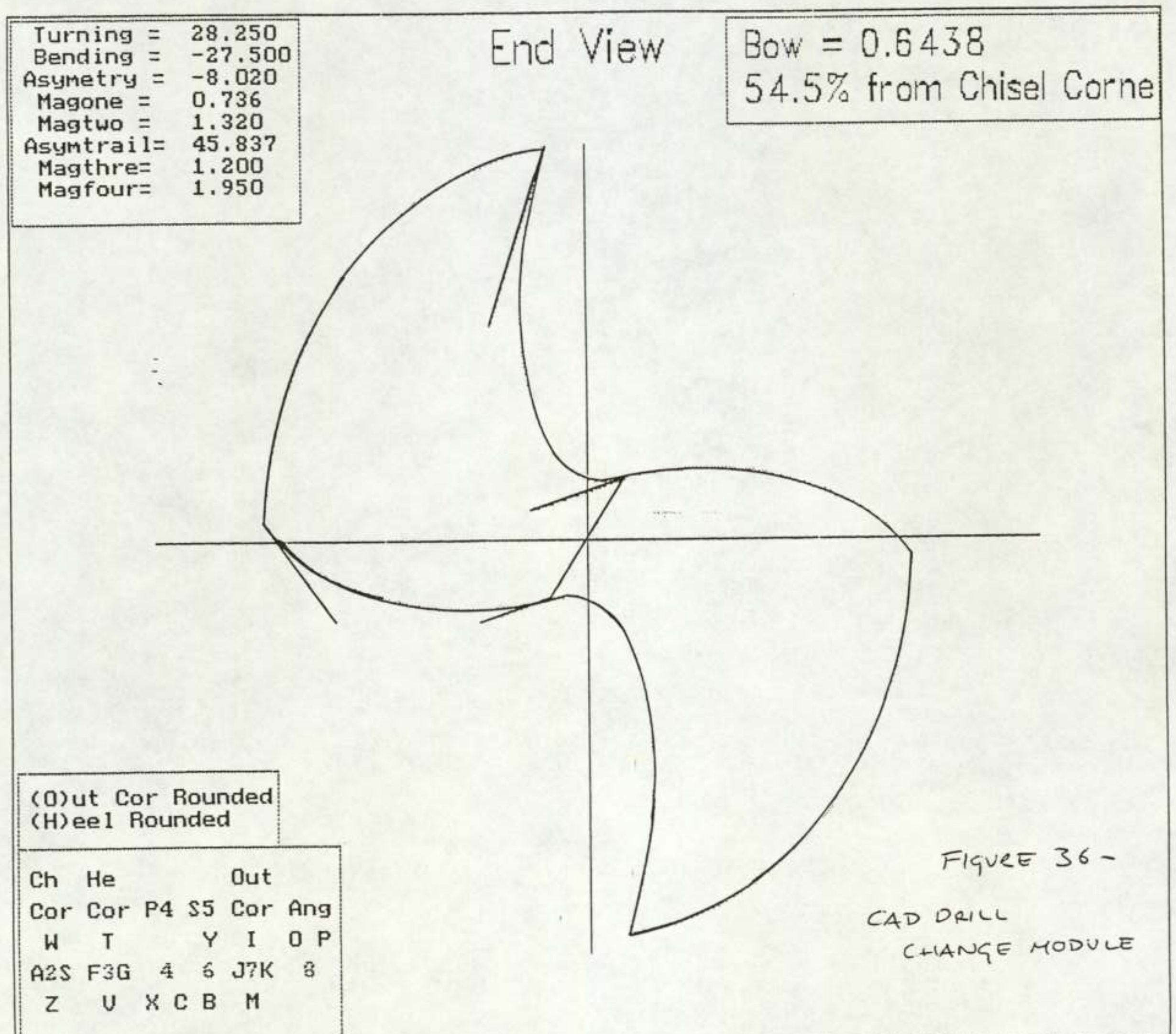


FIGURE 36 - CAD DRILL CHANGE MODULE

efficiency of the drill. This allows the drill design team to make a decision based on information that was previously not available.

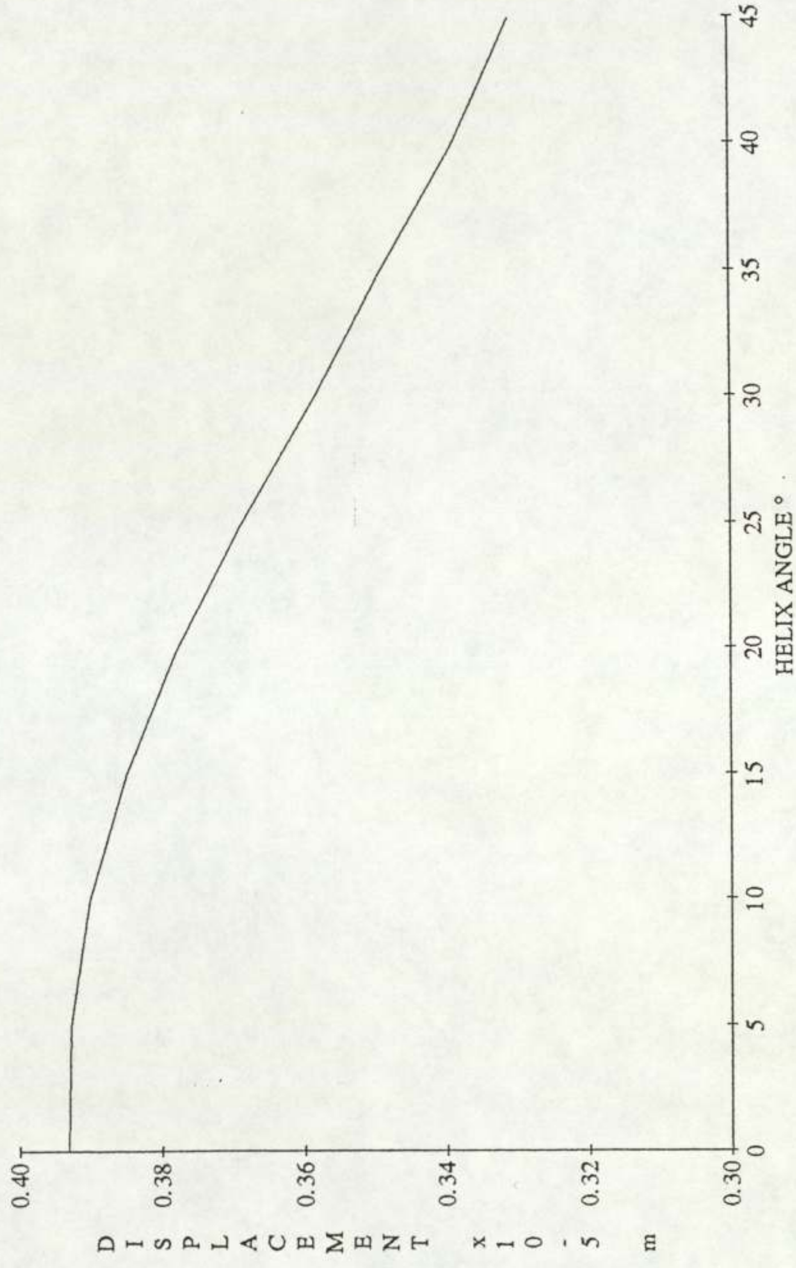
Once the drill cross-sectional shape has broadly been defined, there are only three geometrical variables that will be of major influence on the drill rigidity and chip disposal efficiency. These are the helix angle, the web thickness and the web taper. An investigation was therefore carried out into how these three parameters would effect the performance of the drill using ANSYS and the chip disposal module. The information is presented in graph form to demonstrate the relationships between the geometrical variables and the predicted performance.

- Influence of helix angle on drill rigidity

Using the cross-sectional co-ordinates provided by the CAD program for the original drill shape, the input data for ANSYS was transferred. As described in 4.3, a three-dimensional drill model was created with a parallel web for a range of helix angles. Each model must be of the same length to allow a comparison to be made between the models. Every time a new model is created, therefore, a re-calculation of the co-ordinates in terms of angular and longitudinal position must be carried out, for each new layer of elements. It is however possible to standardise part of the procedure, for example Strt.mac and Mesh.mac, so the relevant commands can be held within a macro program which is conveniently re-used to avoid unnecessary repetitive data input. The results are shown in Figure 37, where the maximum displacement of each model is

Figure 37

DISPLACEMENT vs HELIX ANGLE
TCS DHD



plotted against the corresponding helix angle. It can be seen that the torsional rigidity of the model increases as the helix angle increases, which is what one would expect when considering that a tighter coil requires a greater force to be unwound than a wire with a looser coil. The initial increase in rigidity is not linear, although the curve is approximately linear from about 15 to 45 degrees. It is anticipated, however, that with a further increase in helix angle the curve will start to bottom out. Flute grinding machinery limits the possible helix angle to 45 degrees, which is generally considered to be the maximum in terms of the helix angle. The conclusion can therefore be made that, in terms of rigidity, the DHD will benefit from a large helix angle.

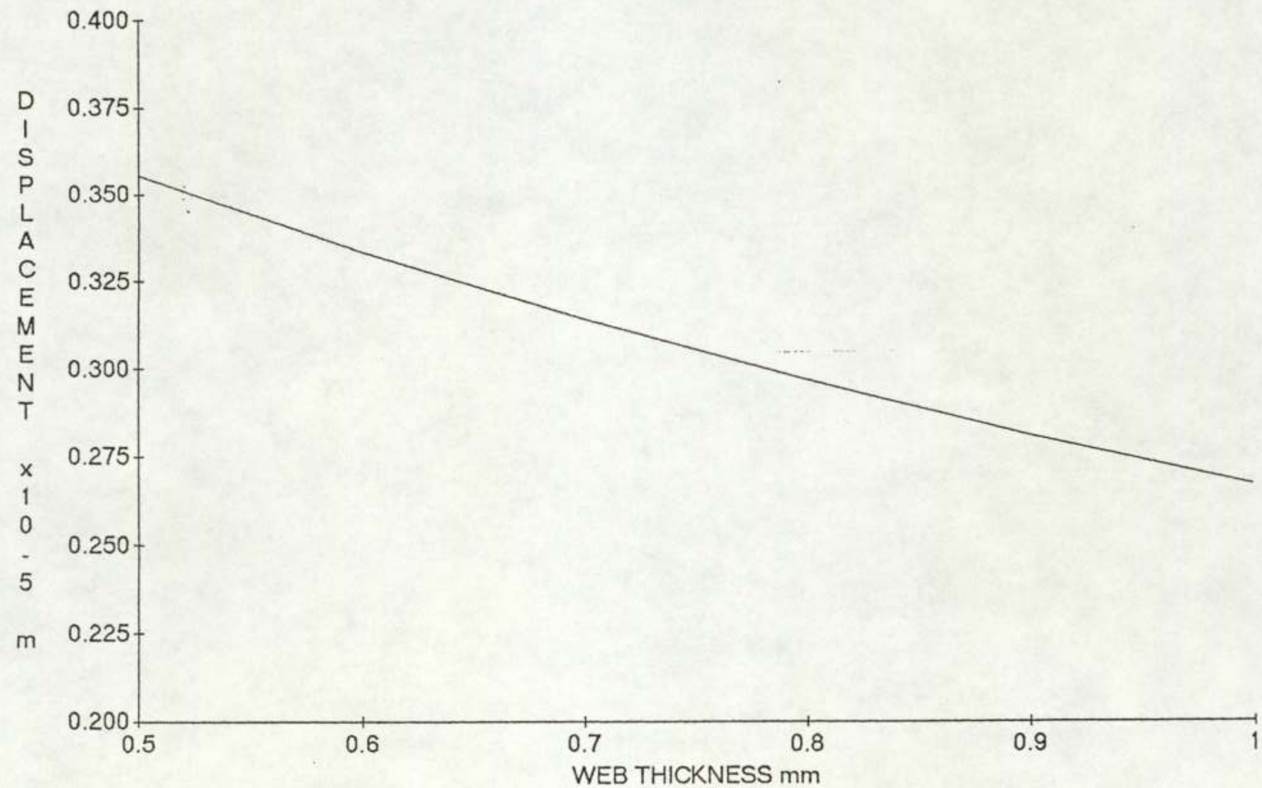
-Influence of web thickness on drill rigidity

To create a range of drills with a varying web thickness, it is necessary to re-create each drill shape using the CAD Modeller. The range of values chosen, from 0.5 mm to 1.0 mm in steps of 0.1 mm, is standard for a web thickness of this drill diameter. The six drill cross-sections were created on the CAD system and the relevant input data required by ANSYS was printed off in hard copy. From these co-ordinates six different drill models were analysed using FEA, all with the same length and helix angle (randomly chosen as 40 degrees) and, for simplicity, a parallel web. The graph shown in Figure 38 has the maximum displacement of each model plotted against the corresponding web thickness. The relationship appears to be linear, with the drill rigidity increasing as the web thickness increases. This is no surprise, as a larger drill cross-sectional area will obviously result in a stiffer drill.

FIGURE 38

DISPLACEMENT vs WEB THICKNESS

TCS DHD



To maximise torsional rigidity, the larger the web thickness the better.

- Influence of web taper on drill rigidity

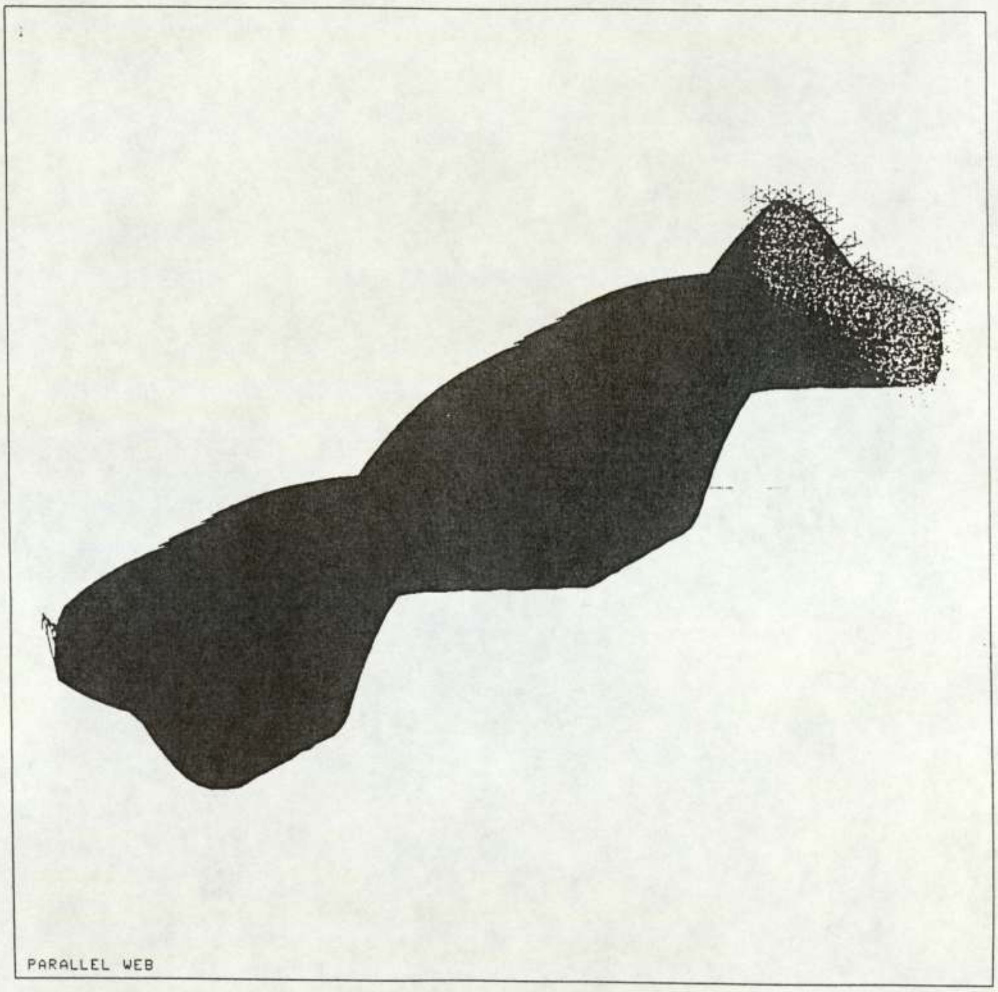
Creating three-dimensional drill models with a range of web tapers requires a different approach when using ANSYS, as explained in the Appendix. If the web is not parallel, the drill cross-sectional shape (although identical to the one used for the range of helix angles) must be defined using fewer co-ordinates for two reasons:

1) The "wave-front" limit on this particular version of ANSYS is 500. This means that at any one time during the solution phase, the matrix cannot handle any more than 500 unknowns. If each degree of freedom on each node is seen as one unknown in the matrix, then as the wave-front passes over any one layer of the drill model, it cannot have more than about 160 nodes, as each node in turn has three degrees of freedom;

2) It is geometrically much more complicated to create a drill with a web taper than a drill with a parallel web. For a parallel web, the cross-sectional shape of the drill remains constant throughout the length of the drill. A tapered web means that the web thickness along the length of the drill increases. It is measured at the thinnest point of the cross-section, although this linear increase in web width results in a change in the whole flute section, not just at the point at which it is measured (see Figure 27). To model this change in the entire flute section is impossible for the pre-processing capabilities on ANSYS, given the element and wave-front limits. Such a geometric problem, imagine a tapered cone inside a helical shape of constant outer diameter, requires

more advanced CAD facilities such as solid modelling. ANSYS, however, uses a CAD pre-processor that relies on the input of co-ordinate data. A simplistic approach to the modelling problem is therefore to create the drill cross-section out of seven separate areas (instead of two - as shown in Figure 24), rather than one for the parallel model. As explained in Chapter 4, this gives the cross-section a rougher shape in comparison to the smoother outline of the parallel web model which has more co-ordinates (compare Figures 39 and 40). The corner co-ordinates of each area are then manipulated in a different way, as the three-dimensional model is being created. Those co-ordinates at the inner web are given a linear expansion in radial co-ordinates that corresponds to the web taper. The co-ordinates at the outer diameter of the drill model are not expanded radially at all, and the co-ordinates in between are changed to approximate the non-linear change in the flute wall shape, and to connect the new web thickness to the constant outer diameter.

Before the drill models were created for a range of web tapers, a comparison was made between a drill with a parallel web and exactly the same drill but modelled as a tapered web drills, with zero taper. The aim was to establish if the two models gave the same amount of displacement under the same conditions, and if not, what the difference was. It was discovered, as expected, that the model created using fewer cross-sectional co-ordinates was less accurate and gave a 20% larger displacement than the parallel webbed model. The two drill models can be seen in Figures 39 and 40. Using the element limit of 5000, the number of layers was maximised (the number of elements in each layer is pre-determined by the



ANSYS-PC 4.4A1
MAY 19 1993
10:00:42
PLOT NO. 2
PREP7 ELEMENTS
TYPE NUM
FORC

XV =1
YV =1
ZV =1
DIST=6.2
ZF =-6.384
FACE HIDDEN

FIGURE 39

ANSYS MODEL WITH PARALLEL WEB

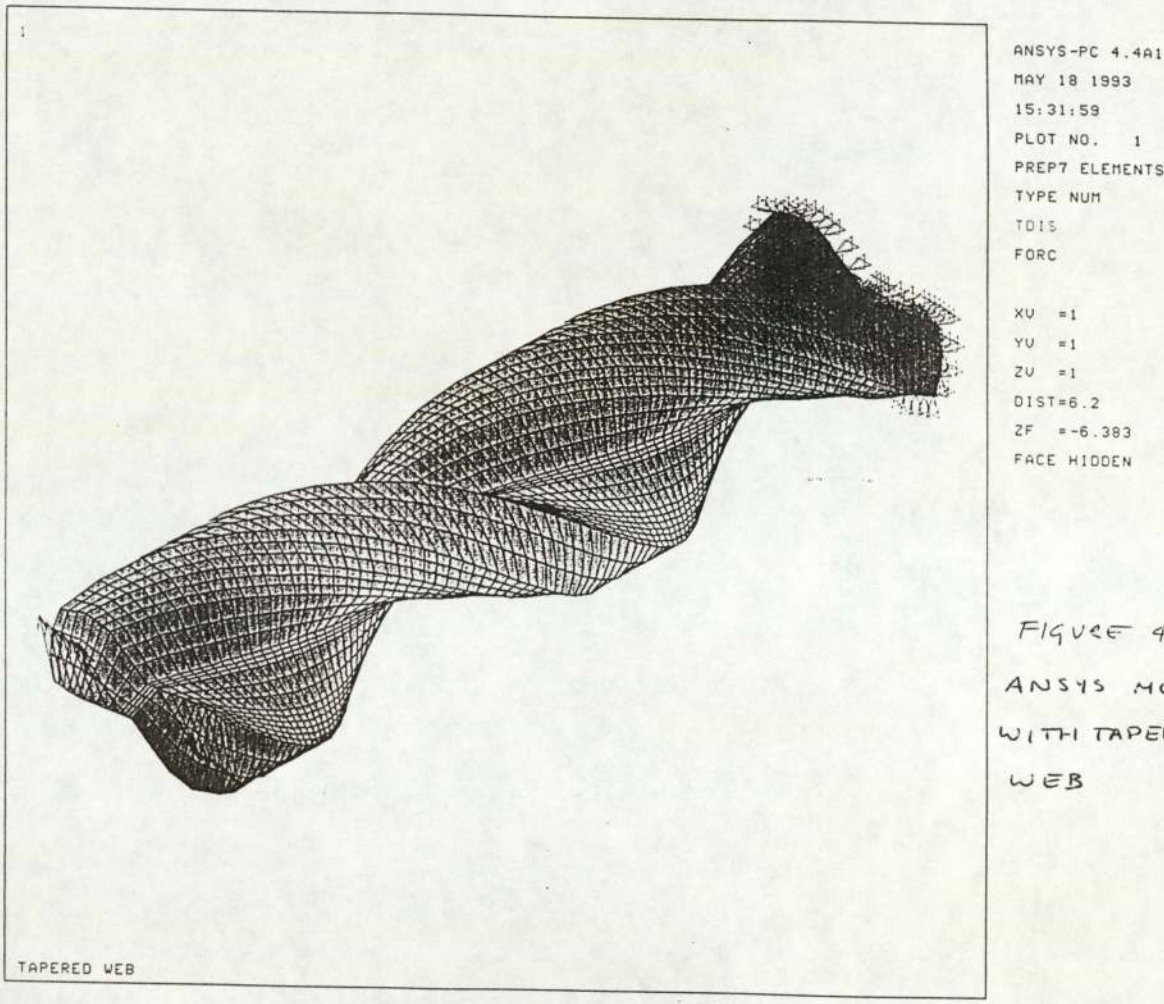


FIGURE 40
ANSYS MODEL WITH TAPERED WEB

wave-limit) to improve the accuracy of the model as much as possible. This reduced the discrepancy in the displacement results to an acceptable 10%.

Now that the technique of creating a drill model with web taper had been optimised a short macro program was written by the author containing all the standard input data that would need to be repeatedly typed in for each model (see Supporting Material). Again, a standard range of web tapers was selected (0 to 0.005 mm/mm in steps of 0.001), common to this diameter size. The results plotted in Figure 41, show a linear relationship between the increase in drill rigidity with an increase in web taper. Again, as with the web taper, this is anticipated since as that drill cross-sectional area increases, the drill will become stiffer and more resistant to torsional twist. The greater the web taper the stiffer the drill.

- Influence of helix angle on chip disposal efficiency

The data for the TCS DHD was input to the CAD system and the origin drill shape was created. From the data base linked to the program a helix angle of 33 degrees was selected. This was then altered through a range from 0 degrees through to 45 degrees, in steps of five degrees. It was, however, necessary to interpolate the value shown in Figure 42 for a helix angle of zero degrees as the computer would not recognise this data input. This is due to the value of the helix angle being used to calculate the lead, and would have resulted in an infinite value for the lead of the drill. The graph shows a relatively constant inscribed circle area from 0 to 30 degrees, whereafter the space available for chip disposal rapidly decreases.

FIGURE 41

DISPLACEMENT vs WEB TAPER

TCS DHD

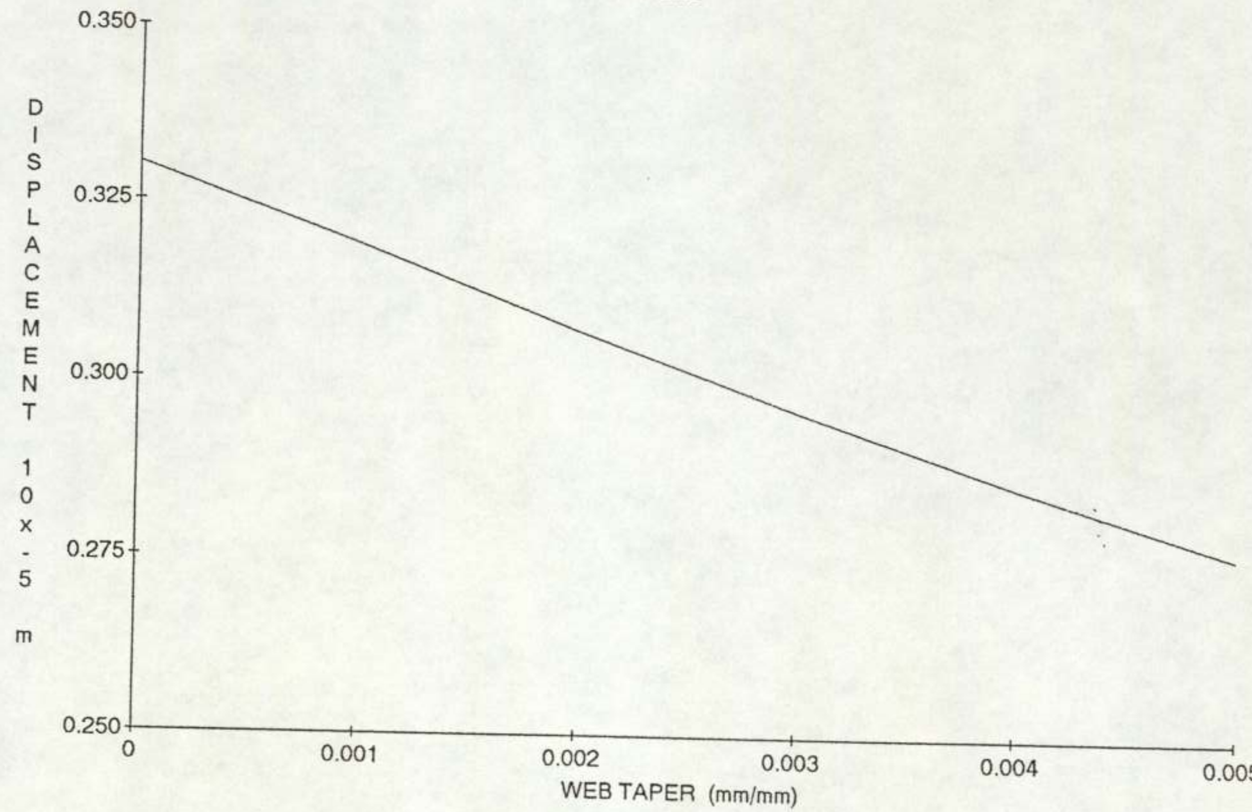
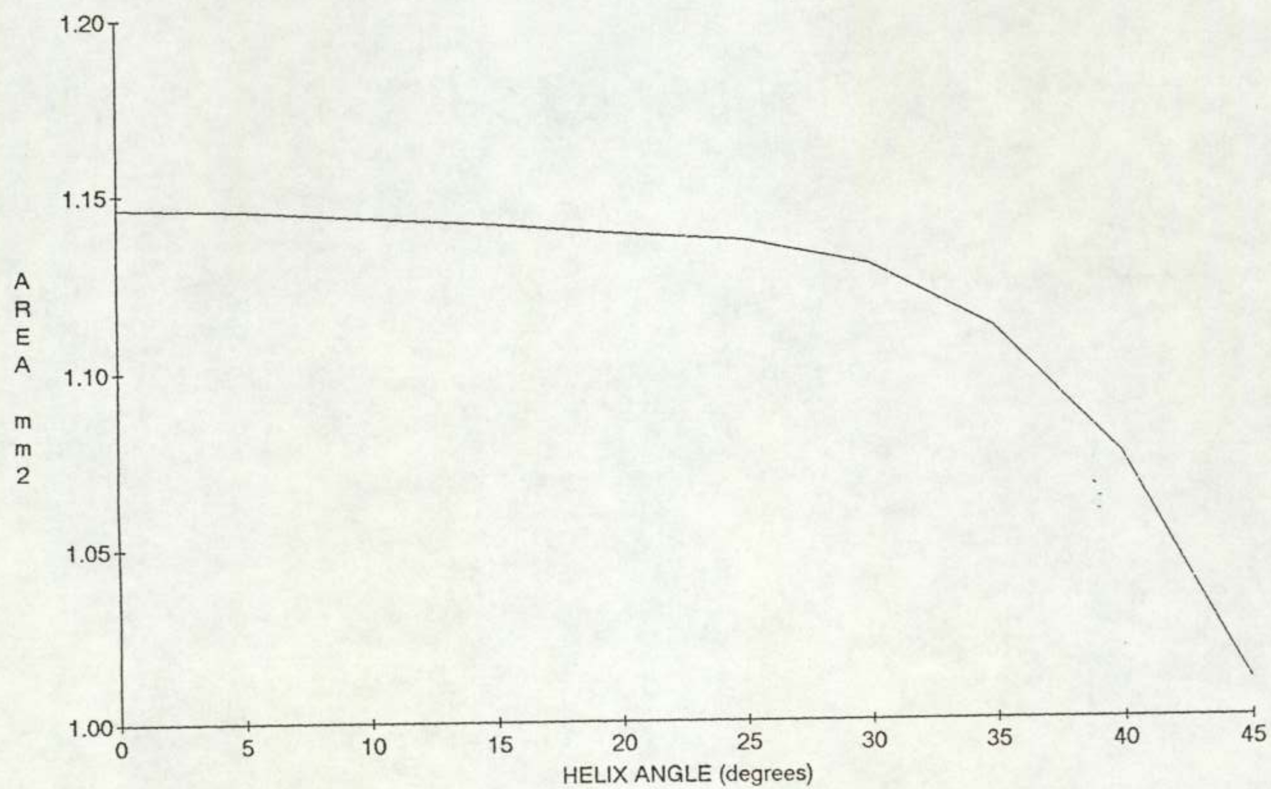


FIGURE 42

CIRCLE AREA vs HELIX ANGLE

TCS DHD

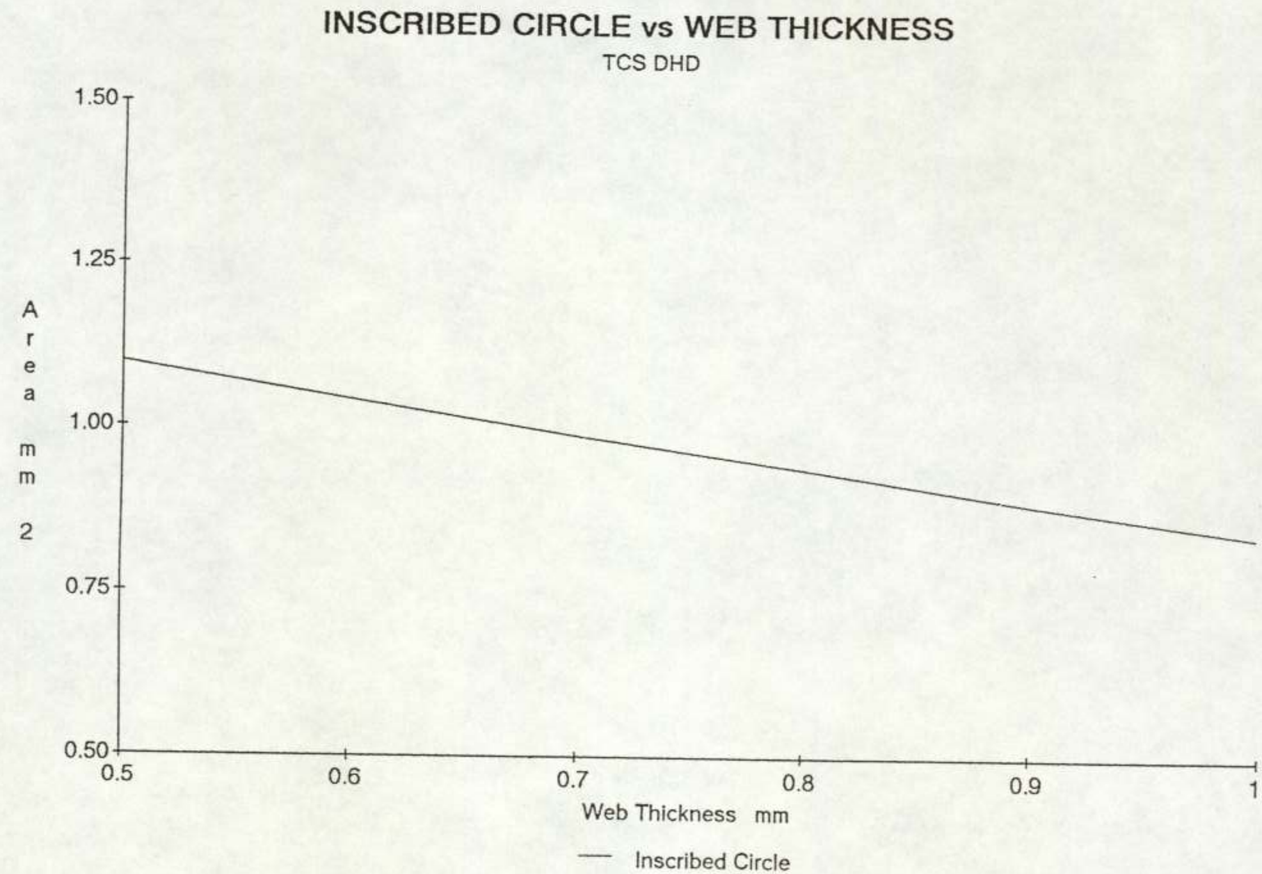


Again, the realistic limit of 45 degrees was selected. It can be seen that although an increase of helix angle beyond thirty degrees would have dramatically decreased the chip disposal efficiency, the rigidity of the drill increases at a rather constant rate (Figure 37). This supplies information on how the two inter-related characteristics behave as the drill design is altered. Unfortunately, El Wahab [21] did not investigate the relationship between helix angle, chip disposal efficiency and rigidity, but his graph relating to the influence of land margin relates a very similar picture to the one given here for the effect of an increasing helix angle. It can therefore be concluded that the chip disposal efficiency will be maximised by selecting a small helix angle.

- Influence of web thickness on chip disposal efficiency

Similar to the investigation into the helix angle on chip disposal efficiency, the original data input was used on the CAD system to create the DHD. The value of the web thickness was automatically selected as 0.76 mm from the data-bank, but was altered throughout the range of 0.5 to 1.0, in steps of 0.1, based on the general values used for a diameter of 3.175 mm. The results displayed in Figure 43 show a linear decrease in the area of the chip disposal circle with an increase in web thickness. This is to be anticipated as it corresponds to a constant increase in drill rigidity. El Wahab [21] does investigate this relationship and shows an identical picture of a linear increase/decrease in the rigidity/chip disposal efficiency with an increase in web thickness. There is a slight discrepancy where his graph displays a short, initially constant, prediction of the chip disposal value. It is

FIGURE 43


INSCRIBED CIRCLE vs WEB THICKNESS
TCS DHD
Area mm2
1.50
1.25
1.00
0.75
0.50
0.5
0.6
0.7
0.8
0.9
1
Web Thickness mm
Inscribed Circle

possible that if our graph were to examine the circle area corresponding to a web thickness of less than 0.5 mm, a similar trend may be found. There is little reason to investigate this, as such a situation would place an unrealistically large physical demand on the tool. Especially considering the web is the most common area of fracture in practical drilling. In conclusion, the chip disposal efficiency can be seen to benefit from a small web thickness.

- Influence of web taper on chip disposal efficiency

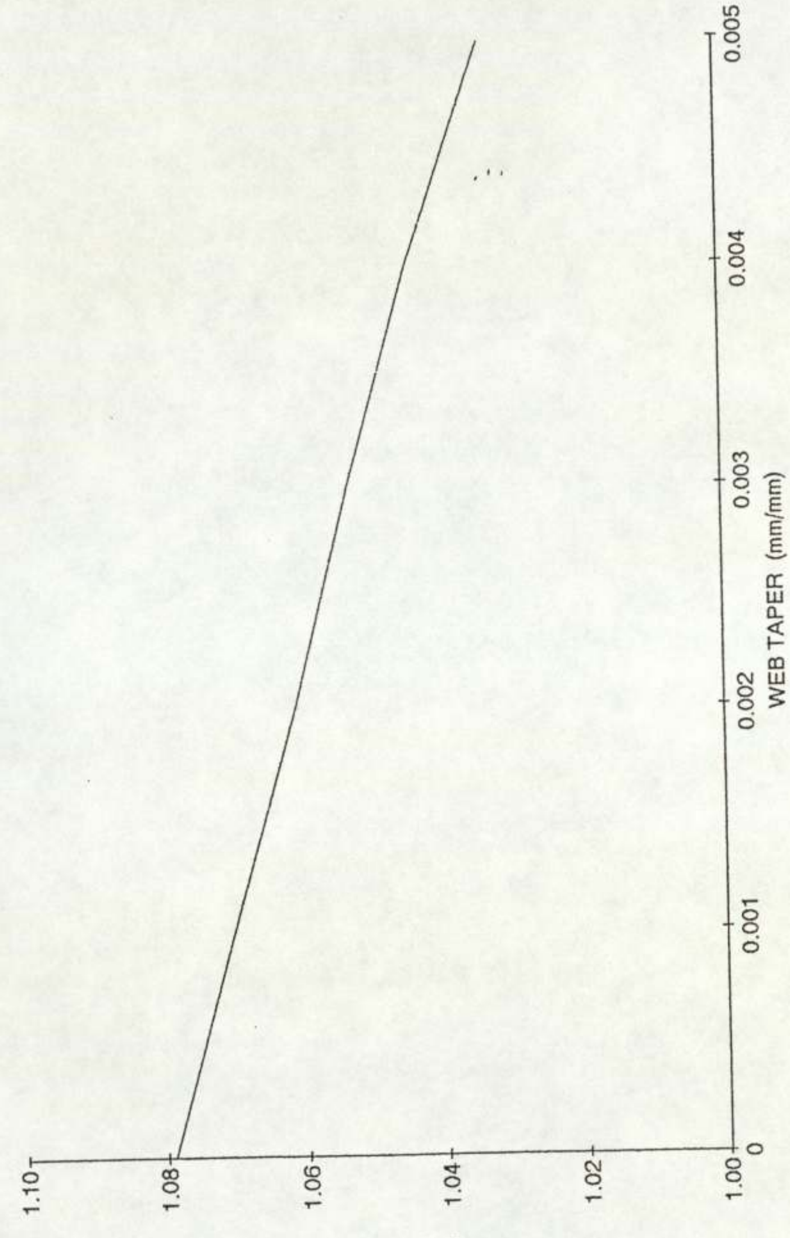
Using the same range of web tapers from the ANSYS investigations, the original drill cross-section was altered to have the web thickness corresponding to the cross-section of each of the six models at the distance of one unit of twist from the point (equal to the lead of the drill). The corresponding value of the web thickness was calculated for the range of 0 to 0.005 mm/mm taper (in steps of 0.001) and six models were created. The inscribed chip circle for each one was found and the results are shown in Figure 44. As would be expected with an increase in web taper, there is a linear decrease in chip area. The best design for maximum chip disposal is therefore one with zero taper.

Selection of the optimum cross-sectional shape and helix angle is a compromise between maximum flute area for chip disposal and maximum drill cross-section for rigidity. At the moment, this selection procedure is a task that cannot be automated due to the degree of human skill required. The design team studied the data gathered from the CAE system, presented in Figures 37, 38, 41, 42, 43 and 44. Bearing the design

Figure 44

CHIP CIRCLE vs WEB TAPER

TCS DHD



specification in mind and the specific application of this product, decisions were made with regards to the variables that had been investigated. The following parameters were selected:

- A helix angle of 38 degrees, to ensure a rigid tool with an acceptable chip circle area (a greater helix would have sharply reduced the circle size, but made little difference to the stiffness). A fast helix angle is also associated with a rapid removal of chips from the cutting lip and up the flutes (see 6.1);

- A web thickness of 0.75 mm, a compromise to reach a balance between the rigidity and the chip disposal efficiency;

- A web taper of 0 mm/mm was selected, given the web thickness and helix angle selected, the drill was deemed to be sufficiently rigid without the need for a web taper. A parallel web was considered to be the best solution, especially when considering the extra distance the chips would be required to travel.

Once all the variables have been selected, the CAE system automatically searches for the manufacturing standards to produce a product specification for the new design (see Figure 32). This information is then prepared along with set-up data for production and supplied to the machine operator for the manufacture of the new TCS DHD. Apart from some external delays in the delivery of the drill blanks to the manufacturing plant, the actual internal manufacturing cycle was achieved within the time limits set of six to eight weeks. The total development time for a new product using the CAE system was also within a maximum of six months, in comparison to the maximum of two years which experience has shown would have previously been the required time allocation.

6.3 PERFORMANCE RESULTS

When the selected TCS DHD, here called A, had been successfully manufactured, it was subjected to a series of predictive and actual performance tests together with three competitor drills from the same category, called B, C and D.

* Predicted Results

The TCS drill and the three competitors' drills were subjected to flute area comparisons to assess each drill's chip disposal efficiency, shown in Figure 45. The drill with the greatest circle and flute area was Drill C, followed by A, D and B.

Similarly the four drills were analysed using ANSYS, as described previously for parallel webs, for a prediction of their relative torsional rigidity. In order of most to least rigid, the drills rated B, D, A and C.

It was not possible to make a prediction of the torque and thrust results using the CAD Modeller as the three competitor drills had modified point shapes. This will effect both the torque and thrust experienced by the tools. Although work is currently being carried out to add this geometric modelling

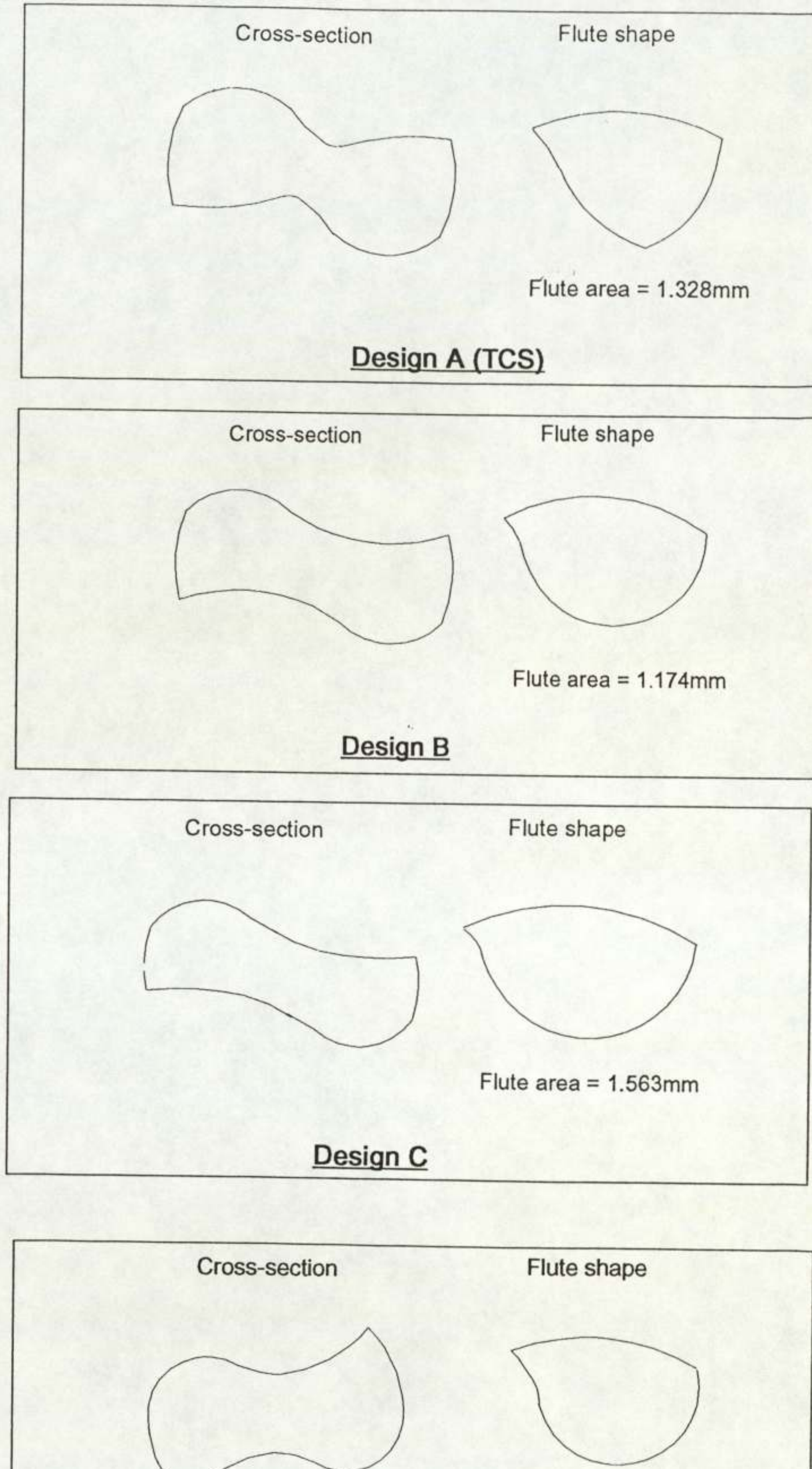


FIGURE 45 - DHD CROSS-SECTIONAL AND FLUTE AREAS

facility to the CAE system, there is no possibility yet to model anything other than a standard unmodified point. The three types of point that are of most interest and that are being investigated are point thinning, split point and double angle point.

* Experimental Results

Drills A, B, C and D, were physically tested for torsional rigidity using the purpose built test rig shown in Figure 30 and described in Chapter 4. The results are displayed in Figure 46, showing the actual order of rigidity to correspond identically to that predicted by ANSYS (ie. D, B, A and C). There is no actual comparison in terms of magnitude of displacement or load.

As explained in Chapter 3, it is very difficult to physically test for chip disposal efficiency. Observations can, however, be made during the drilling process when testing each drill to obtain an impression of each drill's ability to dispose of waste. Drill D, in particular, was seen to have the tendency to 'bird-nest', which was explained in 3.2, and is known to be hazardous to drill life. Although the drills were not tested for life (a expensive and time-consuming task when testing such a ductile material as Aluminium) this drill is more than likely to be the first to fail as a result of clogging. The other drills seemed to be able to dispose of the swarf without any signs of bird-nesting. All drills produced characteristically continuous Aluminium chips of a helical conical shape.

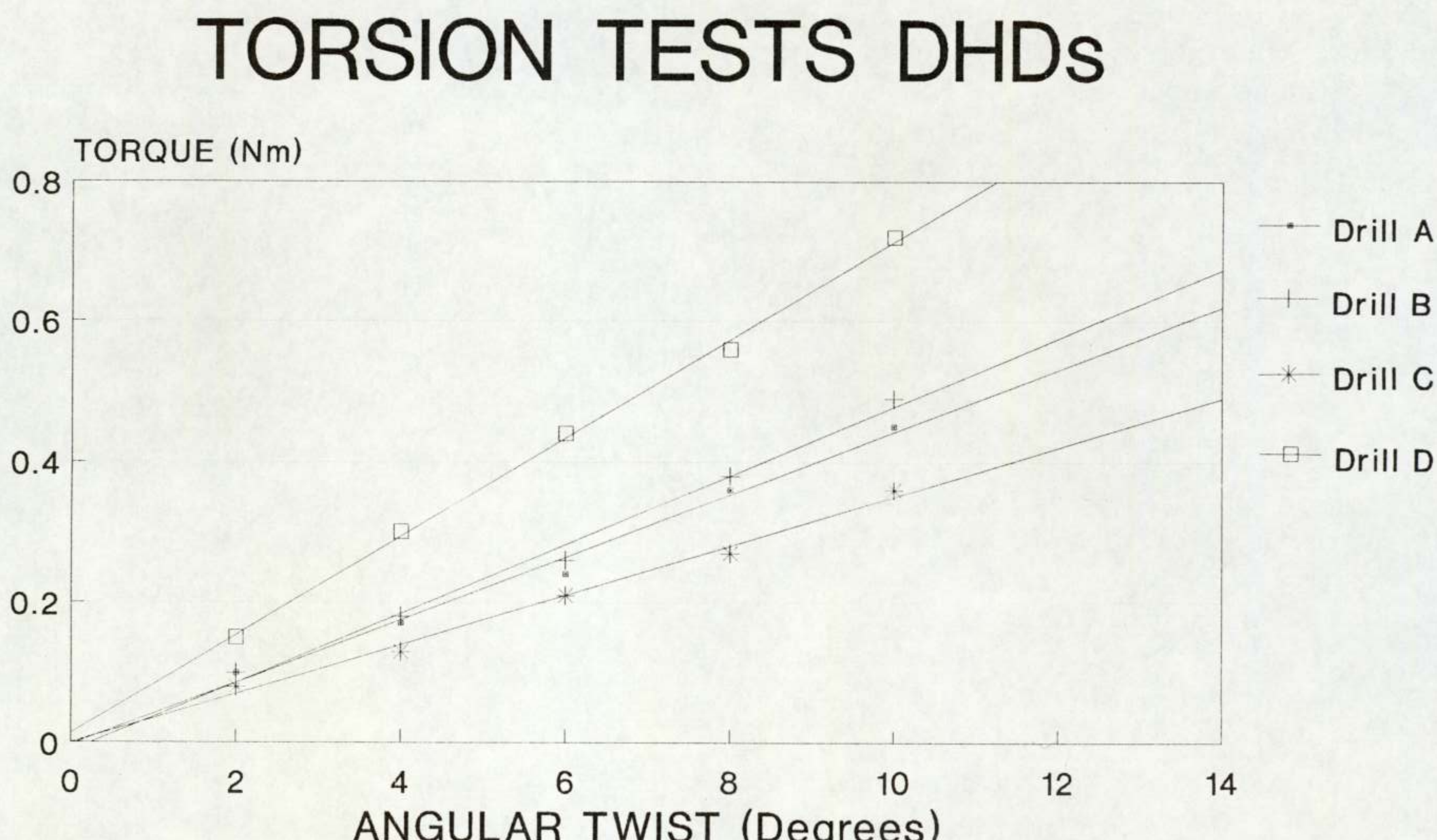


Figure 46 - Actual DHD Rigidity Results

Tests were carried out on the Bridgeport drilling centre at Aston University to measure the torque and thrust undergone by the tools during drilling. The drilling machine is linked to the same amplifier and MacLab computer as the torsion rig (Figure 30), which displays the forces. The holes were only drilled to 10 mm depth, as this is not a test of their ability as DHDs but simply as a torque and thrust test which requires a normal depth of two to three times diameter. Speed and feed were selected, as recommended by the Dormer technical handbook, as 40 m/min (or 4010 rpm) and 0.08 mm/rev, respectively. This produces a penetration rate of 320 mm/min. The results shown in Figure 47, show the order of performance from lowest to highest (ie best to worst), in terms of torque, to be C, B, A and D. Also shown are the thrust results in order of lowest to highest (again best to worst) as A, C, B and D.

Further experimental testing was carried out to examine the hole positional and dimensional accuracy, a particularly important aspect of drilling deep holes. So far, there is no method of predicting performance for these criteria. Figure 48 shows the degree of hole over-sizing of the four drills using nine drills of each design. The order of the most to least accurate is A, B, D and C. Visually, the flatter the trace and the nearer the centre of a line to the desired diameter of 3.175 mm, the better the drill in terms of dimensional accuracy.

To establish their positional accuracy, tests were carried out using each of the four drills to drill the same number of

TORQUE AND THRUST RESULTS

DRILL TYPE	TORQUE (Nm)	THRUST (N)
DRILL A	0.21	125.80
DRILL B	0.19	153.31
DRILL C	0.17	143.85
DRILL D	0.23	190.73

Figure 47 - DHD Torque and Thrust Results

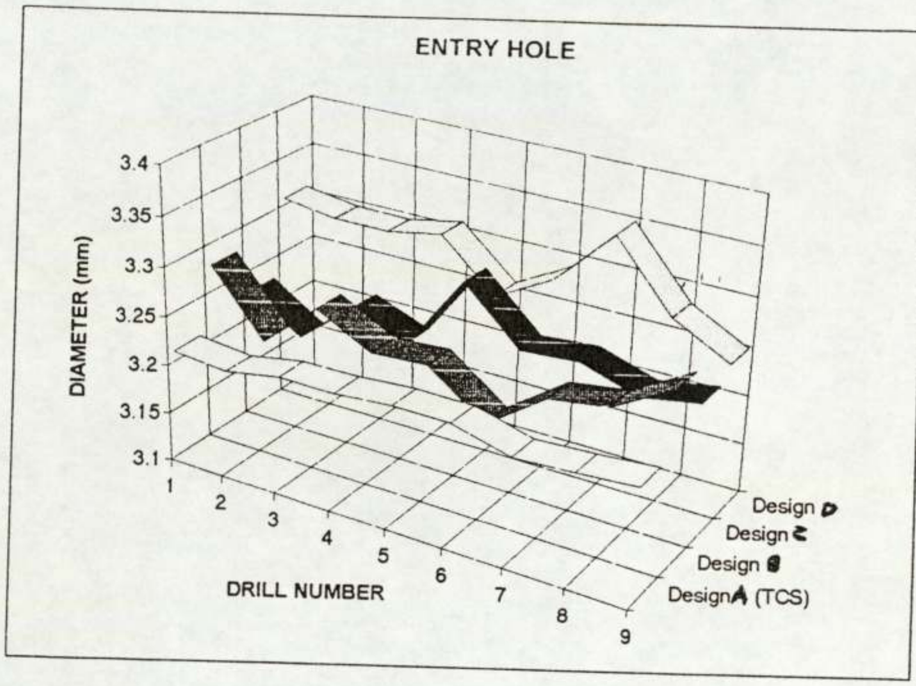


FIGURE 48 - HOLE OVER-SIZING

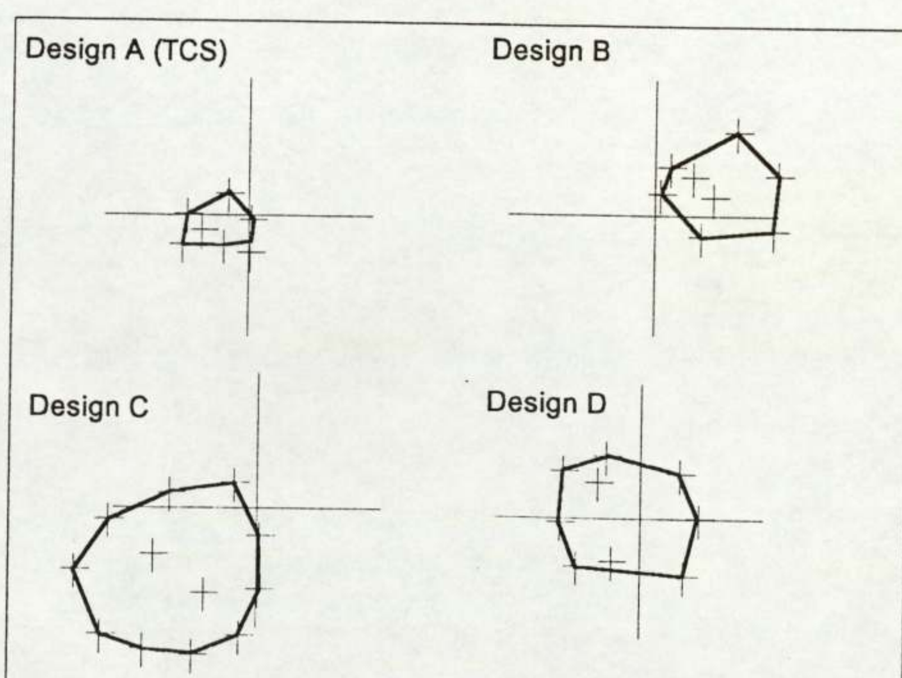


FIGURE 49 - BULL'S EYE PLOTS - HOLE ENTRY

multiple holes. The entry and exit positions of all the holes were measured and recorded in relation to a datum point, set equal to the centre of the drill. The deviations calculated are plotted in Figure 49, known as a "Bull's Eye" plot. The straightness of the holes, eleven times diameter in depth, are visually expressed by the size and position of the traced outline encompassing the positions of the holes. The results showed that Drill A had the least deviation from the datum, followed by Drill B, then Drill D and the least accurate being Drill C.

* Discussion of Results

Drill A has the best performance in terms of hole straightness and dimensional accuracy. This is possibly a result of the correct balance between the demand for rigidity and chip disposal efficiency and the selection of point modification. Drill C has, for example the greatest ability to dispose of chips and experiences little torque and thrust, but is weak in terms of rigidity and subsequently accuracy. Drill D, on the other hand, is very rigid, with little space for chip disposal. This results in the drill becoming clogged with chips which has a detrimental effect on the general performance of the tool, which can be seen in the accuracy and the force tests. Drill B performs in a similar manner to drill A, but is superseded in terms of dimensional and positional accuracy. Finally, although Drill B encounters less torque than Drill A, it is well known in drilling that 70% of the forces undergone by the tool are thrust forces, and it is therefore far more important to have a drill design that

enhances less thrust than less torque. The results show Design A to outperform the other drills in terms of thrust.
As stated at the beginning of Chapter 6.2, the objective of this project was to demonstrate the ability of the CAE to successfully produce a Deep Hole Drill, and simultaneously prove that the design methodology actually works. Considering the success of the TCS DHD, in comparison to equivalent competitor drills and in the light of the requirements set by the specification, it can be concluded that this project has been successful. This project also demonstrates that the CAE system has provided several pieces of something that can be compared to a large, and previously unattempted, jig-saw puzzle. Although an attempt has been made to solve the puzzle, so far only a selection of the pieces are present, and the picture is by no means complete. This piece of work also illustrates that the pieces must be put together by a group of experienced persons from the field of drilling, in order to produce a successful product. This is not seen as a negative aspect of the system as the CAE system is not expected to be an all-singing-all-dancing machine that can perform on its own. On the contrary, if the system is to be continually developed, it requires the correct design environment and personnel to respond to the requirements made.

In conclusion, the CAE system has been shown to create a successful product using a logical approach to drill design. This has also resulted in a realistic design proposal with a much shorter lead time. The total development and prototype manufacture time for a new product has been reduced from 1 to 2 years down to 4 to 6 months.

6.4 FUTURE WORK

A comparison was drawn, in the previous section, between the CAE system and a jig-saw puzzle. There are still many pieces missing, that will certainly not be covered under the time scale of the Teaching Company Scheme. Some work is currently being carried out, as mentioned in 5.3, at Aston University on the development of a wear rate index. This would provide an unprecedented insight into the life of a drill and its behaviour throughout the drilling process. Similarly work is on-going with Dormer Tools Ltd to achieve a better understanding of the relationship between dimensional tolerances and drill performance. There are many other performance parameters that would be of great interest to assess their influence on the life of a drill, for example - heat generation, oil coolant holes, lubrication, tool material, coatings and many more.

With regards to this particular piece of work, there are certain areas of interest that follow on directly from here. Given the availability of the Finite Element package, ANSYS, it becomes possible to investigate dynamic and static models. One main area of interest, which has attracted previous attention [39,40], is drill vibration. Drilling is ultimately a dynamic process, and the drill behaves in a complex three dimensional manner during cutting. Problems in vibration can lead to poor quality holes (either in terms of positional and/or dimensional accuracy) as well as actually be the cause of failure. ANSYS provides the ability to carry out modal analysis to assess the different modes of vibration of a drill model and assess its natural frequency. This is, however, a vast and complicated topic, and one that certainly deserves investigation, but falls outside the scope of this thesis.

Other work that can be carried out using ANSYS, could include the analysis of drills under various types of loading, other than torsional. By placing a radial point load on a drill model, the drill can be evaluated as a cantilever under bending for the resultant stresses and displacements. This would provide some information about the stiffness of the tool with regards to positional accuracy. Some work has already been carried out in this field [31].

ANSYS was also used during this TCS to analyse drills with oil-coolant holes. An investigation had been set up as a result of a large amount of failures in industry, for oil-coolant drills of a certain diameter size. In this case, the stress analysis results indicated no apparent reason for this spate of failures, and further research work (carried out by others) located the actual cause of failure, which was a manufacturing error. This example demonstrates how this FEA tool can be applied in the future to similar cases to provide an insight into problems that would have previously not been possible.

1) The only chip disposal efficiency theory found has been successfully computerised and linked to the CAD Modeller. The module has expanded on El Wahab's limited theory, by introducing a three-dimensional insight into the inscribed circle theory. Using a case study, it has been shown how information can be attained with regards to the effect of a particular drill design parameter on the predicted chip area. In particular the direct effect of web thickness, web taper and helix angle were demonstrated.

2) A link-up to ANSYS, a commercial FEA package, was made in order to examine torsional rigidity. This provided a pre-processing tool that can create complex three-dimensional models from data provided by the CAD modeller, with relative ease. No work has been found that has previously used FEA to investigate the effects of geometrical drill properties on the performance of the tool. Again, an investigation was carried out into the effect of helix angle, web thickness and web taper on the maximum displacement of a drill in torsion.

3) Torsional analyses have been carried out using ANSYS on drill models and special macro programs have been written to facilitate the programming procedure. A procedure to model drills with web taper was created, which was particularly complicated by the CAD pre-processing facilities available. The analyses have provided accurate relative rankings of several groups of drills. The predicted results have been verified using a purpose-built rig, which is a very accurate

piece of testing equipment set up to measure the torsional stiffness of drills. In comparison to previous experimental techniques used, this method is far superior in terms of accuracy and repeatability.

4) Most importantly, the work has been continually geared towards creating a user-friendly system that does not require a great amount of computer or theoretical knowledge to be used. This is essential for the product to be successfully transferred to industrial drill designers and others involved with product development. Great savings in time have been made when comparing the traditional design process to the process that incorporates the TCS CAE system. The development time of a prototype has been reduced from 1 to 2 years down to 4 to 6 months. This obviously has financial benefits for the company as well as improving their ability to compete in the marketplace.

5) So far a successful a rough approximation of both chip disposal efficiency and drill rigidity has been made using computers. Each module has successfully been linked to the existing CAD Modeller as part of a greater CAE system, allowing the same drill model to be analyzed for both performance criteria. An example has been given of how a design methodology can be applied using the CAE system and a design team. A Deep Hole Drill was successfully designed and manufactured, and tests with competitors drills showed an outstanding performance from the new product. Areas that require attention have been identified and suggestions have been made of possible areas for development.

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<u>APPENDIX</u> DRILL NOMENCLATURE - DEFINITION OF TERMS

CHISEL EDGE: The edge formed by the intersection of the flanks and connects the cutting lips.

CHISEL EDGE ANGLE: The obtuse angle between the chisel and the cutting lip in a plane perpendicular to the drill axis.

CHISEL EDGE CORNER: A corner formed by the intersection of a lip and the chisel edge.

DIAMETER: The diameter is the maximum diameter of the drill.

FACE: A face is that surface of the flute which the chip touches as it leaves the work-piece.

FLANK: A flank is that surface on a drill point which extends behind a lip to the following flute.

FLUTE: A flute is a helical groove extending from the drill point to the shank.

HEEL: A heel is the intersection between the body surface and the flute, situated on a trailing edge of the body.

HELIX ANGLE: The acute angle between the leading land of the drill and the drill axis.

LEAD OF HELIX: The lead of the helix is the distance, measured parallel to the drill axis, from an initial point on the helix to an identical radial point travelling along the leading edge.

LIP: A cutting lip is the face edge along which the chip is separated from the work, and is formed by the intersection of the flank and face.

OUTER CORNER: A corner formed by the intersection of a lip and the leading edge of a land.

POINT ANGLE: The angle included between the lips.

RAKE ANGLE: The angle at any specified radius between the face and a line parallel to the drill axis and intersecting the lip at the specified radius.

TANG: The tang is the tongued portion on the end of the drill shank.

WEB: The web is the central portion of the body that joins the lands. The extreme end of the web forms the chisel edge.

WEB TAPER: The increase in web thickness from the drill point to the shank end of the drill.

WEB THICKNESS: The minimum width of the web at the point.

TORSION THEORY

Any moment vector that is collinear with a mechanical body, in this case a bar, is known as a torque vector. The moment causes the body to be rotated about that axis and therefore a bar subjected to such a moment is said to be "in torsion".

The diagram below shows a bar of circular cross-section which is twisted by the torque, T, which is designated by the arrows on the surface of the bar, indicating the applied direction. The bar is prismatic, ie. the cross-section does not vary in the axial, z, direction. The angle of twist for a round bar is:

$$\varphi = \frac{Tl}{GJ}$$

where T = torque
l = length
G = modulus of rigidity
J = polar moment of inertia

For a solid round bar, the shear stress is zero at the centre and maximum at the surface. The distribution is proportional to the radius p and is:

$$t = \frac{Tp}{J}$$

where t(max) occurs when p is equal to the outer radius r.

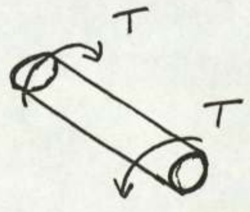

Diagram of a bar in torsion

Several assumptions are made in the analysis of a bar in torsion:

1) The bar is acted upon by a pure torque, and the section under consideration is remote from the point of application of the load (to remove any localised stresses that occur at the point of application);

2) Adjacent cross-sections originally plane and parallel remain plane and parallel (no plastic deformation) and any radial line remains straight;

3) The material obeys Hooke's law.

The polar moment of inertia is easily determined for a solid round section by the following equation:

$$J = \frac{\pi d^4}{32}$$

where d is the diameter of the bar. For bars with non-circular cross-sections, the determination of J and the torsional stresses is a difficult problem. Information on the determination of J for standard cross-sections, such as a rectangle or a triangle can be found in technical formulae handbooks, for example, Gieck [41]. More complex shapes, such as the drill section, are generally handled experimentally using a soap-film or membrane analogy [28].

FINITE ELEMENT ANALYSIS

* Introduction

The finite element method was first introduced in the early 1950s and since then has been continually developed and improved. As a result of low cost, more powerful computers, FEA is now within the reach of most engineers. It is widely used and accepted, and by far the most common numerical analysis procedure used by Industry today. The design of modern aircraft and automobiles is impossible without the technique, which is applied over a wide range of engineering systems from thermal stress analysis of engines to acoustic vibration analysis of passenger compartments.

The need for and popularity of the finite element method can be understood by appreciating the difficulty of solving the stresses and strains in any branch of engineering. Most engineering structures have become complex three-dimensional structures, that are extremely hard to analyse using textbook methods. The laws and equations that apply are fundamental, but the main structural problem of geometrical shape is complex. A vast amount of information is required to analyse such a situation, which is why the method lends itself so well to computerization.

Present day commercial FEA packages require a minimal amount of mathematical knowledge from the operator. The interaction with the engineer has become more user-friendly, and the results are presented with high quality graphics. These improvements can give the results an appearance of unquestionable accuracy. It must be stressed at all times that the finite element method is an approximate method of solution and must be used correctly in order to provide accurate and reliable results.

* Concepts

The name *finite element* summarizes the basic concept of the method - to transform an engineering structure with an infinite number of unknowns to one with a *finite* number of unknowns related to each other by *elements* of a finite size. The unknowns are referred to as the degrees of freedom and represent the responses to applied actions. For example, a displacement results from an applied force, or a temperature results from a heat flow rate.

These degrees of freedom and the corresponding actions are related by a set of basic equations. The finite element method sets out to solve these equations across the entire engineering structure being analysed. The simplest form of the basic equation is

$$[K]\ \{d\} = \{A\}$$

where {d} is the degree of freedom, {A} is the action vector, and [K] is the matrix relating to {d} and {A}, often called the stiffness or coefficient matrix. Generally, it is {d} that is unknown, with {A} and [K] given. The form of this basic equation varies according to the application. In a static structural analysis, as used in this thesis, [K] is the structural stiffness matrix, {u} is the displacement vector, and {F} is the force vector.

If an engineering structure is to be analysed it is essential that an accurate model is created, before being divided into a finite number of elements. The determination of the individual [K] matrices, precedes the assembly of the set of simultaneous equations [K]{d} = {A}, the solution of which provides the values of the degrees of freedom across the entire structure. Once the degrees of freedom are determined, derived results are calculated within each element. For a static structural analysis, as described above, the derived results are presented in terms of stress and strain.

The choice of element is critical for the model to be a true representation of the given structure. The element type determines the number of degrees of freedom at each mathematically determined point (node) and their meaning (displacement, temperature, etc.). Also, the nature of the actual response of the structure must be correctly represented by choosing elements that will allow quadratic or linear distributions where applicable. The operator must therefore have a reasonable understanding of the type of problem (s)he wishes to solve and the method he is using.

* Phases

An engineering structure to be analysed using the finite element method, is solved in three main phases:

1) Preprocessing

2) Solution

3) Postprocessing

The preprocessing phase is the start of any analysis, as well as the most operator-intensive part. The engineer must describe the problem to be solved by providing the model geometry and material data. Depending on the type of analysis required, the relevant finite element data must also be entered, and finally the boundary conditions applied (eg. zero displacements, forces). The model is now ready for analysis.

In the solution phase the operator has very little involvement, as the program assimilates the data, assembles and solves the simultaneous equations, and evaluates the stresses. The greater, or more complex, the model, the longer the solution phase will take.

Finally, the postprocessing phase allows the user to evaluate the results calculated in the solution phase. This data is often presented in terms of numerical data (eg tabular listings of displacements) or graphical displays (contoured stress plots).

* Drills

A drill is simple in its construction as it consists of a single unit, but in contrast is extremely complex in its three-dimensional geometry. The modelling of a drill shape poses a challenging mathematical problem, one ideally suited to computerization. Furthermore any analysis can be carried out by a computerised numerical method, such as FEA.

* Preprocessing

The creation of a drill model starts with the input of cross-sectional coordinates as provided by the drill modelling program. This work has been extended to cover two different types of web - parallel and tapered. The process to create each one is different, and is described below.

When creating a parallel web, the outline of the drill shape is firstly defined as two areas, joined at the chisel edge, and subsequently meshed automatically by the program. The meshing procedure produces two dimensional elements and nodes in one plane. These nodes are then simultaneously rotated and extruded to provide intermediate layers in a single unit of turn of the drill model. The rotation is necessary as the drill is not a prismatic bar, but contains helical flutes. The first two layers of nodes are then used as coordinates for one layer of three dimensional elements, automatically generated using a macro written specifically for this purpose. The two dimensional elements can then be erased, leaving a layer of three dimensional elements that form one end of the drill. This layer of elements is re-generated using the coordinates of the existing nodes to form the final complete drill shape (without a point).

The process used to form drill shapes with tapered webs is more time-consuming and complicated. The original drill cross-section is split into five areas. Each area is individually meshed using key points, rather than nodes. The key points belonging to each area are manipulated in various ways to represent the changing cross-section of a drill with a tapered web. The central area is considered to be the web, and increases in diameter along the length of the drill as depicted by the web taper specification. The two outer areas do not change in width, when being extruded. The two off-centre areas are expanded by one half of the web taper on either side. Any four key points on the first layer that form a square within an area, are joined to the corresponding key points on the next layer. These eight key points are then defined as the corners of a volume, and identical volumes are generated along the length of the drill. This is repeated for all key points, and then all volumes, until a full three dimensional drill model exists. These volumes can then be meshed automatically to give elements and nodes, necessary for the solution phase.

Both models are then given boundary conditions in an identical manner. All nodes on one end of the drill have their three degrees of freedom of each node set to zero, to represent the drill being held in the drill chuck. The nodes at the other end (representing the point end) have a distributed force applied along the cutting edge. Information from the drill modelling program's torque and thrust prediction module was used to determine the correct loads, that were applied to simulate a realistic load situation.

* Solution

The solution time on a model with maximum 5000 elements (the limit on this particular version) was typically around one hour. A selection of processing information appears throughout the duration on screen, although no actual interaction takes place with the operator.

* Postprocessing

Once the program has completed the solution phase, the results of the analysis are ready for evaluation. In this thesis the analysis is of a static structural nature. It is possible to review tabular results of displacements (including maximum displacements) and stresses (von Mises, Principal, Equivalent etc). It is also possible to view the displacement of the drill, with the maximum displacement exaggerated to allow visible movement. Contoured stress plots of the drill are also available, giving impressive colour displays that make the high stress spots easy to find.

THE INFLUENCE OF TWIST DRILL DESIGN ON RIGIDITY AND CHIP DISPOSAL

SUPPORTING MATERIAL

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ANSYS MACRO PROGRAMMES

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Master of Philosophy

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September 1993

ANSYS MACRO PROGRAMMES

START.MAC

```
/PREP7
KAN,0
ET,1,42
ET,2,45
MP,EX,200E6
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QUAD.MAC

```
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*get,etop,Elmx
*get,n1,en1,etop
*get,n2,en2,etop
*get,n3,en3,etop
*get,n4,en4,etop
*get,n5,en5,etop
*get,n6,en6,etop
*get,n7,en7,etop
*get,n8,en8,etop
*e,n1,n2,n3,n4,n1+ninc,n2+ninc,n3+ninc,n4+ninc
euse,type,2
euse,elem,etop
*if,etop,GT,ebot,:lab
```

MESH.MAC

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kplo
larc,7,8,1,1.5875
rp27,16,16,16
csys,0
v,6,7,8,9,22,23,24,25
rp26,16,16,16,16,16,16,16,16
v,5,6,9,10,21,22,25,26
rp26,16,16,16,16,16,16,16,16
v,4,1,2,3,4,20,17,18,19
rp26,16,16,16,16,16,16,16,16
v,16,4,3,11,32,20,19,27
rp26,16,16,16,16,16,16,16,16
v,15,16,11,12,31,32,27,28
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v,14,15,12,13,30,31,28,29
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THE INFLUENCE OF TWIST DRILL DESIGN ON RIGIDITY AND CHIP DISPOSAL

RHONA ELSBETH LEADBETTER

Master of Philosophy

CAD/CAM APPLIED TO TWIST DRILLS

THE UNIVERSITY OF ASTON IN BIRMINGHAM

September 1993

Title

CAD/CAM Applied to Twist Drills

Authors

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Programme

between

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and

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CAD/CAM

APPLIED TO TWIST DRILLS

SKF

SKF & Dormer Tools

ASTON UNIVERSITY

CAD/CAM APPLIED TO TWIST DRILLS

1. INTRODUCTION

1.1. THE PRESENTERS

The contract started in June 1990 and is of 2-4-2 construction. The first two associates, based in Research and Development, are to produce the CAD and analysis systems. They are Peter Webb, who received his first degree from Aston in 1986 and this year received a PhD degree for research in drilling, Rhona Leadbetter who received her first degree from Hull in 1990 and is currently registered for a higher degree with Aston. Associates three and Four are based in Manufacturing and will produce the CAM link. The scheme is now one year old and associate three is Michael McColl who has just joined after completing his first degree at Salford.

1.2. THE COMPANY

The Scheme is established in partnership with a leading manufacturer of metal cutting tools. The company was established in 1913, at that time employing 20 people in the manufacture of twist drills. Originally called the SHEFFIELD TWIST DRILL & STEEL COMPANY, in 1924 the company registered the trade mark of "DORMER" Tools which it still uses today.

The company was renamed SKF and DORMER TOOLS (SHEFFIELD) Limited on being aquired by SKF of Sweden, and now employs over 1000 people in and around Sheffield. CUTTING TOOL TECHNOLOGY, the multi-national parent, is the largest manufacturer of engineering cutting tools in the world.

1.3. THE UNIVERSITY

The academic partner to this scheme is the University of Aston in Birmingham. Aston has been working in the field of metal cutting, specialising in drilling, for many years. A series of research projects have been run, sponsored by the SERC and also supported by a number of companies who are users of cutting tools.

The most recent contract was aimed at the development of the accumulated knowledge to examine its impact on drill design. Aston is now a recognised authority on drilling.

1.4. HISTORY

The thrust of the last research project was to be able to compare the performance of a twist drill against a different drill or against another form of metal cutting. The cutting edges of the drill are produced by two seperate manufacturing operations, one to produce the helical flute and the other is to produce the conical point. From these two operations the research project developed a geometric model of drill shape. This model allows the geometry of the cutting process of the twist drill to be known in the same terms as a more simple tool.

This work was rated as category 1, good research content and good value for money, by the ACME, (Application of Computers to Manufacturing Engineering), Directorate of the SERC.

One aim of the Teaching Company Scheme is to promote the export of academic ideas to industry. This Contract developed from SKF and DORMER TOOLS interest in the above work. SKF (Tools) is involved in the manufacture of a number of different metal cutting tools, but, in Sheffield, is primarily involved in the manufacture of twist drills. The company wanted to enhance the design and development of these tools by making more use of computer technology.

2. INDUSTRIAL CONTEXT

2.1. THE TWIST DRILL MANUFACTURING INDUSTRY

When small, family companies first started to manufacture twist drills specialist machines were not available. The companies had to learn by experience how to modify a variety of machine tools just to be able to make drills. Several started to manufacture specialist manufacturing machinery, at one time this company marketed a range of machines with the "DORMER" brand name. More recently, however, only a few specialist machine tool manufacturers have survived. The company now buys its machines from all around the world. These new machines are good but their availability has opened the drill market to new competitors.

The days when there were only a few drill makers have gone. In order to survive the company must manufacture large quantities of high quality tools. We manufacture vast quantities of standard drills but have also expanded the range of tools, developing many new and different tools each aimed at a specific drilling task.

What started as a trickle has, however, now developed into a flood. The vast proliferation of materials to cut, the improved properties of materials used to make tools and the ever increasing sophistication of drilling machines has led to the need to develop many more new drill designs.

2.2. THE AREA COVERED BY THE SCHEME

2.2.1. SPECIFIC BACKGROUND

The cutting process of simple lathe tools is well understood. The geometry is simple and may be represented by two dimensional pictures. Predictive methods have been developed, both empirically and by analysis, which provide accurate estimates for the performance of individual lathe tools.

This is not the case with twist drills. Both the design of the tool and the performance of the tool are complex three dimensional situations. There are no simple approximations. Drill design has historically been a practical art based on trial and error. The development of improved drill designs is labour intensive and requires many years experience of drill manufacture. Change has sometimes been initiated by the instinct of the tool designers.

2.2.3. PROBLEMS AND OBJECTIVES

What we are looking for is a definition of industrial performance. Given the information in the preceeding paragraphs, a logical if simplistic measure of industrial performance is the ability to produce successful new tool designs.

The scheme has the following objectives:

i, To develop a computer model to describe the geometry of drills.
ii, To optimise the drill point and flute geometry.
iii, To develop and implement computer based design and manufacture.

3. SPECIFIC APPROACH

This section examines how to use CAD to design twist drills.

3.1. CAD - COMPUTER AIDED DESIGN

CAD may be used to help visualise new designs by using computer graphics. Associated Numerical Analysis routines may be used for the prediction of performance, for example, by stress analysis.

Previously there was no method of visualising the shape of the tool or predicting the cutting process prior to manufacture, the tool shape being the interaction of two complex curved surfaces. CAD is able to provide computer generated graphic pictures of twist drill designs. It will improve understanding of the interactions. Associated numerical analysis is able to predict several aspects of tool behaviour allowing the selection of the best combination of properties and geometry for a specific application.

3.2. SYSTEM SPECIFICATION - USER DEVELOPED

The twist drill is a complex three dimensional shape with a complex three dimensional cutting action.

The basic drill shape, however, is produced by just two grinding operations. These operations can be described mathematically and when combined may be used as the basis of a geometric solid model of drill form. Attempts to use more traditional CAD descriptions, such as sets of points or planes, are unable to use the simplicity of the above relationships.

For these reasons the use of a commercial CAD system was dismissed. The mathematics is based on these two manufacturing operations and a surface mesh is calculated. This system is now in use at SKF, Sheffield and provides a three dimensional wire frame graphic display of drill form.

One of the things we have learned from Industry is that the terms CAD & CAM have been used fairly loosly. There are many different interpretations. A two-dimensional CAD system has been in use by the company for some time. This system stores numerous engineering drawings. Set side by side, a simple wire frame representation of a three-dimensional drawing cannot compete for visual impact with the sophistication of a commercial 2-D CAD system. CAM also has a difficult interpretation in a world with a mix of CNC and manually set machinery. The computer generated designs must be processed to provide Manufacturing with setting information for manual machines as well as CNC data.

4. Current situation

This section explains what design systems are been developed and what hopes we have for the second year.

The Geomtric Model is well established. It is controlled by a number of manufacturing parameters and is able to write a manufacturing specification for the designed shape. The analysis systems are based on the cutting angles present across the cutting edge. This input is available from the geometric model. Both these areas have developed under the heading of research and development, by Associates 1 and 2 and the two parts are slowly coming together. The link to manufacturing will be established by Associates 3 and 4 over the next year and will also be blended into the central drill model.

Two of the three parts are currently available and some work on the third has been completed. The optimum from year two is to be able to throw away any consideration of intermediate parameters and provide a seamless design analysis from manufacture across to testing. In order to be understood and accepted, at each stage the computer tool must work with local terms and information.

5. CURRENT ACHIEVEMENTS

5.1. FIRST TANGIBLE BENEFITS OF A PARTIALLY IMPLEMENTED SYSTEM

Only a few of the opportunities have, as yet, been identified.

Drills are classified by a number of angles and distances that may be measured on the tool, such values as Point Angle and Outer Corner Clearance. These result from interactions between the two basic manufacturing processes. A few may be modified depending on the range of optional finishing operations. The geometric model allows these angles and distances to be pre-determined for Manufacturing. The level of "trial and error" of machine setup is much reduced.

The CAD display provides, also for the first time, a three dimensional visualisation of the drill form prior to actual manufacture of prototypes. The main drill cutting edge is generated as the intersection of the surfaces created by the two basic manufacturing operations, the shape of this cutting edge is dependant on both operations. This will have an impact on machine set-up and the identification of the best manufacturing routes. A by-product of analysing the kinematics of manufacture will be the ability to recognise where CNC machinery is required to achieve the necessary increase in manufacturing flexibility.

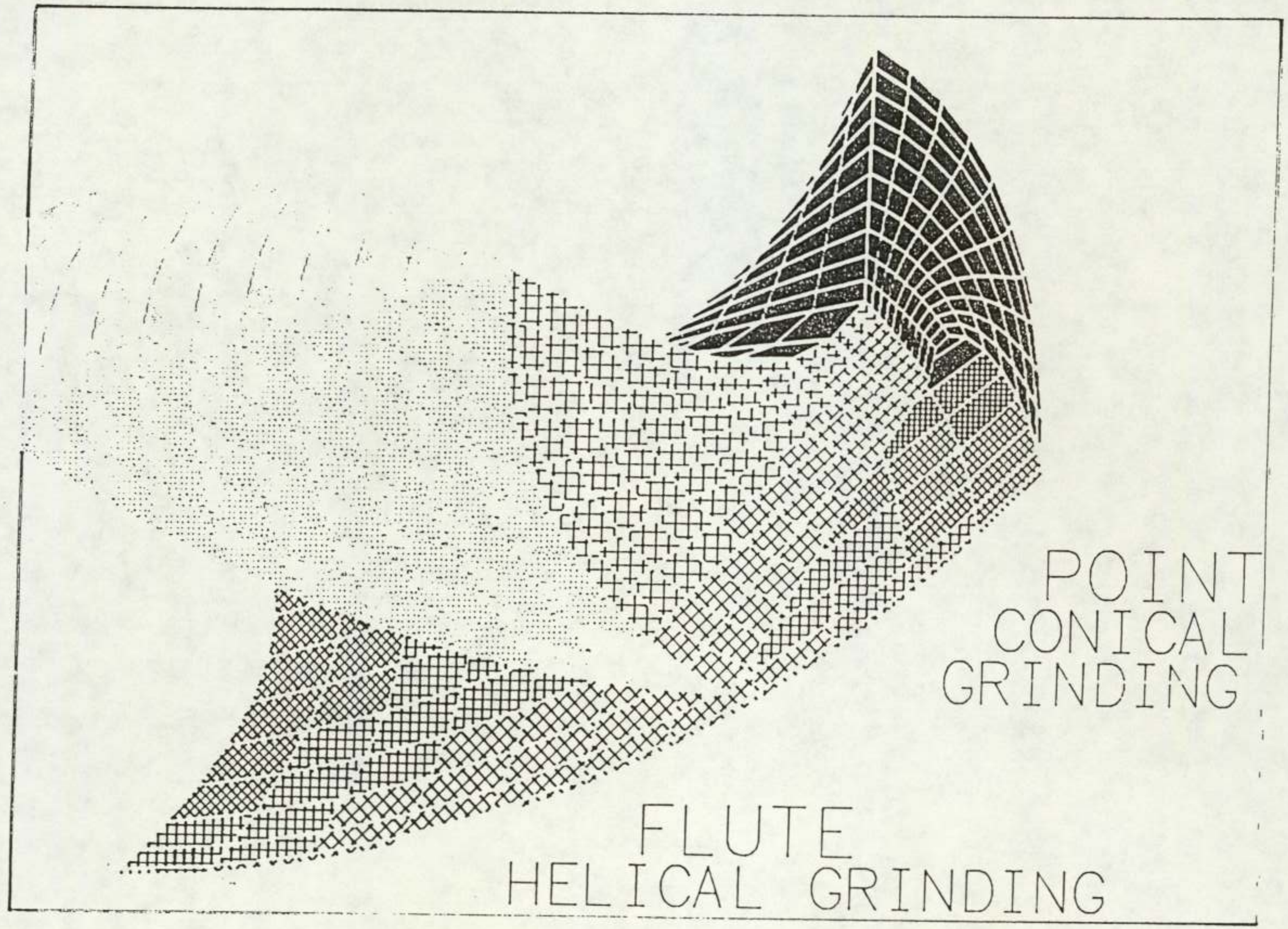
Numerical Analysis of performance and cutting efficiency is able to rank the properties of new designs. This is able to compliment practical testing performed during the development of prototype tools. Practical testing also only measures the total forces. The distribution of cutting forces along the cutting edges is predicted by this analysis. Shapes can be adjusted to the most efficient form.

The most significant problem to arise has been the need to define an improved drill. Drills have many interrelated behavioural characteristics, for example the cutting force while drilling or the shape of the swarf cut by the tool. Some of these properties are very important in one task while almost irrelevent in another. For each design task the important characteristics vary. It is necessary to specify the aspects of performance of a tool that are addressed by the design and then evaluate those same aspects in the test program. The specification of these aspects has not been required before. In the past designs could only be compared by their performance in a standard test.

6. CONCLUSIONS FROM THE WORK

The benefit to the Company in Research and Development is a system for the design and simulated testing of new drills, allowing a greater range of parameters to be evaluated more quickly. Associates Three and Four will be the focus of an investigation into more flexible manufacturing.

At the same time Aston University has increased its understanding of the theory and practice of metal cutting and has gained inside knowledge of Drill Manufacture.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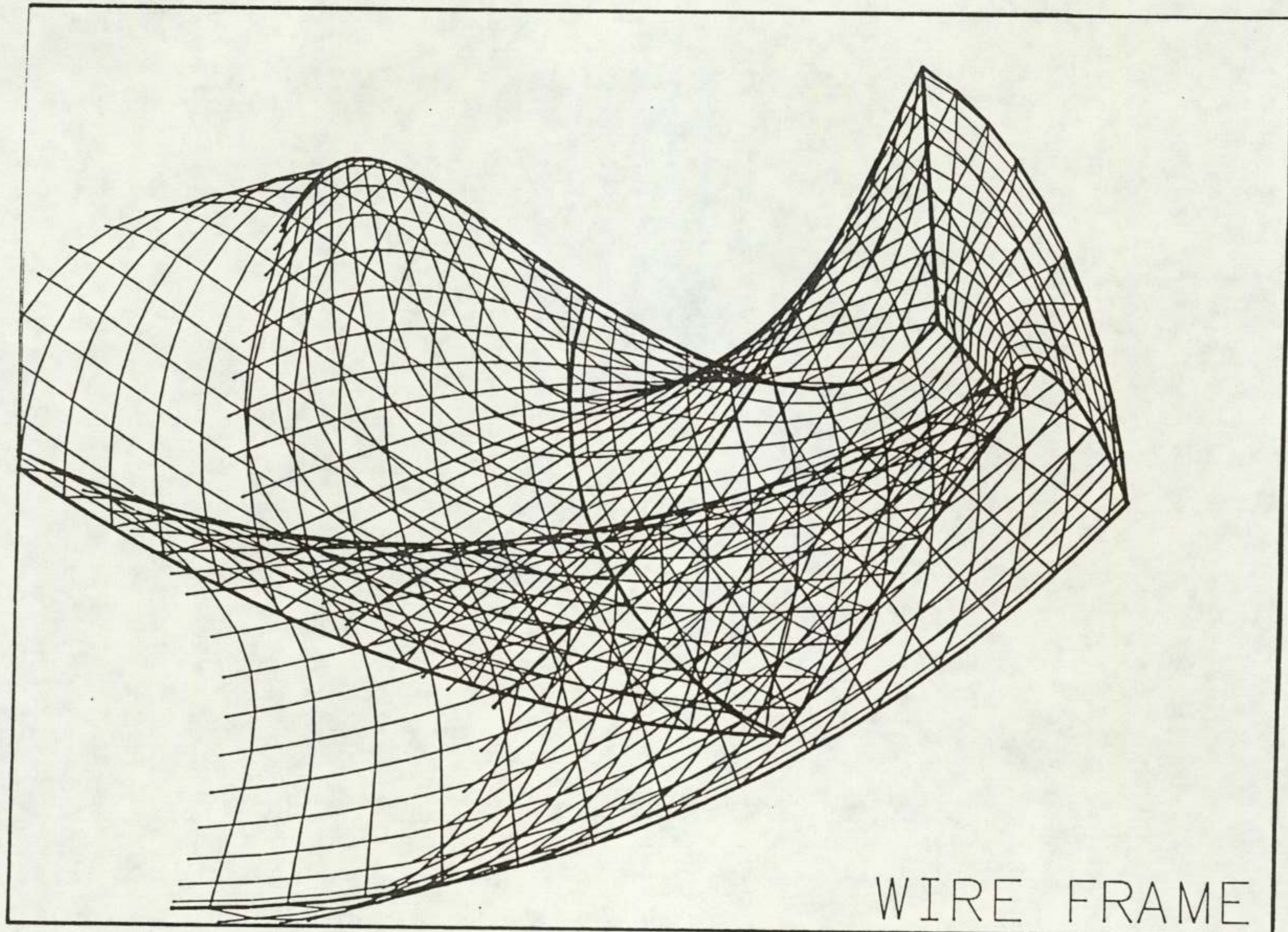
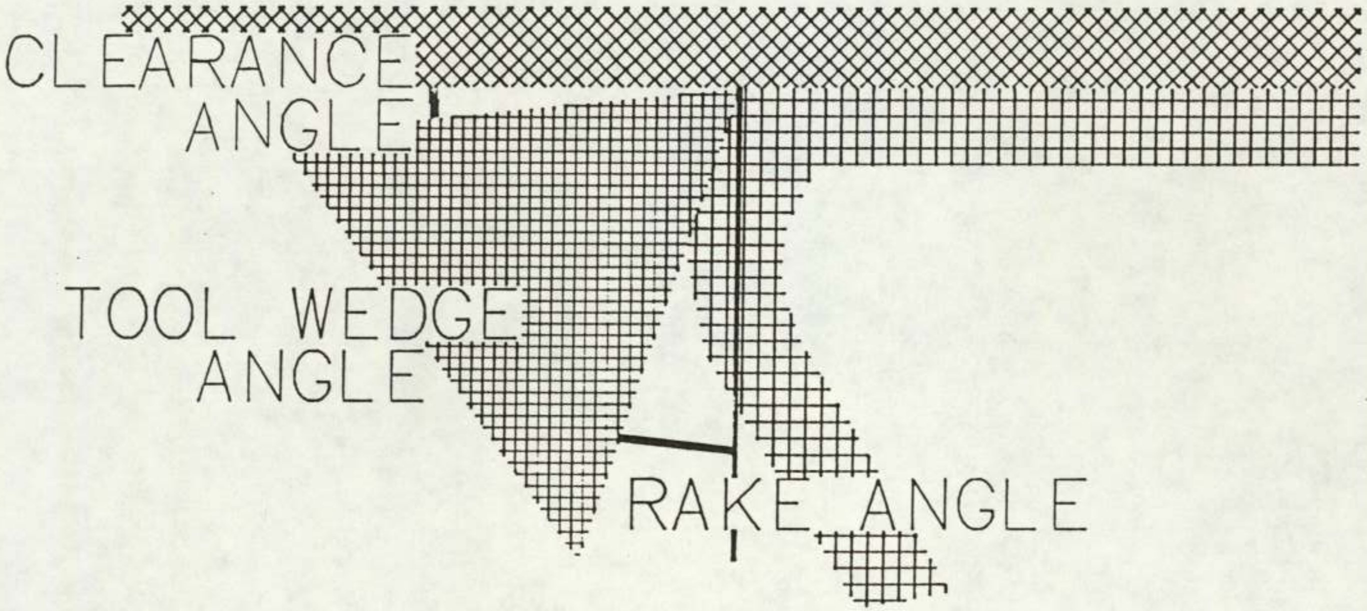

WIRE FRAME

METAL CUTTING



LATHE CUTTING

SKF & Dormer Tools

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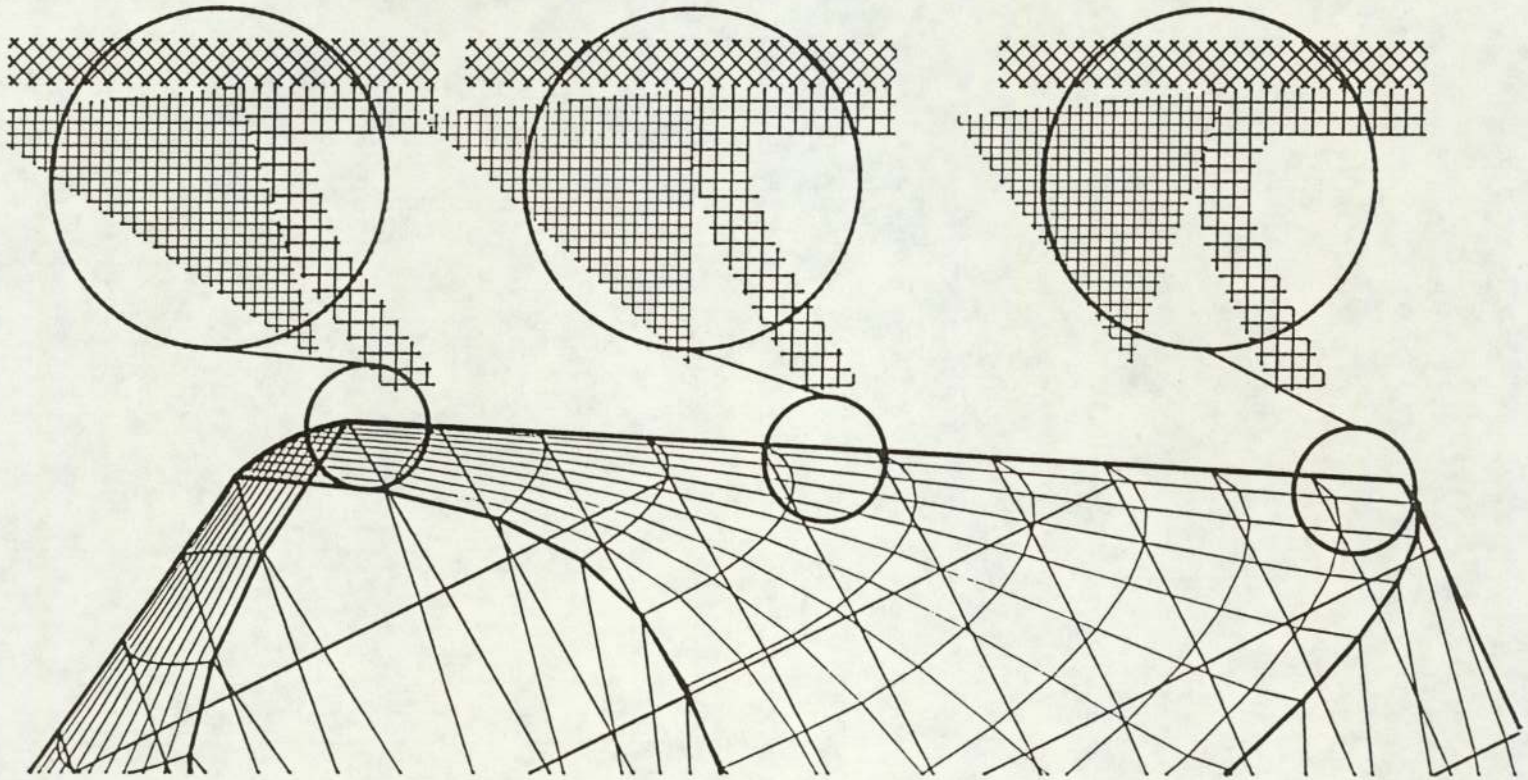
METAL CUTTING



SKF

SKF & Dormer Tools

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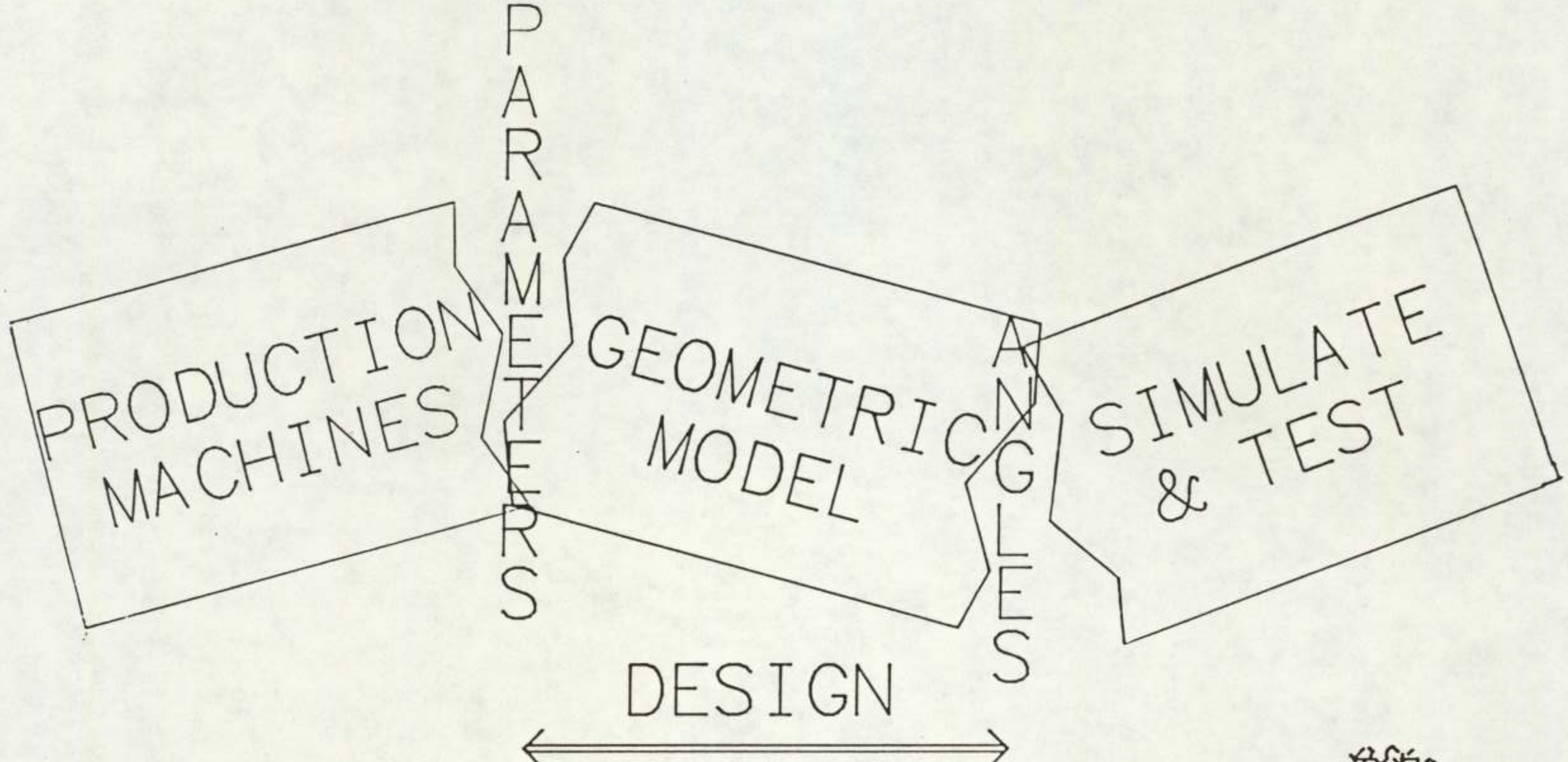
THREE INDIVIDUAL PIECES



SKF & Dormer Tools

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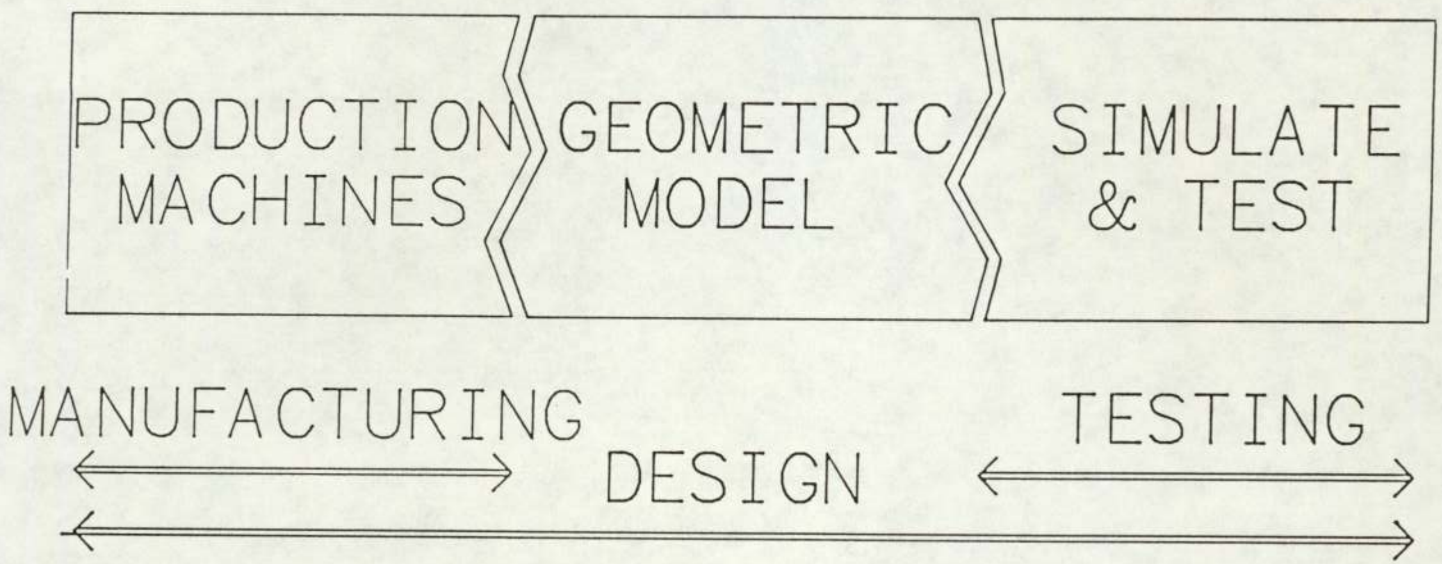
UNIFIED CAE SYSTEM



SKF & Dormer Tools

ASTON UNIVERSITY

BENEFITS

Pre Manufacture

- Visualisation
- Analysis of Performance

Manufacturing

- Machine Set-Up
- Route/Method

Improved Design

Understanding

SKF & Dormer Tools

ASTON UNIVERSITY

THE INFLUENCE OF TWIST DRILL DESIGN

ON RIGIDITY AND CHIP DISPOSAL

RHONA ELSBETH LEADBETTER

Master of Philosophy

<u>TWIST DRILL DESIGN FOR COMPETITIVENESS</u>

THE UNIVERSITY OF ASTON IN BIRMINGHAM

September 1993

TWIST DRILL DESIGN FOR COMPETITIVENESS - A CASE STUDY

by Rhona Leadbetter and Michael McColl

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TCS SEMINAR 23rd JUNE 1993

ABSTRACT

The implementation of concurrent engineering methods and CAE to the manufacturing industry plays a critical role in a company's competitiveness. The resultant reduction in development and testing, the major part of product cycle time, reduces the cost of the entire design process.

This paper describes how a TCS has successfully implemented a CAE system, using concurrent engineering methodology, to facilitate the design and manufacture of twist drills. Using a dimension driven CAD drill modelling program as a platform, several modules were added to carry out performance predictions. This included linking up to a commercial drawing, AUTOCAD, and a commercial Finite Element Analysis package, ANSYS.

As a result of this TCS, the total development and prototype manufacture time for a new product is being reduced from 1-2 years, to 4-6 months. This is partially a result of the manufacturing aspect of design being considered at the beginning of the design process, when creating a design specification. The result is a realistic design proposal with a much shorter lead-time.

In this paper, a case study demonstrates how the CAE system is used to develop a new product. A Deep Hole Drill (DHD) was designed and manufactured, fulfilling the requirements set in the design specification by a group of design and manufacturing engineers. The TCS drill was tested for its ability to perform as a DHD, together with three competitor drills from the same application group. The results from the tests show the new design out performs the other drills in one of the main performance criteria of deep hole drilling, the dimensional accuracy of the holes.

1. INTRODUCTION

In order to be competitive, a company must deliver innovative products of a high quality and reliability, in the shortest time and for the lowest cost **[1]**. As the major part of product cost is estimated to be committed at the design stage, substantially reducing the amount of development and testing time can give a manufacturer the leading edge. With the aim of getting it 'right first-time', it becomes essential for design and manufacturing engineers to collaborate throughout the design process. The term "concurrent engineering" (also known as "simultaneous engineering") has been introduced as a methodology based on the need for Design For Manufacture **[2]** and is concerned with reducing development times and cutting costs in order to improve competitiveness in the manufacturing industry. By encouraging manufacturing to contribute at the earlier stages of design, problems likely to occur during manufacturing can be prevented and the product's suitability to automation can be enhanced. This broader view of design also involves other parties in the design process, including quality control, marketing and, ultimately, the customer.

The work described in this paper was carried out under a Teaching Company Scheme run jointly by Aston University and Dormer Tools Ltd. Michael McColl, currently a TCA, is a production engineer and Rhona Leadbetter, an ex-TCA, is a design engineer. The main objective of the scheme is to implement a Computer Aided Engineering (CAE) system within the company, using concurrent engineering methods to facilitate the design and manufacture of twist drills **[3]**. For the company to maintain its position as market leader, the development and manufacture of successful drill designs must be carried out quicker and at a reduced cost. A case study describing the application of the CAE system to the design and manufacture of a Deep Hole Drill (DHD) is presented in this paper.

2. DESIGN PROCESS

The design process must be systematically planned and executed if it is to be efficient and successful. The implementation of concurrent engineering methodology introduces many more variables and persons that require organisation, emphasising the need for communication and control. A systematic approach to design is best executed by breaking down the design process into phases and steps, and having regular reviews to assess progress. Two major stages of the design process are task clarification and development / testing. An approach to both stages used by the TCS and implemented at Dormer Tools is discussed here.

2.1 Design Specification

It is widely recognised that the beginning of the design process, the design specification, is given insufficient time and thought. By involving all parties from the very beginning, to contemplate the problem to be solved, and complete a relatively simple task of preparing the product specification, future time-consuming problems may be avoided.

A design specification basically involves the determination of critical requirements of the future product. A detailed list of those demands that must be fulfilled **[1]**, should aim to;

- Quantify the requirements wherever possible, into tangible amounts
- Identify the requirements in terms of essential demands and less important desires
- Determine the source of requirement for clarification and relativity.

Once the product design specification is agreed upon, it needs to be approved by the entire product design team before any further progress is made. One aim of concurrent engineering is to facilitate the process of reviewing and updating the specification at regular intervals after this point.

2.2 Computer Aided Engineering

Although the concept 'concurrent engineering' predates the introduction of computers, the combination of CAE and concurrent engineering is the future key to competitiveness in manufacturing. The use of computer aided techniques speeds up the design process considerably, and as software becomes more affordable, product development costs can be considerably cut. Communication between design and manufacture has been much improved due to Computer Integrated Manufacturing (CIM) systems, with CAD/CAM systems providing a link directly from design to production.

To adequately support concurrent engineering, a CAD/CAM system must move beyond simple geometric definition of a product. Concurrent engineering environments require sophisticated, unambiguous product information to be distributed to all engineering functions. Traditionally, CAD systems have worked with entities such as lines, circles and surfaces which had to be altered appropriately to produce a given dimension on a product. When dealing with a complex geometrical shape (such as a drill) this is a near-impossible task. Dimension Driven Geometry systems **[4,5]** use modelling methods that automatically translate dimensional changes into geometric changes.

The major difference between an ordinary CAD system and one based on variational geometry lies in how dimensions are treated. In an ordinary CAD system, dimensions are subordinate to geometry, whereas in variational geometry this relationship is reversed. Hence, systems based on variational geometry have also been called dimension driven systems (DDG). When creating a part in an ordinary CAD system the user defines the model geometry which in turn determines the values of the dimensions. If changes in the dimensions are required it is necessary to erase part, or all, of the model and create it again with the new dimensions; this can be a cumbersome and costly process.

In a variational geometry based system, the relationship between dimensions and geometry is reversed, the geometry is derived from the dimensions. Changes in the dimensions can be made directly, and the new geometry is automatically computed without a complete rebuilding of the model. The process of selecting new values for dimensions, and automatically creating a corresponding new model to match, is called re-dimensioning.

Another feature required by the design process within CAD/CAM systems is the need for possible links to other design tools. This can be, for example, a drafting tool, such as AUTOCAD, or an Finite Element Analysis tool, such as ANSYS. In the drive to reduce development times, and with more engineers carrying out their own analyses, such tools can be vital assets, with the benefits outweighing the disadvantage of the high initial investment costs.

3. DRILL DESIGN

The design of a standard twist drill (Figure 1) still closely resembles the original drill design as patented in 1863. Since then, however, many improvements have been made in twist drill design, producing numerous designs for the wide range of applications in which drills are presently used. Some of the most important changes have been the introduction of point modifications, oil-coolant holes, improved tool materials and coatings **[6]**.

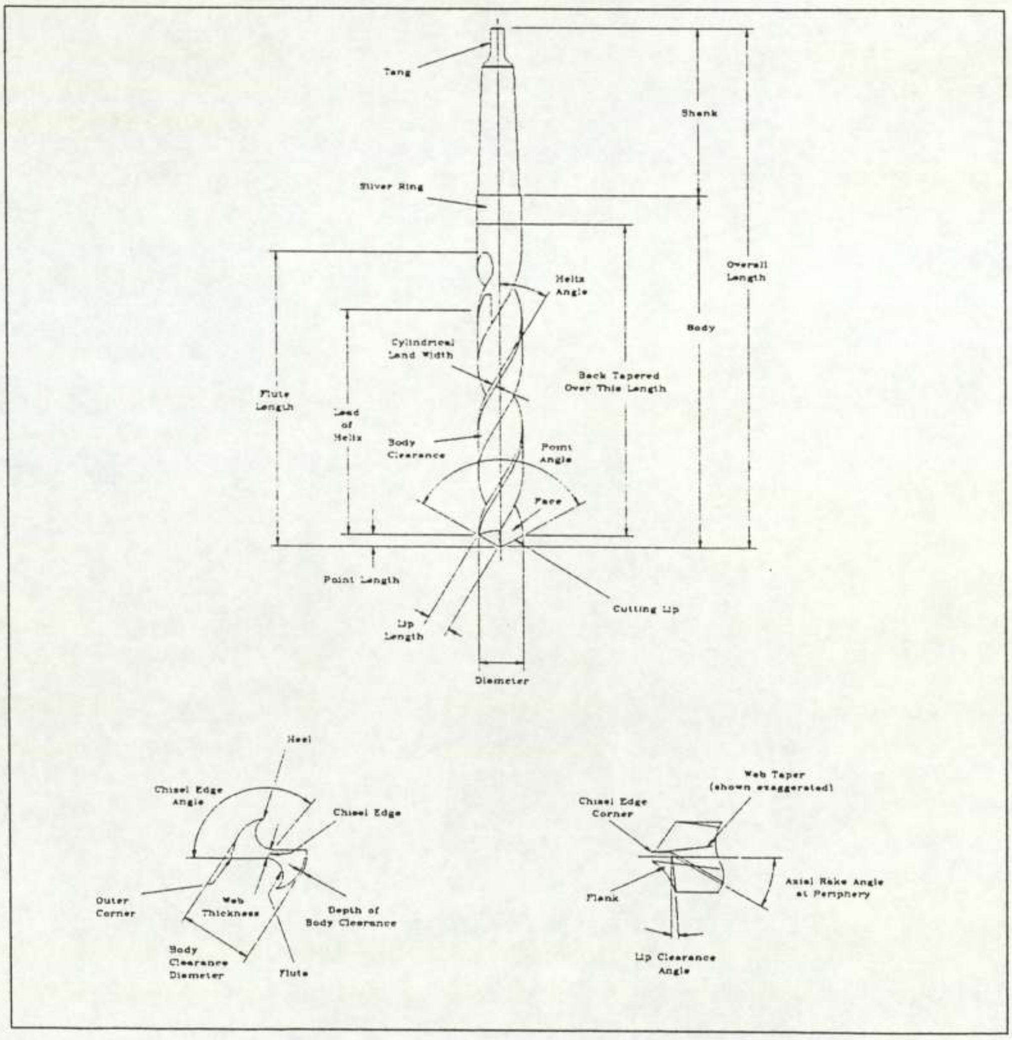

Figure 1: Standard Drill Nomenclature

Historically, the design of drills has been based on years of experience and was considered to be somewhat of a 'Black Art', with little or no use of logical analytical methods within the design process. The main reason for this being the complexity of the drill's design due to the various interdependent geometric features. When examining the performance of a twist drill is it impossible to vary one of these geometric parameters without affecting another. It is therefore a very demanding task to assess the influence of a design parameter on a drill's performance, and subsequently make logical design improvements. The development of drill design over the years has therefore been evolutionary, in the sense that many of today's designs are the result of extensive trial-and-error experimentation. Those alterations that were found to be beneficial for a given application would be selected and incorporated in future drill designs for that application. A major objective of this TCS has been to introduce a scientific approach to drill design, making use of modern sophisticated, affordable and user-friendly computer software. Not only has CAD been used to describe the complex inter-relationships of drill dimensions, but CAE has also been applied to performance analysis, providing a logical approach to the drill design process.

4. CASE STUDY

4.1 Introduction to Deep Hole Drills

Drilling any type of hole can present problems, such as chip removal, heat generation, hole finish, tool life and other performance criteria. When drilling 'deep' holes (anything deeper than three times diameter) these problems become increasingly critical. The main source of concern with deeper holes is the excavation of chips. If the chips are allowed to clog the flute, the drill will overheat and failure will follow. This problem can be overcome by changing the plane of drilling or by 'pecking', which involves regular removal of the drill from the hole to clear the chips. The design of the drill can also be altered to promote efficient chip disposal, consequently increasing the hole depth achievable in one single pass.

Some general design modifications for successful deep hole drilling are;

- Fast helix angle (typically around 40 degrees) for swift removal of the chips from the cutting edge and increased rigidity, resulting in reduced vibration and consequently a straighter hole.
- Parallel web for increased rigidity, and a constant flute area along the length of the drill to prevent the clogging of chips.
- Point modification to increase positional accuracy and to reduce the thrust force caused by a greater web thickness.
- Parabolic flutes, obtained by rolling the heel on the drill cross-section (see Figure 2).
- Increase the flute area to improve chip transport.

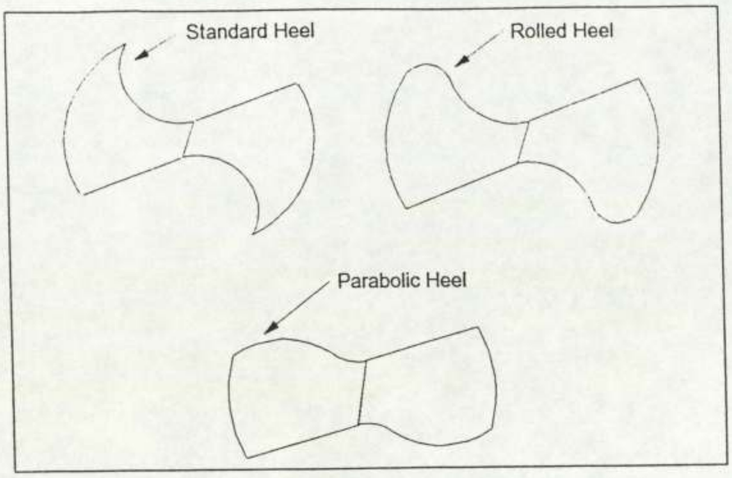

Figure 2: Types of heel

4.2 DHD Design specification

The objective of this TCS exercise was to 'design a deep hole drill to give the greatest straightness of hole at eleven times the diameter in an aluminium alloy without 'pecking'. The drill was specified as having parabolic flutes (a rolled heel), and manufactured using certain designated machines (for ease of manufacture) within a cycle time of six to eight weeks. The measure of the drill's success was to be assessed in comparison to the performance of other drill designs in the same category.

The drill's dimensions were determined in collaboration with manufacturing, and took into consideration the mechanical limitations of the machines to be used. The following dimensions were optimised for ease of manufacturing;

- It had been decided to maximise the helix angle, given the machine available, to 40° degrees.
- The design of the point angle was limited by the point grinding machine to133° with a tolerance band of plus or minus three degrees.
- The flute shape of the new design was considered with regards to the point grinding machine, which required a shape in which the locating pegs of the machine could be correctly positioned within the flute.
- The overall length, flute run-out and cylindrical land were all set according to International standards.
- A range of point modifications was selected to determine the most beneficial point type for DHD applications. Again the mechanical restrictions of the point grinding machine were taken into consideration.

4.3 CAE applied to Deep Hole Drills

Using the information specified above, the CAD drill modelling program created by the TCS was used to determine a drill shape and the corresponding dimensional data. By altering the lip shape and the heel shape, a range of possible design solutions were arrived at and selected for Finite Element Analysis. Using a commercial package,

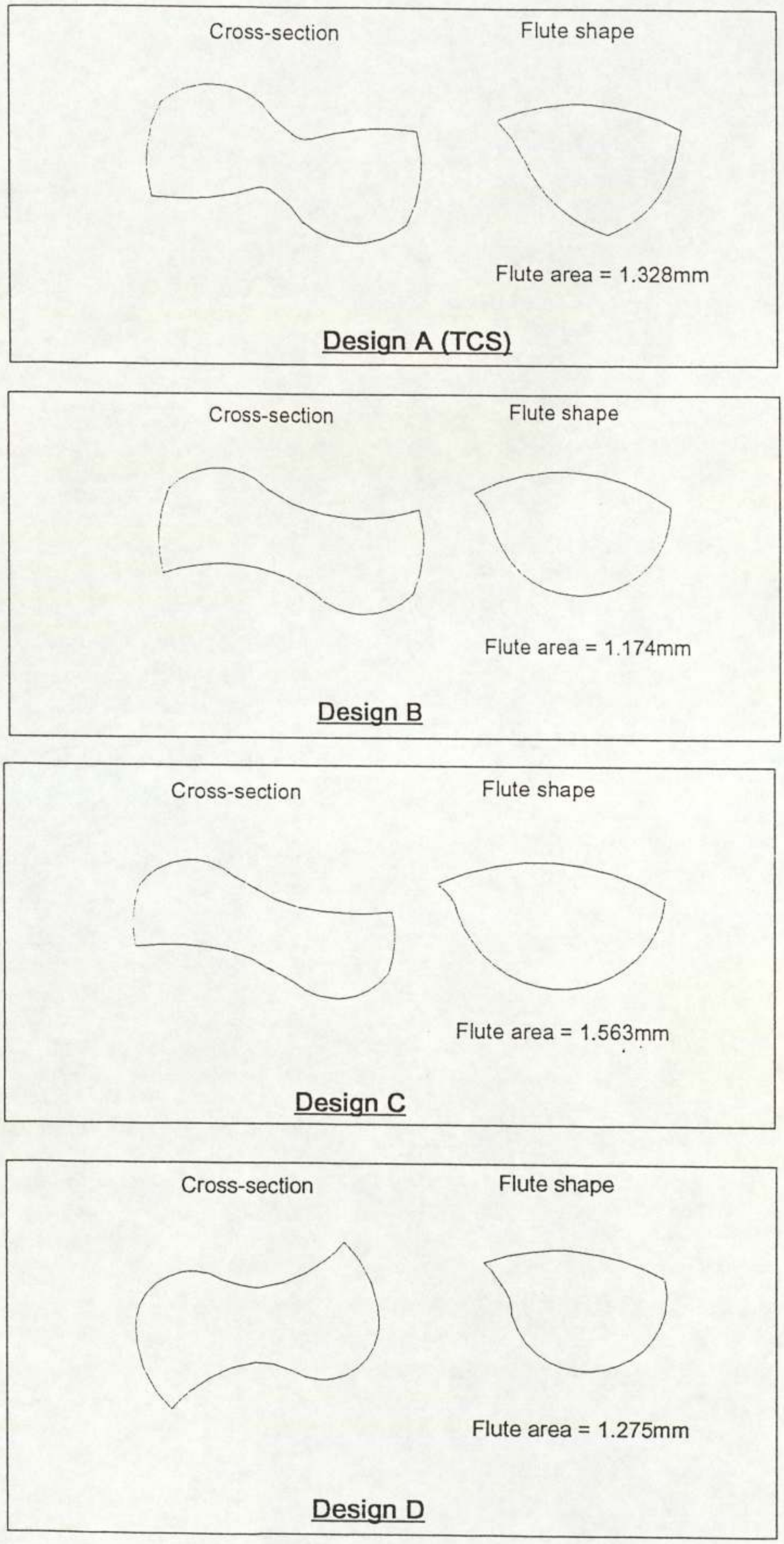

Figure 3: Cross-sectional and Flute area views

ANSYS, a torsional analysis was carried out on the new designs, in order to determine the rolled heel/lip shape combination which would provide maximum rigidity. Selection of a cross-sectional shape is a compromise between maximum flute area for chip disposal and maximum drill cross-sectional area for rigidity.

Once the design has been selected, the CAE system automatically searches for the manufacturing standards to produce a specification for the new design. This information was then prepared along with the set-up data for production and supplied to the machine operator for the manufacture of the TCS DHD.

4.4 Experimental test data

The selected TCS drill design , called A, together with competitors' drills B, C and D, were subjected to flute area comparisons to assess each drill's chip disposal efficiency, which can be seen in Figure 3. The drill design with the greatest flute area was Drill C, Followed by A, C and D.

Similarly the four drills were analysed using FEA to predict their relative torsional rigidity. In order of most to least rigid the drills rated B,D, A and C.

The TCS drill, A, was physically tested for torsional rigidity against the three competitor drills B, C and D, using a purpose built rig at Aston University. The results can be seen in Figure 4, and the order of rigidity corresponds to the order predicted by ANSYS.

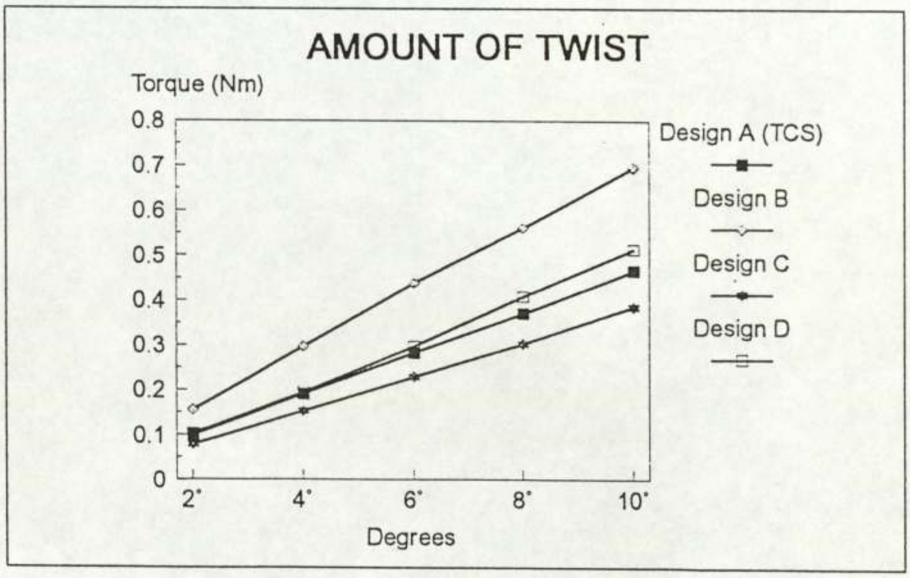

Figure 4: Actual torsional rigidity results

Each hole of the drill is measured for the degree of hole oversizing, the results of which are plotted in Figure 5. The order of the most to least accurate is A, B, D and then C.

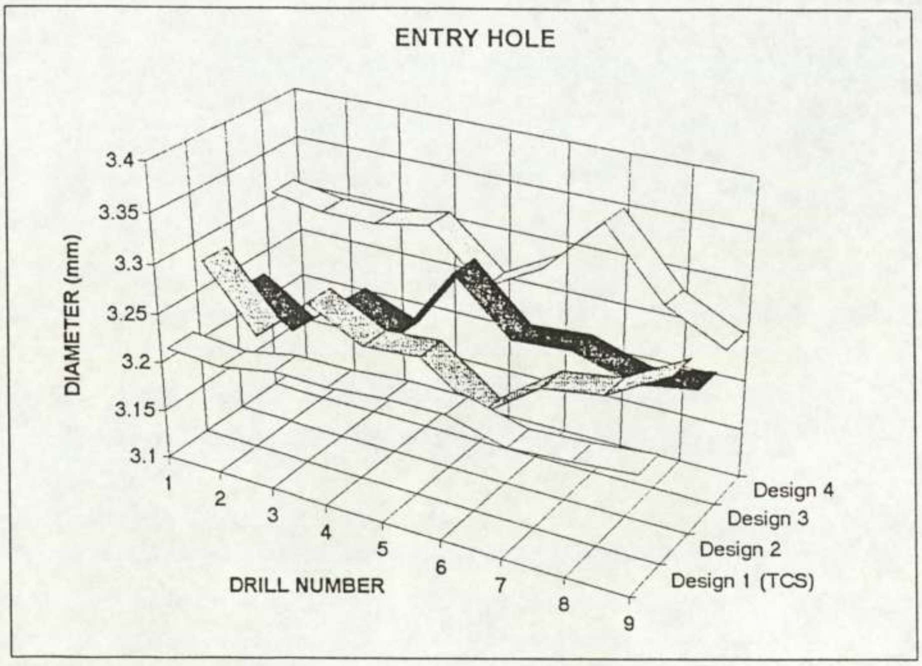

Figure 5: Hole oversizing

Ten holes drilled by each drill, had their entry and exit holes measured. The deviations from the datum were then calculated and plotted. The straightness of the holes, eleven times diameter in depth, drilled by A, B, C and D can be seen in the 'bull's eye' plots in Figure 6. Drill A had the least deviation from the datum, followed by Drill B with a greater accuracy than Drill D, and the least accurate being Drill C.

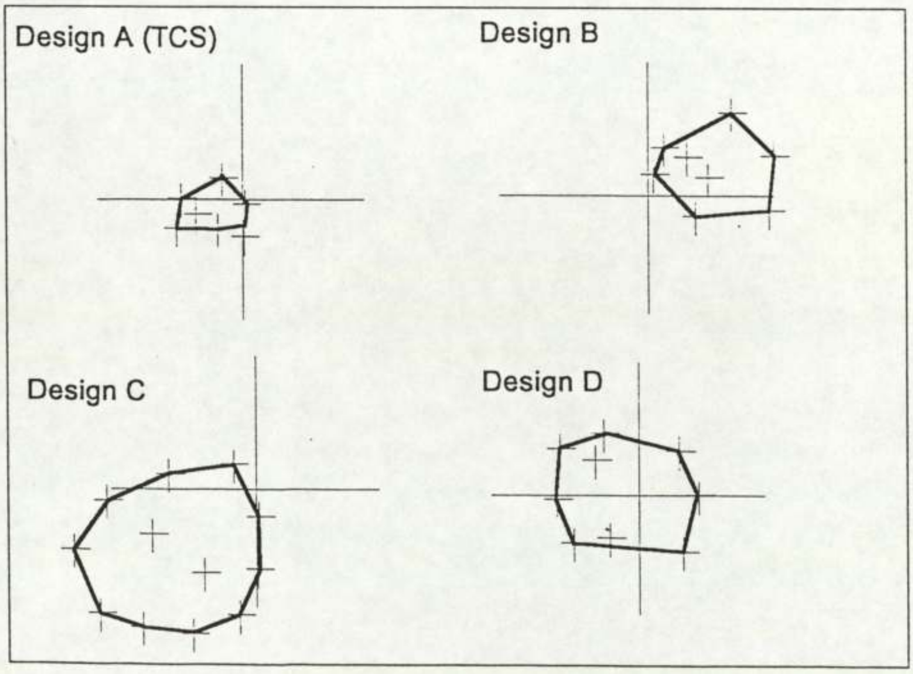

Figure 6: Bull's eye plots - Hole entry

5. DISCUSSION OF RESULTS

Drill A has the best performance in terms of hole straightness and dimensional accuracy. This is possibly a result of the correct balance between the demand for rigidity and chip disposal efficiency. Drill C has, for example the greatest ability to dispose of chips, but is weak in terms of rigidity, and subsequently accuracy. Drill D, on the other hand, is very rigid with little space for chip disposal. This results in the drill becoming clogged with chips, and diminishes the drilling performance of the tool. Drill B performs in a similar manner to Drill A, but is superseded in terms of the required performance criteria, positional and dimensional hole accuracy.

6. CONCLUSIONS

The implementation of concurrent engineering methods and CAE to the manufacturing industry plays a critical role in a company's competitiveness. The resultant reduction in development and testing, the major part of product cycle time, reduces the cost of the entire design process.

A TCS has successfully implemented a CAE system to facilitate the design and manufacture of twist drills. The manufacturing aspect of design has been considered at the beginning of the design process, when creating a design specification. The result is a realistic design proposal with a much shorter lead time. The total development and prototype manufacture time for a new product is being reduced from 1 to 2 years, to 4 to 6 months.

Using the CAE system, a DHD was developed and manufactured that fulfilled the requirements set in the design specification, and resulted in a new drill design that out performed the competitor drills from the category.

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THE INFLUENCE OF TWIST DRILL DESIGN ON RIGIDITY AND CHIP DISPOSAL

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Master of Philosophy

<u>CAE APPLIED TO TWIST DRILLS</u>

THE UNIVERSITY OF ASTON IN BIRMINGHAM

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CAE APPLIED TO TWIST DRILLS

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SUMMARY

As part of an on-going project to implement CAD-CAM techniques to twist drill manufacture, a CAD modelling program was created. Using the CAD Modeller as a platform, the program is being further developed to allow performance predictions to be made in the areas of torque and thrust, chip disposal, rigidity and wear. The aim of this work is to provide a CAE system that can be involved from the initial design stage through to the actual drill manufacture.

INTRODUCTION

A common goal for forward thinking manufacturing companies is the implementation of a successful CAD-CAM (or CAE) system. One measure of the success of a CAE system is the reduction in the time and cost of the design-to-manufacture process, with changes in design being filtered through to production as quickly as possible, with a minimal amount of inconvenience and expense. This reduction in lead time and operating costs allows the company to respond quicker to the demands of the market-place, improving its ability to compete.

Work has been carried out to create a CAE system that will facilitate the design and manufacture of twist drills, as well as allow performance analysis of the drills. Initially a CAD surface modeller is used to create a drill's geometric shape [1]. Using this drill modelling program as a platform, several performance prediction modules are added to permit analysis of various drill designs. The program therefore enters the area of CAE, as a result of its ability to design and predict the performance of the model created. This will enable a range of drill designs to be analyzed, with the aim of assessing the best model to meet a given specification.

The life and performance of a drill are dependant on many aspects of its design. Four main performance criteria have been selected - Torque and Thrust, Chip Removal Efficiency, Torsional Rigidity and Wear (see Figure 1). By predicting the ability of a drill design within each category, a relative estimation of how well and how long a drill is likely to perform can be made.

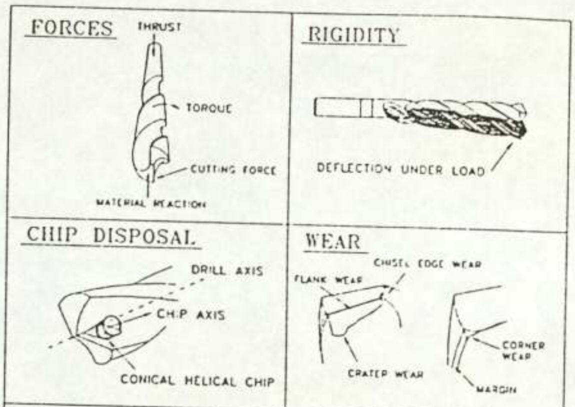

FIGURE 1: PERFORMANCE CRITERIA

This paper consists of two parts, the first describes the development of the performance prediction modules in terms of theoretical and experimental work done as part of this project and an assessment of work done to date by others. The second part is concerned with verifying the output from the modules by comparing predicted performance results to those measured experimentally. The achievements made in the area of performance prediction will be presented, as well as those areas that require further development.

PERFORMANCE PREDICTION

Torque and Thrust

The bulk of research work on forces in metal cutting concentrates on single point cutting tools. Drills, however, are far more complex as they have a varying rake angle and cutting speed across the cutting lip. There is the added complication of the metal removal process that occurs around the centre of the chisel edge which resembles the process of extrusion. This creates a complex three-dimensional situation which is often sub-divided into cutting lip, chisel edge and chisel centre for separate analyses [2]. The cutting edges are often approximated by comparing them to a collection of single point cutting tools, each with a different rake angle.

There are some theorists who have created mathematical equations in an attempt to accurately predict the torque and thrust undergone by the drill during cutting [2,3]. One criticism of most theories is that they are highly complex, and even with the aid of computers are difficult to apply to the modelling of "real" drills (in contrast to theoretical shapes). This results from the difference in drill theory parameters and drill nomenclature used in industry as described previously in [1]. Although it is possible to theoretically model a drill shape, as the input variables for the modelling equations are not the same as the information required to actually manufacture a drill, the modelling of "real" drills is prohibited. Predictions of "real" torque and thrust are therefore similarly restricted. The CAD Modeller used in this work has bridged the gap between the two sets of variables, using iterative routines within the program [1]. This is an essential pre-requisite for realistic performance predictions.

The mathematical equations used by the torque and thrust module on the CAD Modeller were based on fundamental cutting theory. Due to work carried out on a joint project between Aston University and SKF & Dormer Tools Ltd, these basic equations have been modified to include the empirical findings of experimental work. This has greatly enhanced the ability of the module in terms of accurately predicting torque and thrust.

The torque and thrust are calculated at numerous points across the cutting lips and chisel edge, allowing for the extrusion effect at the centre of the chisel. This numerical data is displayed as output from the program and is summed to give the total torque and total thrust undergone by the drill. One requirement of the torque and thrust predictions was that they have to be equal to or greater than the experimental results. This is also known as being consistently upper-bound. The user of the module therefore has the confidence of knowing that, even if the predictions are not accurate, the actual torque and thrust will never exceed those predicted.

The equations that calculate the torque and thrust are work-piece material dependant, and require information about the material to be drilled. The input data, i.e. the material dependant variables, are determined from lathe cutting tests of the material in question. To date, the materials tested at Aston University have been a selection of four of the most common engineering materials - Cast Iron (Grade 150), Mild Steel (080M46), Aluminium (LM5) and Stainless Steel (304515). This information has been used to create a data-bank within the drill program.

Chip Disposal

A drill differs from other cutting tools in that the work it does is carried out within a confined space. This can cause problems for waste disposal where chips that become stuck in the flutes can "choke" the tool when chips fold back on themselves and block the flutes, preventing other chips from escaping. If this situation occurs it is possible that the drill will fracture, possibly causing damage to the work-piece and endangering the safety of the machine operator. It is therefore beneficial to the life and performance of the drill to encourage the swift transportation of chips away from the cutting lips, up the flutes and out of the hole.

The term "chip disposal efficiency" was introduced to quantify the ability of a drill to dispose of swarf [4]. El Wahab presented an equation to assess the chip disposal efficiency using as input the drill's dimensions. The size and shape of the flute area at right angles to the drill axis were used as a measure of the drill's ability to dispose of chips. By placing a best-fit circle in the flute area in the cross-section of a drill, the value of the critical circle diameter was determined for each design (see Figure 2). This circle represented the area filled by the cross-section of a typical drill chip, i.e. of a conical helical form. The size of this circle is seen as proportional to the chip disposal efficiency of the drill.

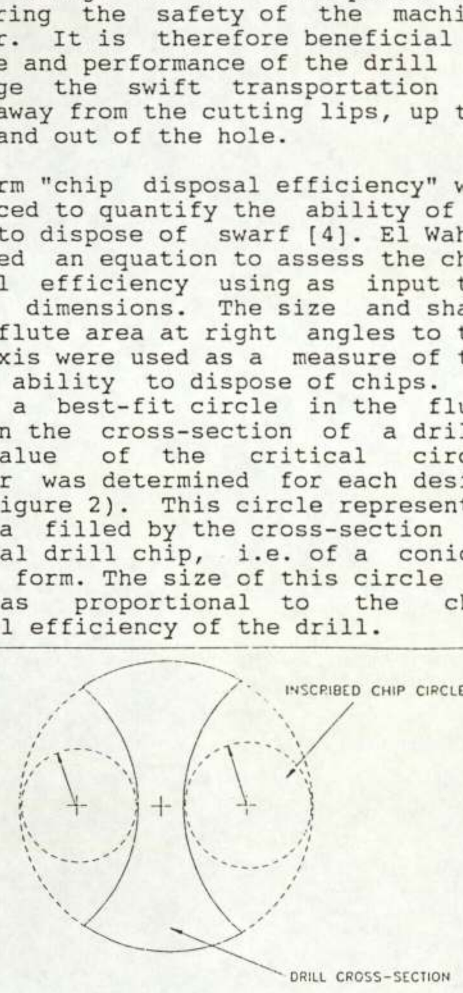

FIGURE 2: EL-WAHAB'S INSCRIBED CIRCLE IN THE FLUTE SPACE

Work carried out in the present project has re-assessed this theory and considers that a conical chip will fill the circular area at right-angles to the chip axis, not the drill axis. The movement of a drill chip up the flute [5], is better approximated by this modification. A module has been linked to the drill modelling program that is capable of determining the area of a circle at right-angles to the chip axis. This was achieved by firstly producing a view of the flute at the correct angle corresponding to the chip axis (or the pipe helix). The outline of the flute shape is then determined in X and Y co-ordinates as a two-dimensional curve, and the best-fit circle for the area under the curve (Figure 3) is calculated using an iterative procedure within the program. Once the angle of view corresponds to the pipe helix, the program provides an output which contains a numerical reading of the total flute area, the radius of the critical circle as well as the matching pipe helix and angle of view. Based on this theory, a relative quantification of the chip disposal efficiency can be made for each drill model.

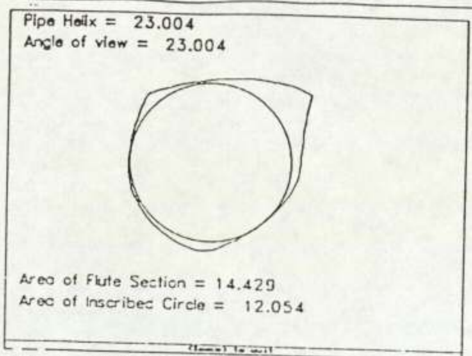

FIGURE 3: INSCRIBED CIRCLE IN MODIFIED FLUTE VIEW

This method of assessing "chip disposal efficiency" is somewhat inadequate, as it is based purely on the geometry of the drill cross-section and does not consider the influence of other geometric features on the chip disposal, such as the helix and point angle and any point modification [1]. The theory is also negligent of non-geometric factors that have a decided effect on the chip disposal process, for example the cutting conditions (feed and speed), lubrication and choice of work-piece material. The theory assumes that the chips produced will be continuous conical chips, a situation normally found when drilling ductile materials, such as Aluminium and most Steels (depending on feed and speed). If this is not the case, however, the theory is the assumption of the inscribed circle diameter is no longer valid, as the chips may be discontinuous and not conical in shape. It is generally believed within the drill industry that the actual shape and overall flute size are of critical influence on the chip disposal efficiency. The success of the wide parabolic flutes commonly seen on Deep Hole Drills cannot be explained by the circle theory, for example. The "inscribed circle theory" is therefore only considered to be an indication of the chip disposal efficiency under limited conditions.

Rigidity

Although the chip disposal efficiency improves by increasing the flute area, this has been shown [4] to have a detrimental effect on the torsional rigidity of the drill. As rigidity is known to greatly influence drill life [6], it is necessary to ensure an optimum is reached between these two conflicting performance criteria. This can be done by assessing each drill model in terms of chip disposal efficiency and torsional rigidity, considering the given application, and determine the combination of design parameters that best satisfy both performance criteria. An example of such an optimisation can be seen in [4].

Several theories postulate that the best way to calculate the torsional rigidity of a drill is from its cross-sectional dimensions [4,6]. This is complicated by the cross-section of a drill being an irregular shape which does not lend itself to conventional methods of torsional analysis. For example, the torsion of a circular prismatic bar is analysed using the second polar moment of area, J, of the cross-section of that bar. Along similar lines, approximations of the drill shape have been made that involve inscribing circles in the drill cross-section and using these as a measure of rigidity [6]. The drill shape has also been approximated as an ellipse [7] to facilitate torsional analysis. Such approximations are howver very crude. A more suitable approach in the case of irregular cross-sections, is use of the membrane analogy as developed by Prandtl [7]. Work is on-going as part of this project to introduce Finite Element Analysis (FEA) to this problem, and investigate how the cross-sectional area of the drill can be used as an accurate indicator of its torsional rigidity.

One criticism of all the above methods of examining torsional rigidity is that they take an over-simplified approach. The drill cannot correctly be approximated by a two-dimensional cross-section as it possesses helical flutes and is therefore not a prismatic bar. Attempts have been made to investigate the influence of the helix angle and point angle [4,7], but all are restricted to studying simple, conventional drill shapes. A more versatile, user-friendly and less laborious approach is therefore to employ three-dimensional FEA. For this piece of work, a commercial FEA package ANSYS, has been installed to examine various aspects of drill rigidity in relation to drill design.

The data required by ANSYS to create a FEA model is provided by the CAD modelling program in the form of the co-ordinates of the drill cross-section. At present, these X-Y co-ordinates are automatically generated by the drill modeller and the data is manually transferred to the FEA pre-processing program. It is anticipated that this data transfer will be automated in the future. Using the graphics facilities within ANSYS, the outline of the cross-section is then extruded and simultaneously rotated to create a three-dimensional model of the drill. ANSYS has the ability to automatically mesh the drill model, i.e. divide it up into a finite number of elements. Boundary conditions are then applied to the model, one end fixed with zero degrees of freedom (as if clamped in a chuck) and the other end loaded with a distributed force along the cutting lips (simulating a situation of pure torsion). The computer then analyses the model, where the solution time is typically about 45 mins. This produces both graphical and numerical results in terms of stresses and displacements. This information can be used to assess the torsional rigidity of each model.

Wear

A drill will cease to function through actual breakage or accumulated wear. It is most common for wear to take place at the outer corners of lip and along the chisel edge. Wear on drills is currently being researched at Aston University as part of this project. The aim is to determine a wear index that will act as a basis for a performance prediction module linked to the CAD Modeller. The wear index will be based on the values of the clearance and rake angles as determined by the geometric drill program, and will take into account the cutting conditions, material properties of the tool and workpiece and the wear mechanisms present.

Initially the intention is to assess the wear rate at the corners of the drill lip as a result of the aforementioned variables. The effect on the torque and thrust due to the amount of wear will also be investigated, by combining the two modules within the drill program. It is anticipated that the study will be extended to include the wear rate across the chisel edge to gain a greater insight into the effect wear has on drill life.

VERIFICATION OF PERFORMANCE PREDICTIONS

In order to verify the predictions made by the drill program, it is necessary to measure the actual performance of a drill within each category and compare results. The experimental methods used to determine torque and thrust, chip disposal efficiency and torsional rigidity are described in the following section. The experimental data from the performance tests is used to build the data-bank of the CAE system and constantly verify and extend its range of prediction (Figure 4).

The dimensions of four test drills are given in Table A. The drills, labelled A, B, C and D, have two variables - the helix angle (fast or slow) and the web thickness (thick or thin). All other dimensions have been kept within bands of manufacturing tolerances. The test drills A, B, C and D are all 3mm diameter, straight lipped, uncoated standard jobber drills.

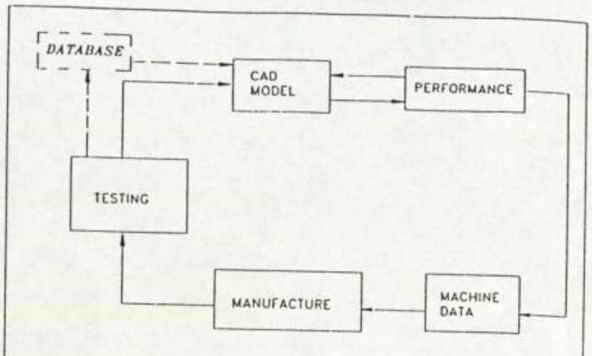

FIGURE 4: CAD/CAM SYSTEM

Torque and Thrust

Much experimental torque and thrust measurement has been carried out to verify this performance module. Drills have been tested with a variety of diameters, lip shapes (curved and straight) and surface chemistries (uncoated, nitrided and TiN coated).

The four engineering materials held in the data-bank were drilled. Accelerated cutting conditions as recommended by the manufacturer were used, with a speed of 2735 rpm and feed of 0.078 mm/min. The torque and thrust on the drills are measured by a dynamometer which is mounted in the table of the drilling machine. The signals from the dynamometer are passed to an amplifier and are displayed graphically in wave-form on the screen of an Apple Mackintosh computer. Here they are analyzed by the operator and numerically defined. The margin of error of the dynamometer is estimated to be about 5%.

The predicted and actual torque and thrust results for the drills are graphically displayed for Mild Steel in Figures 5 a and b. There is a difference in magnitudes of the two sets of torque and thrust, however, the graphs show that this difference is less than 20%. Given the complexity of theoretical metal cutting, especially in the case of drilling, predictions that are within 20% are considered to be quite satisfactory. The requirement that all predictions made must be consistently upper-bound has been fulfilled. Equally important is the ability of the prediction module to correctly determine the ranking order in which the drills will perform (Table B), which has also successfully been achieved. These graphs are typical for all four materials.

Chip Disposal

As stated earlier, a critical aspect of

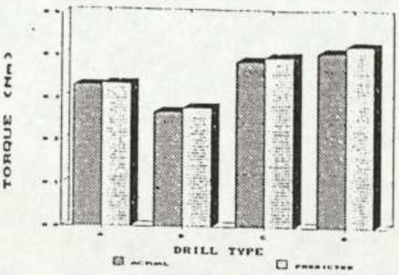

FIGURE 5A: COMPARISONS OF ACTUAL AND PREDICTED TORQUE

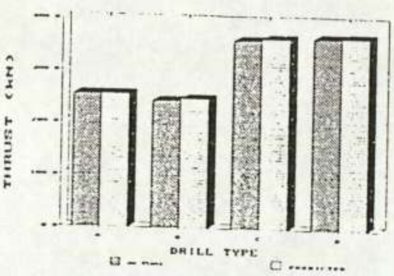

FIGURE 5B: COMPARISONS OF ACTUAL AND PREDICTED THRUST

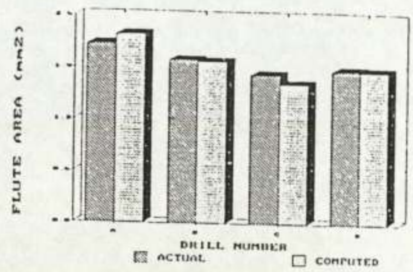

FIGURE 6: COMPARISONS OF ACTUAL AND COMPUTED FLUTE AREA

drill design for efficient chip disposal is the flute size and shape. These can be compared for various drill models using the CAD Modeller's ability to calculate the flute size of the drill cross-section and visual comparison for the shape. In a similar approach to the verification of the model [1], the flute area calculations have also been checked. Figure 6 shows the flute areas as calculated by the computer program for the four test drill cross-sections, compared with the flute areas determined from shadowgraphs of real drill cross-sections. The results are in agreement and therefore verify the accuracy of the flute area calculations.

CAD cross-sections of the four test drills are shown in Figure 7. The flute views (at right angles to the chip axis) with the inscribed circle of critical radius are also shown. The numerical value of this area is given together with the total flute area.The ranking order of size of the inscribed circle (Table B) is the same order as predicted by El Wahab [4]. As may be expected the thin webbed drills are ranked as having a greater capacity for chip disposal.

An experimental measure of a drill's ability to dispose of waste is often stated as the number of holes drilled before failure, either through wear accumulation (normally audibly recognised by the operator as a screeching sound) or fracture. This criteria is also referred to as the life of a drill. The test drills were life-tested on Mild Steel under the same cutting conditions as the torque and thrust experiments. Ten of each drill type were life-tested to eliminate as much experimental error as possible. The Weibull distribution chart from the life test can be seen in Figure 10. The ranking order is displayed in Table B and implies that a fast helix has a beneficial effect on life.

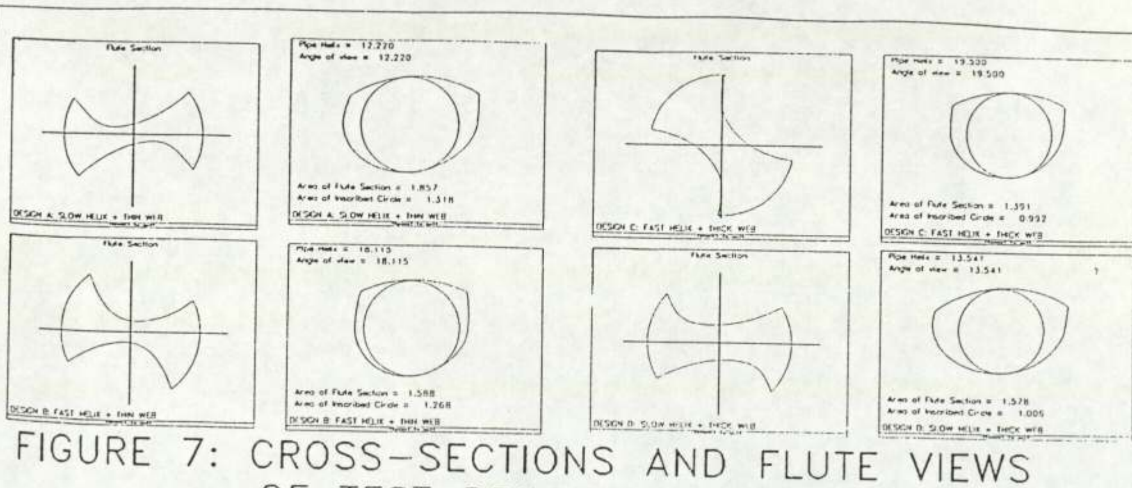

FIGURE 7: CROSS-SECTIONS AND FLUTE VIEWS OF TEST DRILLS A,B,C & D

Rigidity

The maximum displacement of the four test drills when in pure torsion was predicted using FEA. A three-dimensional ANSYS model of Drill A can be seen in Figure 8, where the displaced drill is shown as solid, and the original drill shape as an outline. The value of maximum displacement is given in meters (DMX). The other three drill models were analyzed in an identical way. Table B contains the drills in descending order of predicted maximum displacement.

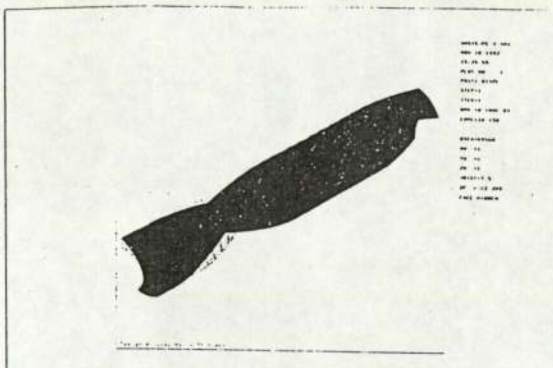

FIGURE 8: F.E.A DISPLACEMENT PLOT

A torsion rig has been constructed at Aston University to experimentally determine torsional rigidity. Each test drill is clamped in a chuck at the shank end, exposing only the fluted portion of the drill. The sharp end of the drill is fitted into a 3mm hole in a thin bar and fixed. The bar is rotated in a direction that simulates the resistive force created when cutting into material. This applies an angular twist along the length of the drill.

The test drills were twisted to a maximum of 8 degrees to prevent any plastic deformation or fracture. The torque was recorded for each twist of 2 degrees through a load cell, amplifier and computer in a similar set-up to the torque and thrust tests. The recorded data had excellent repeatability. The torque versus the angle of twist for the four drills is displayed in Figure 9. The best-fit lines drawn through the points for each drill show the linear relationship between the applied load and the angular displacement as is expected for a material behaving elastically according to Hooke's Law.

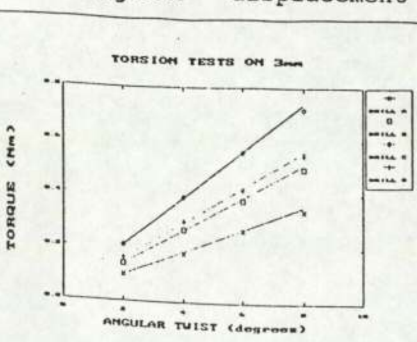

FIGURE 9: TORSIONAL RIGIDITY EXPERIMENTAL RESULTS

The prediction by ANSYS of the most and least rigid drills (C and A, respectively) was confirmed experimentally. There is a difference in the ranking of the two other drills, D and B. The difference in the torque per unit twist for the two drills is only about 10%. Similarly the ANSYS predictions for the two models vary by not more than 10%. It is therefore quite feasible that these two drills are so close in terms of their torsional rigidity that slight error in simulation of experimental conditions has reversed the ranking order. Again the margin of error on the experimental set-up is estimated to be around 5%.

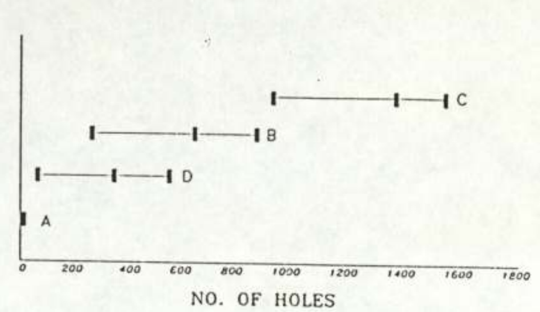

FIGURE 10: LIFE OF TEST DRILLS (WEIBULL DISTRIBUTION)

DRILL TYPE	A	B	C	D
DIMENSIONS	2.997	3.001	2.996	2.999
WEB THICKNESS	0.420	0.456	0.755	0.750
HELIX	21.5	31.4	31.2	21.7
POINT ANGLE	122	119	121	120
CHISEL ANGLE	132	126	126	123
FLUTED LAND	1.589	1.729	1.729	1.734
POINT CLEARANCE	0.2	0.3	0.3	0.4
LIP CLEARANCE	19	13	18	20

TABLE A: DIMENSIONS

RIGIDITY	ACTUAL	C	D	B	A
	PREDICT	C	B	D	A
FLUTE AREA	ACTUAL	A	B	D	C
	PREDICT	A	B	D	C
INSCRIBED CIRCLE AREA	PREDICT	A	B	D	C
TORQUE	ACTUAL	B	A	C	D
	PREDICT	B	A	C	D
THRUST	ACTUAL	B	A	C	D
	PREDICT	B	A	C	D
LIFE	ACTUAL	C	B	D	A

TABLE B: PERFORMANCE CRITERIA TABLE

CONCLUSIONS

A torque and thrust predictor has been developed and successfully mounted on a geometric drill modelling program. The predicted results have been shown to be within 20% of the measured torque and thrust, which is considered to be within acceptable limits, given the complex cutting situation in drilling. The predictions are consistently upper-bound, which ensures the module will never under-estimate a torque or thrust. The order of performance as ranked by the predictions and that of the actual results are the same. This is considered to be more relevant to the user of the CAE system, than identical results. The module has been verified for both uncoated, nitrided and TiN coated drills, as well as those with straight and curved lips.

A modified version of El Wahab's inscribed circle theory has been successfully computerised. The inscribed circle in the flute space can be graphically displayed, together with a numerical reading of the circle area and total flute area. The assumptions made severely limit the conditions under which the theory is considered to be adequate. Work is currently being done to extend the validity of the model to more realistic drilling conditions.

A commercial FEA package has been linked to the CAD system, and sophisticated three-dimensional drill models can be created and analyzed for stresses and displacements. The user can investigate the torsional rigidity of the models, with an estimated margin of error estimated of about 10%. Drills in the lower diameter range and of standard or extended length can be tested for torsional rigidity using a test rig which has been specifically developed and has excellent repeatability.

The order of performance in terms of life cannot be singularly defined from one of the performance criteria considered here, nor is there a straight-forward relationship between the criteria and life. The present procedure employed to assess the best drill design for a given application requires much skill of the system user in analyzing the data presented. It is anticipated that the continued accumulation of such data together with the added input from other performance modules (e.g wear) will assist in working towards accurate life predictions.

However, considering that this is an area where little work has ever been done before (especially in a commercial environment) the results obtained so far are extremely encouraging.

ACKNOWLEDGEMENTS

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SYNOPSIS

A CAD program has been developed to facilitate the design of twist drills. A feature of the system is its ability to accept both the theoretical mathematical parameters used by drill theorists and those used as standard nomenclature in the drill industry. Differences between the theoretical and "real" drills are accounted for. The program presents a variety of views of the three-dimensional drill model and provides relevant numerical information. The CAD program is a platform for a greater CAE system, which is involved from the initial design stage through to manufacture.

1. INTRODUCTION

The twist drill is the most common tool used in manufacturing today. Recent developments in machine tool manufacture and workpiece materials have lead to higher productivity rates and increasingly demanding cutting conditions for drills. Considerable savings could be made to industry by improving the performance of drills in terms of life and efficiency. The performance of a drill is directly affected by its design. An investigation into any aspect of the relationship between design and performance takes a large number of experiments, which are extremely time consuming and expensive. An alternative is to study drills using computers. Any performance predictions to be made firstly require a system that can graphically and accurately create model of the drill. Here we shall examine the creation of such a CAD system for twist drills.

Historically, the design of drills has been based on experience and was considered in many ways a "Black Art", a situation still evident to some extent today. One of the main reasons for this is the complexity of the inter-relationships between the various geometric parameters and the performance of the tool. This is a difficult situation for the drill designer to investigate as it is impossible to alter one geometric design characteristic without affecting other geometric parameters. It is therefore a very demanding task to identify the influence of one single variable.

Much product development down through the years has therefore been evolutionary, in the sense that many of today's designs are the result of a great deal of trial and error experience. If one design feature outperforms another for a specific application, it is selected and incorporated in future versions of that product. Consequeently, this approach makes little use of logical analytical methods which are required to scientifically assess and improve the design and therefore the performance of the drill. As computers become more sophisticated, affordable and user-friendly, analysis of drill designs using scientifically based theories has started to play a greater role in the development of drill designs.

In this paper we will be considering how computers can be applied to help in this process, giving a consistent and logical approach to drill design. One of the major benefits of introducing computers is the possibility to reduce the time it takes for a product to get from the drawing board to production.

The CAD Modeller developed is the platform for a greater CAE system where computers are involved from the initial design stage to the actual production of the tool. This system incorporates three main stages.

1. The creation of a drill shape on the computer in terms of common nomenclature and/or mathematical design parameters.
2. Analysis of this shape to provide performance predictions which permit selection of the optimum design for a given application
3. Instructions and specifications in manufacturing terms to ensure such a drill can be produced.

The success of this system relies on the intimate co-operation between manufacture and design. The intention is to provide the correct information first time round, which will achieve major savings in operating costs. It will therefore be easier and quicker to incorporate the necessary design changes as a result of the feedback cycle around design and manufacture, allowing the CAD/CAM system to continuously improve (see Figure 1).

This paper examines the CAD Modeller and is precedes " CAE applied to twist dills" (1), which deals with predictions of drill performance from the CAE system.

2. TYPES OF CAD MODELLER

The terms Parametric Driven Geometry (PDG) and Dimension Driven Geometry (DDG) refer to modelling methods for automatically translating changes in dimensions into corresponding changes in geometry as stated by Gossard (2).

DDG systems differ from conventional CAD systems in that component geometry can be altered by a change in dimensions. In conventional CAD systems, geometric entities such as surfaces, lines and arcs must be changed first, then the dimensions corrected to match the component shape. Due to the complex nature of a drill shape , a DDG system was adopted to allow drill designers to make the necessary design changes in terms with which they are already familiar.

3. OVERVIEW OF THE CAD MODELLER

The drill design program is written in Turbo Pascal and is implemented on an IBM compatible PC. A user--friendly interface has been written to facilitate its use.

The drill modelling program (see Figure 2) allows two types of data entry . The data input can either be in terms of standard drill nomenclature as stated in British standards 328, or drill design parameters as used by drill theorists , as shown respectively in Figures 3a and 3b. The program uses these design parameters in its mathematical routines to create a unique three-dimensional drill shape, which is stored as a set of X, Y and Z co-ordinates.

Once the drill shape is defined, the user is presented with several options to view various aspects of the drill's shape. These views can be two-dimensional, such as the end and cross-sectional views (see Figure 4a and 4b) or three-dimensional, for example the wire frame drill shape with hidden detail omitted , shown in Figure 5.

4. DEVELOPMENT OF THE CAD MODELLER

The geometric description of the drill shape was developed from the early work of Galloway (3) who used mathematical equations to describe the drill point and from this generate the flute section. These equations were computerised by Fujii et al (4) to produce a visual representation of a drill shape. This was the first real step towards creating a CAD modelling system for twist drills. Several other papers followed describing different approaches to applying computer techniques to the drill modelling problem (5 - 9).

The mathematical equations used in these papers to describe the geometry are based on the movements made during the drill point grinding process. These are not the same as the dimensions commonly used by industry to describe drill geometry. This was a major draw-back to all these models as they were unable to accurately model a "real" drill. The drill models created therefore remained theoretical shapes, rather than drills that could actually be manufactured.

This problem has arisen as a result of drill theorists having adopted a method to model twist drills that is fundamentally different to the manufacturing sequence. A drill manufactured from solid bar, firstly has the flutes ground along its length and is subsequently point-ground. The computer modelling of twist drills , however , has conventionally defined the geometry of the drill point first and then taken the two-dimensional outline at the base of the point to create the three-dimensional drill, using extrusion and simultaneous rotation computer modelling techniques. This difference in approach to create a drill model and to that of actually making a drill, as well as the different geometric terms of drill definition, has prohibited a direct link between design and manufacture.

These differences were bridged by means of two iteration procedures that can accept standard drill nomenclature and iterate towards a solution of corresponding design parameters. This was then applied to Webb's (8) original computer model which was based on a more suitable co-ordinate system derived from galloway's original expressions for defining a drill. It was then possible with this Cartesian co-ordinate system to determine the point shape and the flute contour on the CAD modeller using standard drill nomenclature. Until now, it was not known how these design parameters related to the manufacturing dimensions. The CAD modeller allows us to investigate relationships that were previously too complex to study.

5. DRILL DEFINITION

The mathematical model used in this work can create either straight or curved cutting lips. The user can define the shape of the cutting lip by defining the angles and length of the construction lines fixed to the outer corner and the chisel corner of the lip. By altering the angles it is possible to form several curved lip shapes including "S" curves (see Figure 6). By lengthening the construction lines, the degree of curvature is increased. Once a curved lip has been defined, information becomes available on the position and height of the peak on the curved cutting lip relative to the original straight lip. This information is used when manufacturing curved lip drills.

The trailing edge of a drill is defined by a parabolic curve from the chisel corner to the outer corner of the heel. using this curve it is not only possible to model standard heels of a circular arc, but also to model rolled heels commonly found on deep hole drills with parabolic flutes. The curvature of the trailing edge is not specified by the manufacturing process, but is a result of the grinding wheel shape used in the production of the flute. This section of the drill point does not affect the cutting lip shape and is therefore considered by Fujii et al (4) to be unimportant. It will however have an effect on several aspects of a drills performance such as rigidity and waste disposal capability.

It is well known that the details of the drill point geometry have a significant effect on the performance of a drill. point modifications generally shorten the chisel edge and/or reduce its negative rake angle. the desired effect is to decrease the thrust forces in drilling and improve the centring capability of the drill, as well as promoting better chip ejection and separation (7). A variety of point geometries have evolved , for example, the racon, helicon, radial lip, split and thinned point. Another possibility is the MultiFacet Drill (MFD) which has several cutting edges and planes (6,7).

The CAD modeller has been further developed to allow the user to define the point modification and to observe the effect on performance of different point modifications. Three of the most commonly found point modification have been incorporated into the program. These are the split-point, point-thinned and the double-angled point (see Figure 7). As yet there is no specific way of defining the degree of point modification in each of the three cases, with DIN 1412 only giving a graphical, not numerical, indication. The CAD Modeller expresses the degree to which the point has been modified in each case as a percentage of the length of the cutting lip and chisel width.

Figure 8 demonstrates how a drill model can be point-thinned using the program. Due to the symmetrical nature of the drill point, only half of the end view has been displayed. The user is required to specify the values of X and Y as the value of C is set to a constant. This produces the boundaries of a secondary plane at a set angle to the drill point surface. This secondary plane forms the notch that is seen on point-thinned drills. The splitting of a drill point, as seen in Figure 9, is determined by the values of X1 and X2, which define the position of the secondary plane produced in a point-splitting operation. A similar approach is taken when creating the double point (see Figure 10), in the sense that the radial position Y, at which the secondary point angle commences, is defined by the user.

6. MODELLING FEATURES

It was found when, when using the modelling program, that the theoretical and true chisel angles differ. This is also stated by Fujii et al (3), who claimed that the grinding cone vertex is not on the extension of the cutting lip as assumed by the model. This results from the flute grinding process, where the trailing edge commences before the original starting point A, making the new point A' the chisel corner (see Figure 11a). An alternative hypothesis is that the drill has been rotated during the point grinding process, creating a different angle between the cutting lips (Figure 11b).

This difference is catered for in the model by making it possible to rotate the drill shape, while keeping the chisel edge fixed. The angle between the lip and the chisel edge can then be altered to match the real value.

The position of the outer corner of the theoretical model does not coincide with that of a real drill as the computer does not take body diameter clearance into account (Figure 12). Including body diameter clearance into the model would considerably increase the amount of model co-ordinates and data input, and is considered to be relatively much less influential than changes in point geometry in terms of actual drilling performance. The angle between the two corners is therefore over-estimated, but the difference in size is considered to be insignificant.

7. VERIFICATION

Before any performance analysis can be carried out, it is necessary to verify that the CAD model of the drill is an accurate representation of the "true" drill. This was achieved by comparing the cross-section of the computer-generated drill against that of the true drill. These verification tests were conducted for a variety of drill types, the results of which can be seen in Figure 13.

The true drill cross-section were created by grinding the point off the drill and tracing the outline of the cross-section by means of a shadowgraph. There were two basic differences between the true and computer-generated drill cross-sections:

1. The computer program uses a circular arc to approximate the trailing edge as it is not singularly defined by the design parameters, or by manufacturing data. Therefore the parabolic curve which creates the trailing edge on the computer cross-section may have to be altered to match the actual trailing edge.

2. The drill margin, which is produced as a result of having body clearance diameter, is not present on any drill models. The modelled cross-sections have a maximum diameter around the circumference of the body, in contrast to "true" drill cross-sections that only have maximum drill diameter across the cylindrical lands.

The comparisons of the drill cross-sections show excellent agreement between the true and the computer designed drills. Differences between the theoretical model and the "real" drills have been found and taken into account. Any effect on the accuracy of the model is taken to be negligible. The drill modeller is considered to satisfactorily reproduce a "real" twist drill.

8. CONCLUSION

A CAD model of twist drills has been created using mathematical geometric equations. Various aspects of this three-dimensional drill shape can be viewed on-screen along with precise numerical information about the drill's geometric properties.

The program accepts input in the form of drill design parameters (as used in the mathematical modelling equations) as well as standard drill dimensions (as used in industry). This is a unique feature of the program, which permits examination of the complex relationships between the two sets of variables.

The program allows the user visual and numerical control in defining the shape of both the cutting lip and the trailing edge. Similarly, the user can specify three types of point modification and the extent of the modification.

Differences between the theoretical model and "real" drills have been identified and taken into account. Any effect on the accuracy of the model is considered to be negligible.

This CAD model is the basic platform of a CAE system for performance predictions of twist drill designs. It is continually being developed as the work on the CAE system is on-going.

9. ACKNOWLEDGEMENTS

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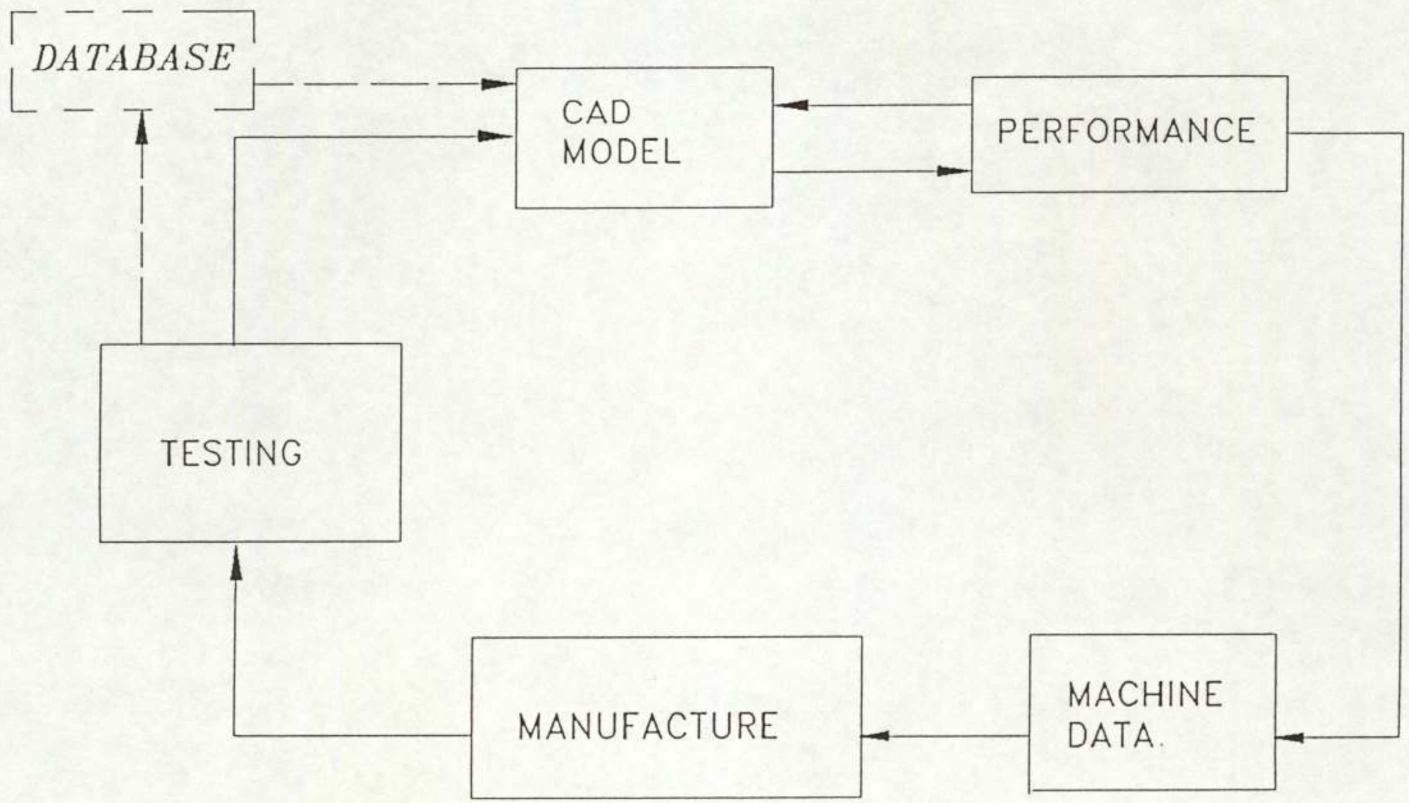


FIGURE 1: CAD/CAM SYSTEM

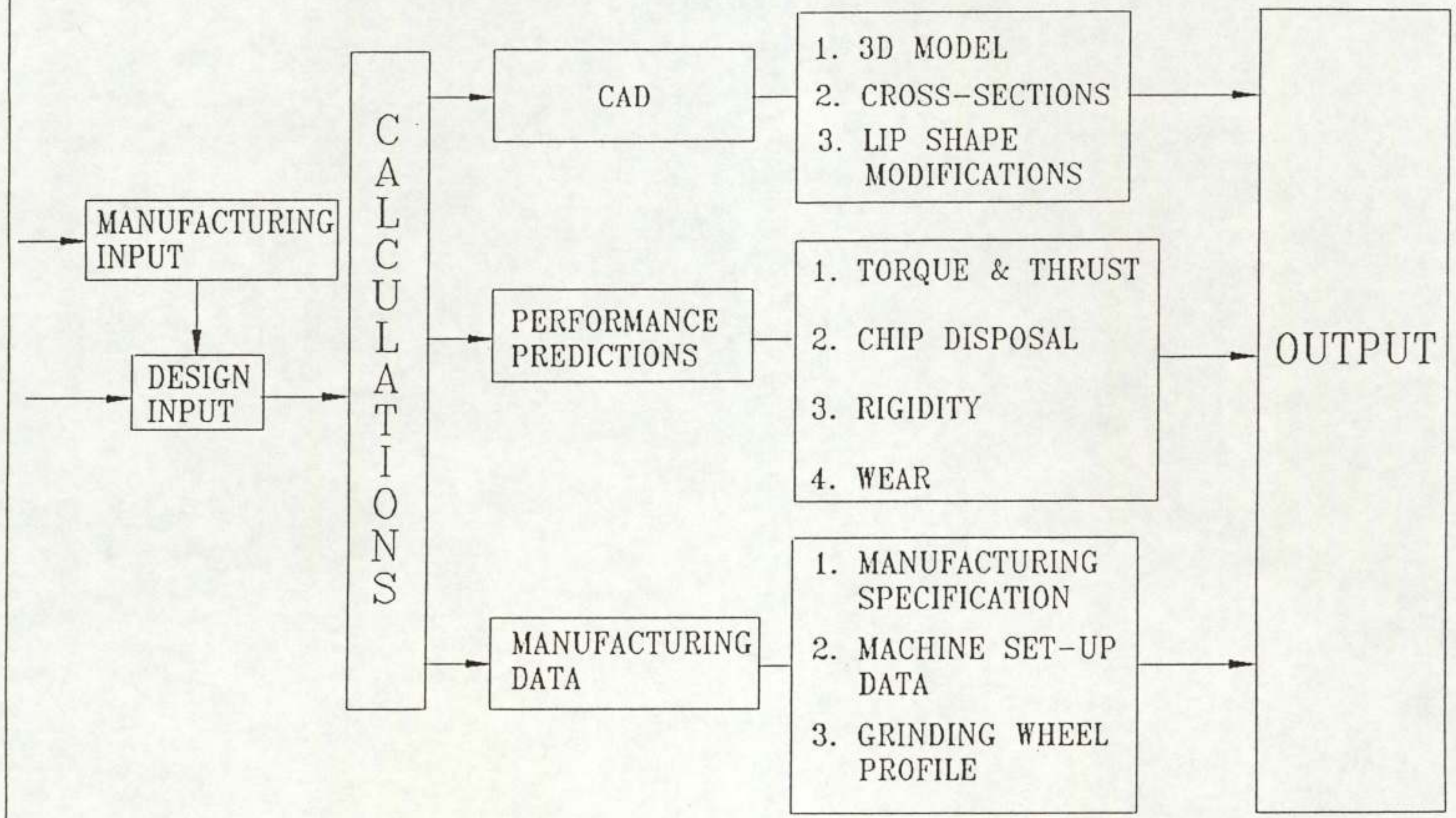
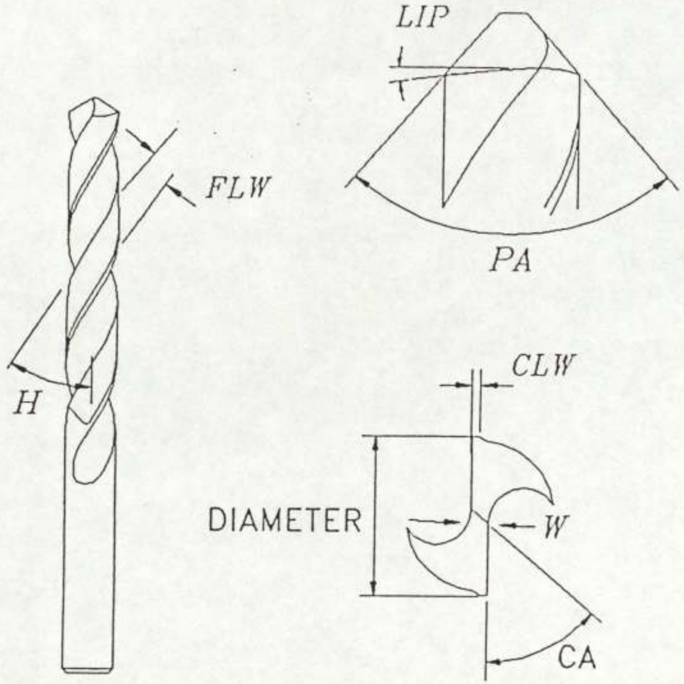
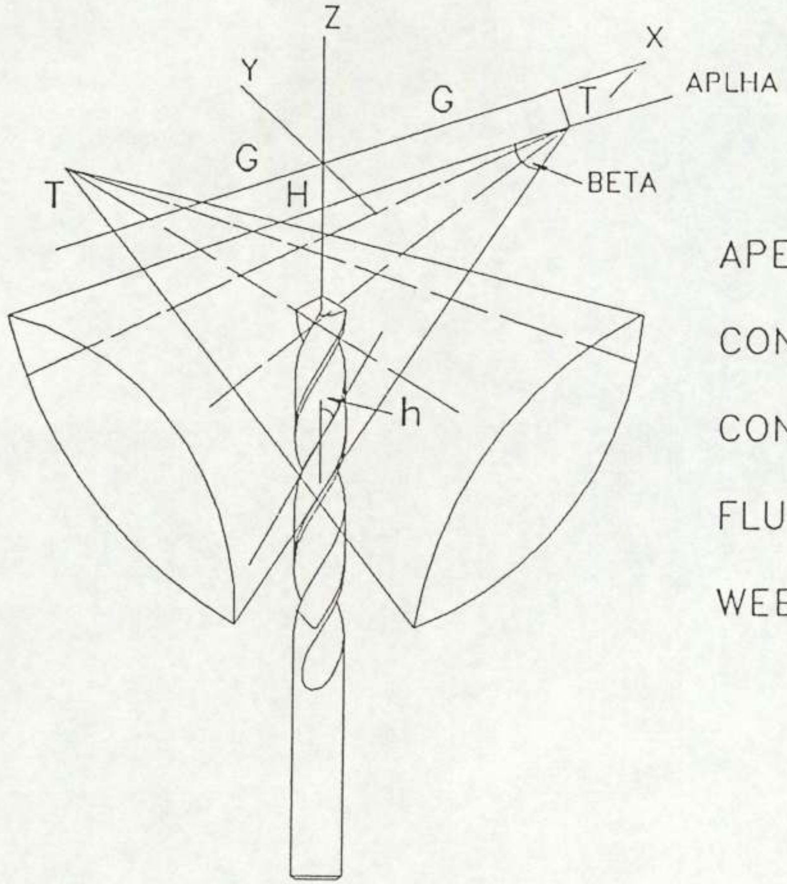


FIGURE 2: TWIST DRILL CAE SYSTEM



WEB THICKNESS W
POINT ANGLE PA
HELIX ANGLE H
CHISEL EDGE ANGLE CA
LIP CLEARANCE LIP
FLUTED LAND WIDTH FLW
CYCLINDRICAL LAND CLW

FIGURE 3A: DRILL NOMENCLATURE



APEX CO-ORDINATES	G,H & T
CONE INCLINATION	ALPHA
CONE SEMI-ANGLE	BETA
FLUTE ANGLE	h
WEB POINT PARAMETER	W

FIGURE 3B: DRILL DESIGN PARAMETERS

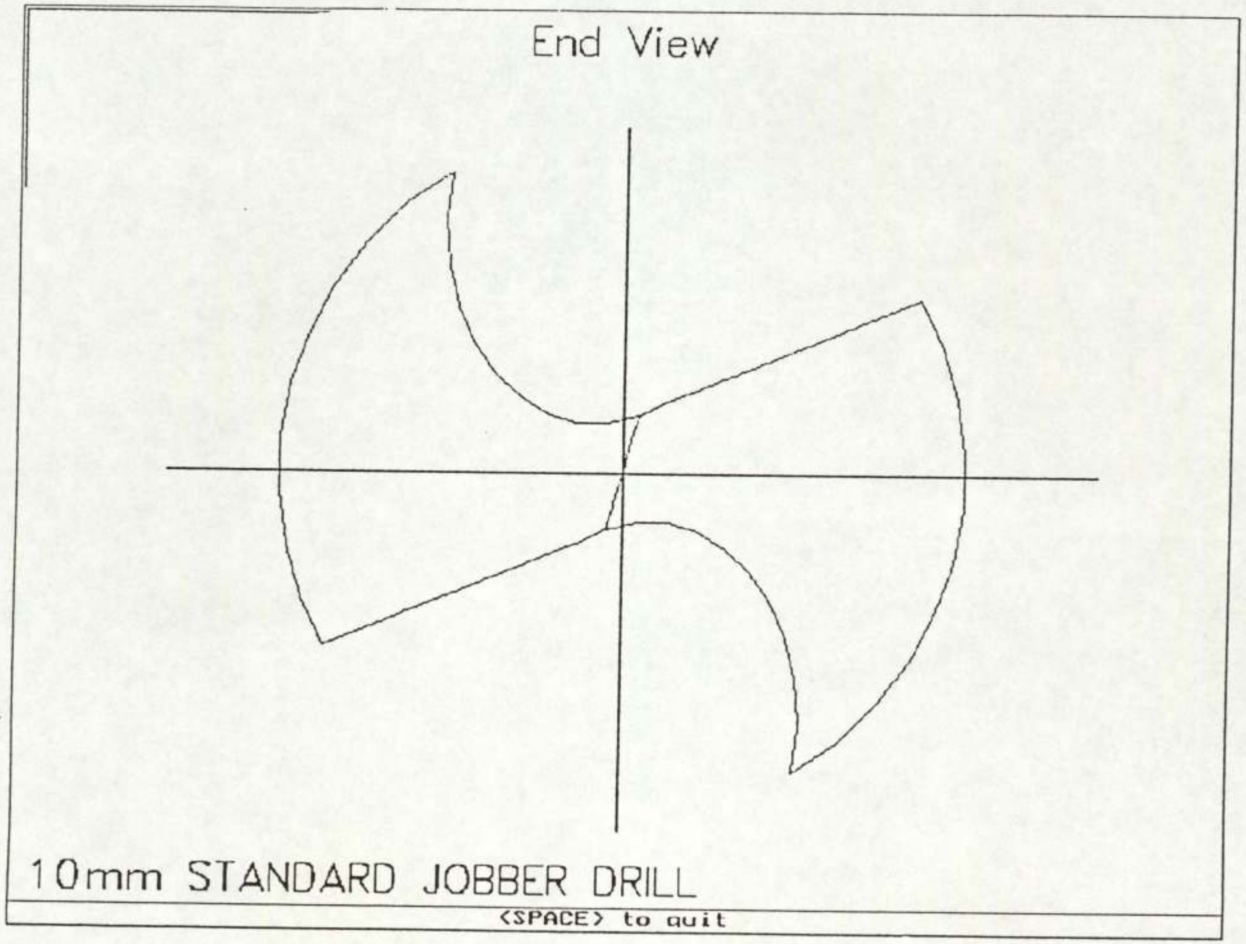


FIGURE 4A: POINT VIEW

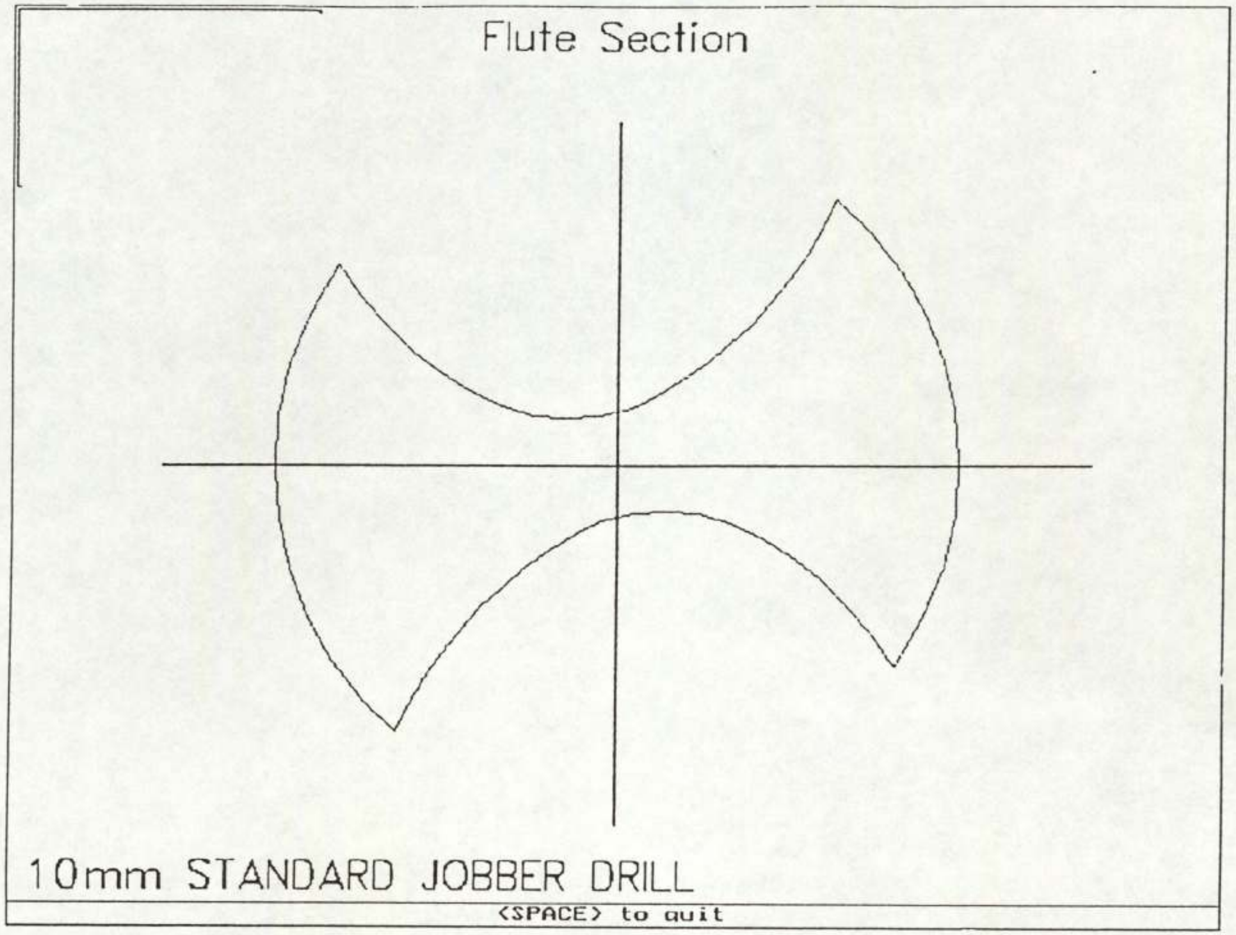


FIGURE 4B: CROSS-SECTIONAL VIEW

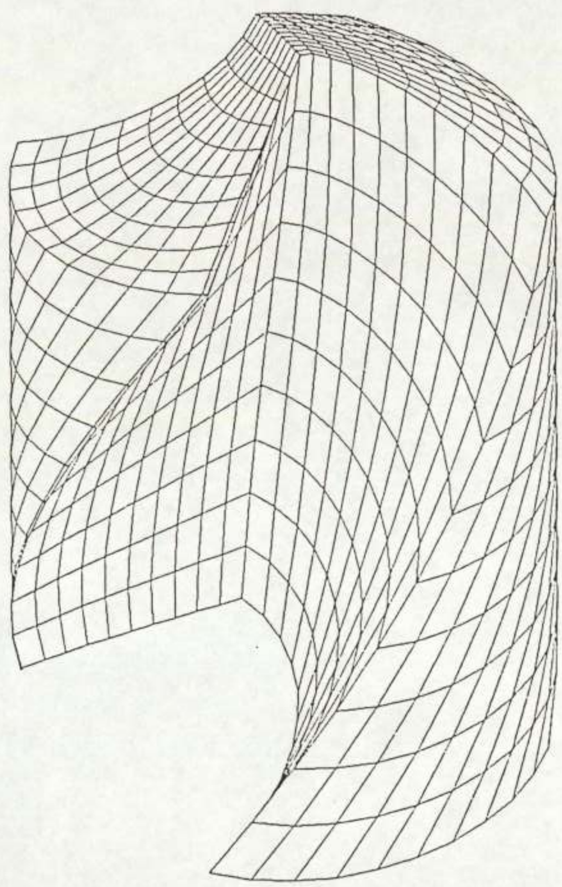


FIGURE 5: 3-D WIREFRAME MODEL

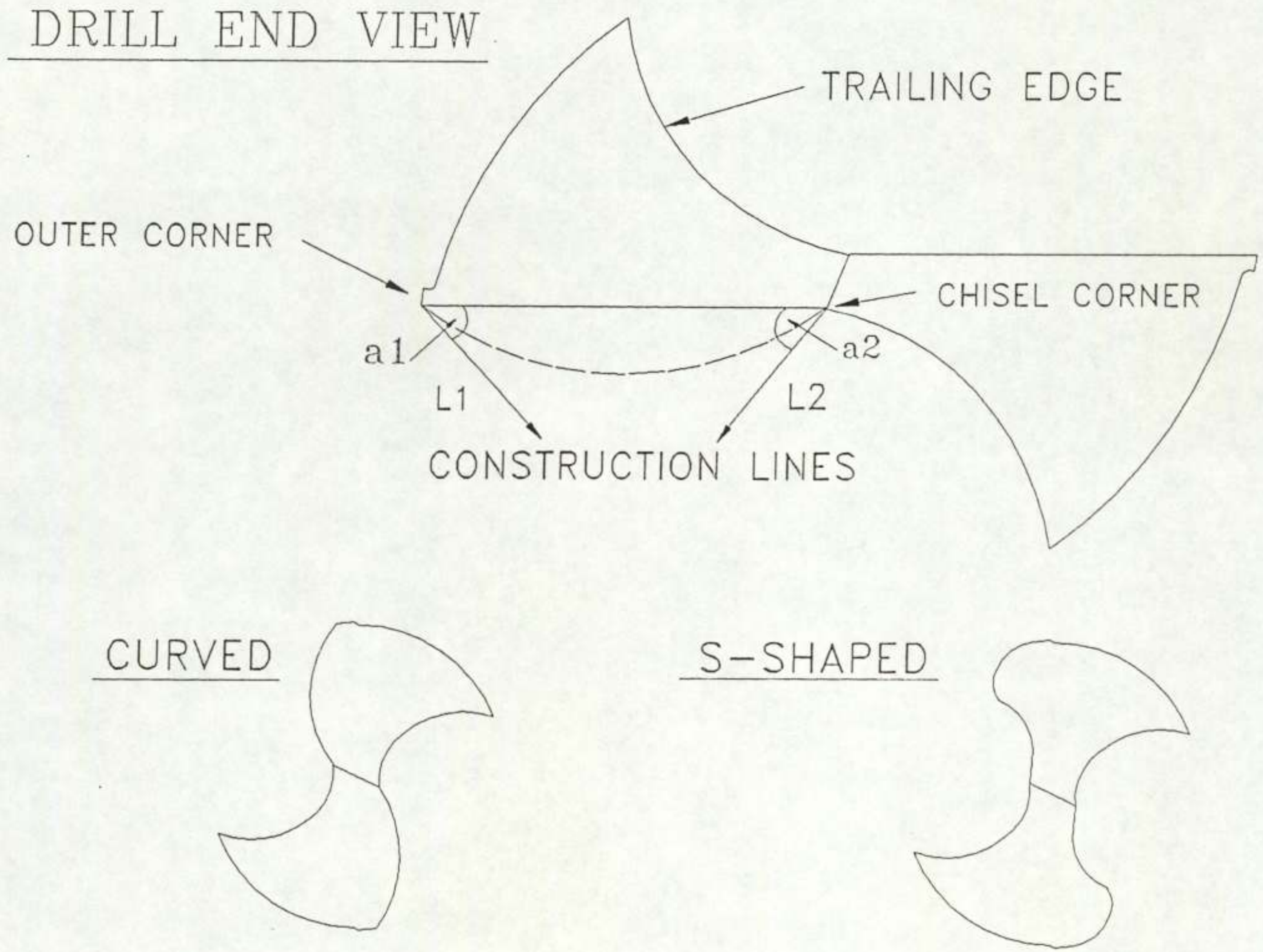


FIGURE 6: LIP SHAPE MODIFICATION

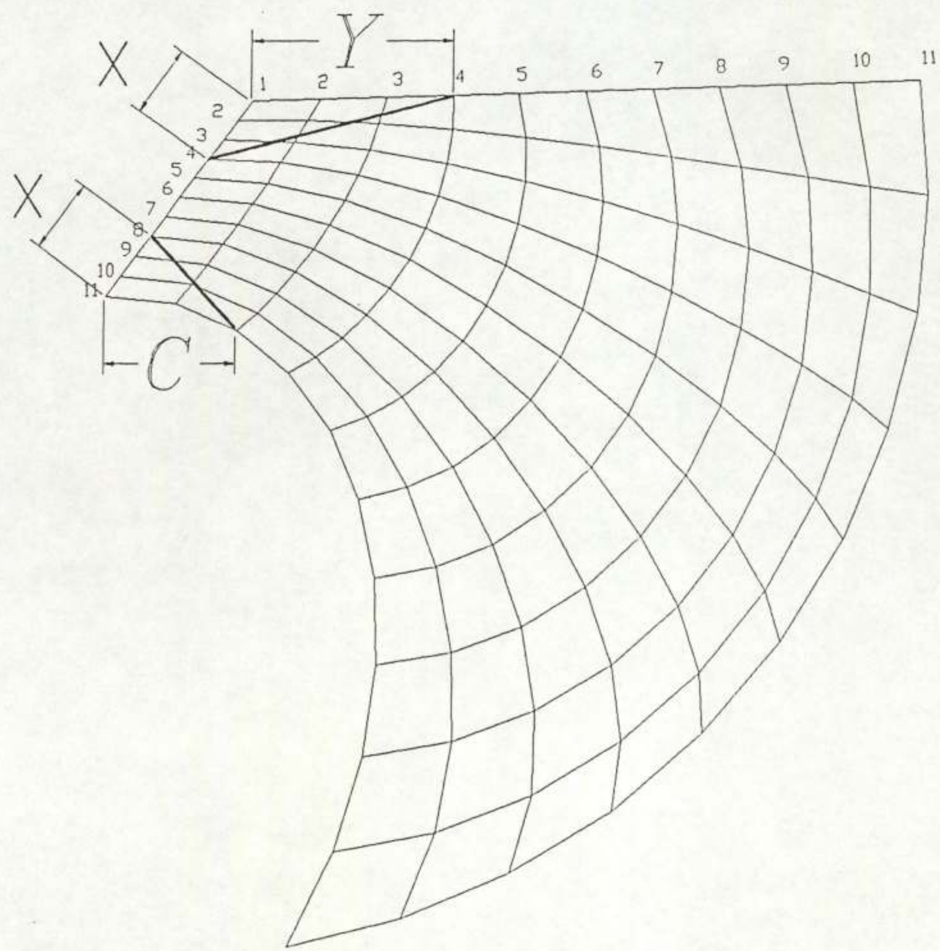


FIGURE 8: POINT MODIFICATION — POINT THINNING

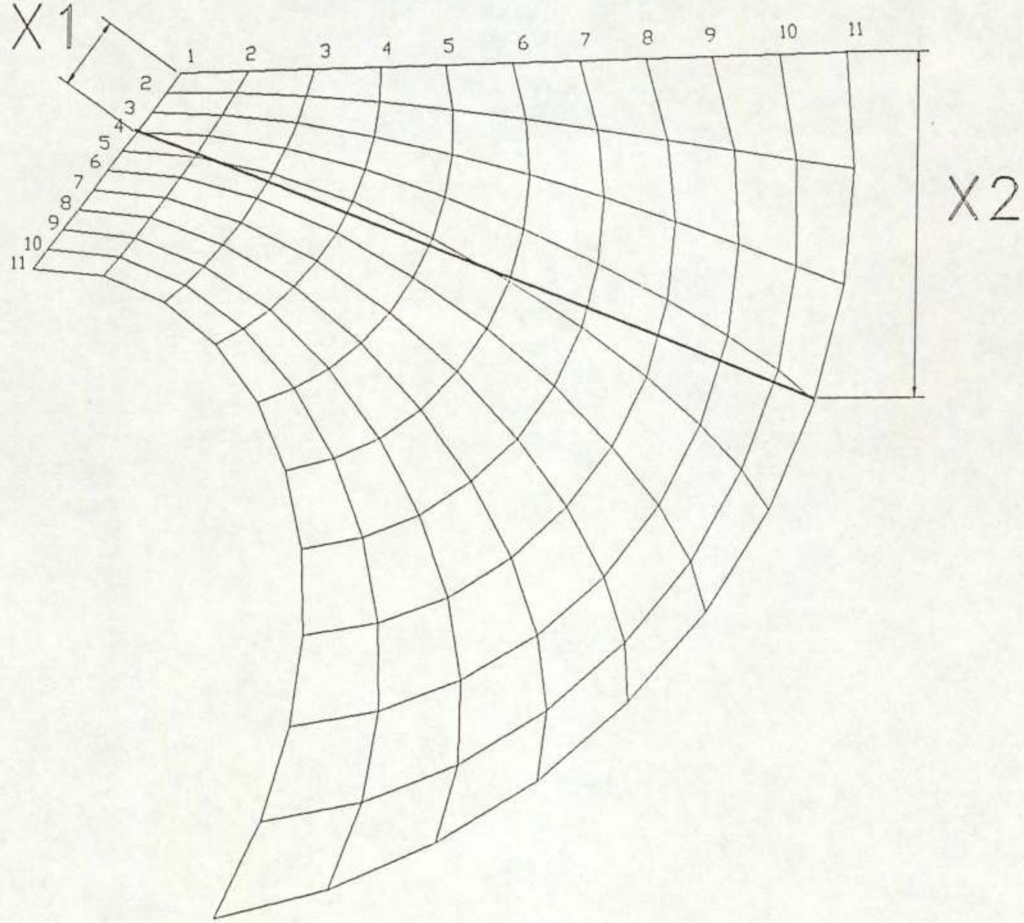


FIGURE 9: POINT MODIFICATION – SPLITTING

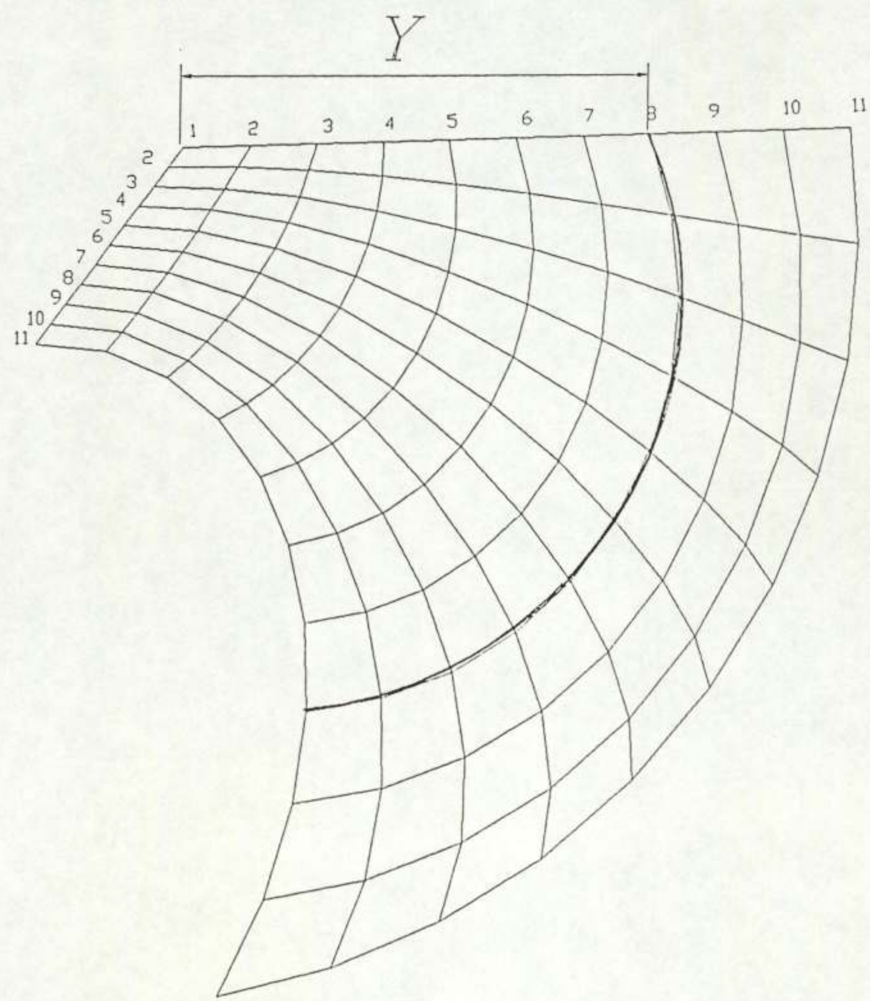


FIGURE 10: POINT MODIFICATION – DOUBLE ANGLE POINT

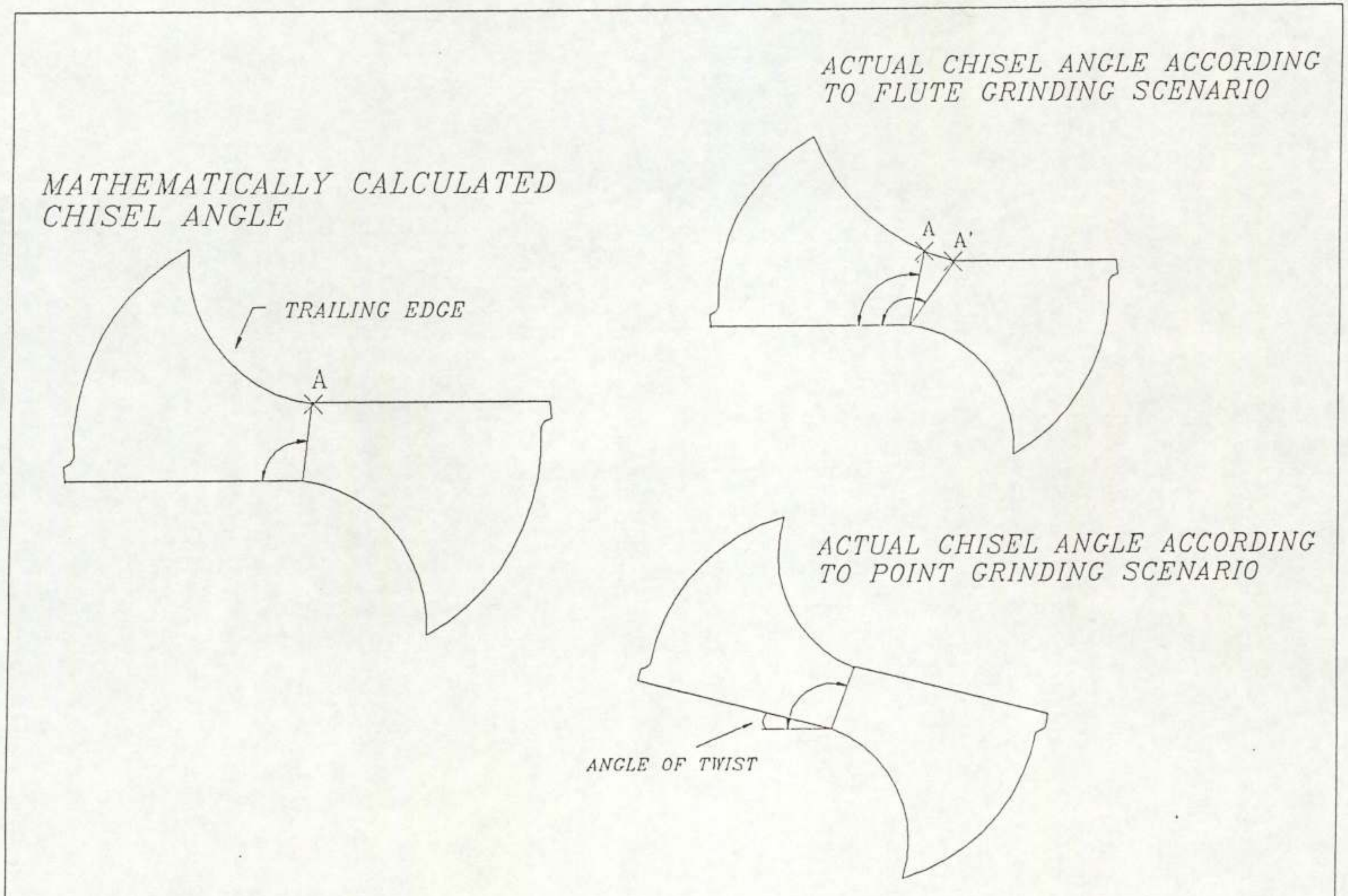


FIG 11: CHISEL ANGLE DESCREPANCIES

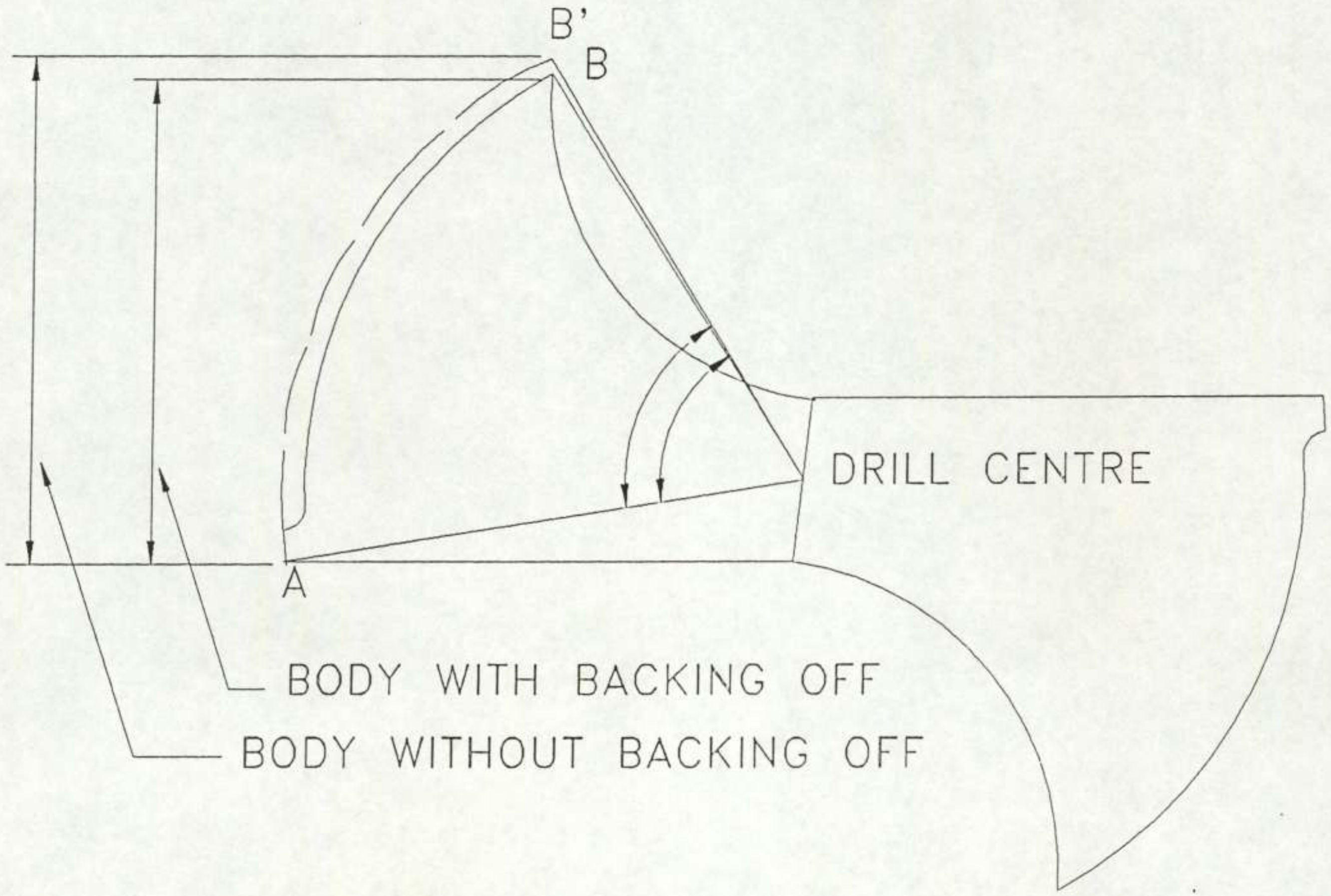


FIGURE 12: THE EFFECT OF BODY CLEARANCE DIAMETER

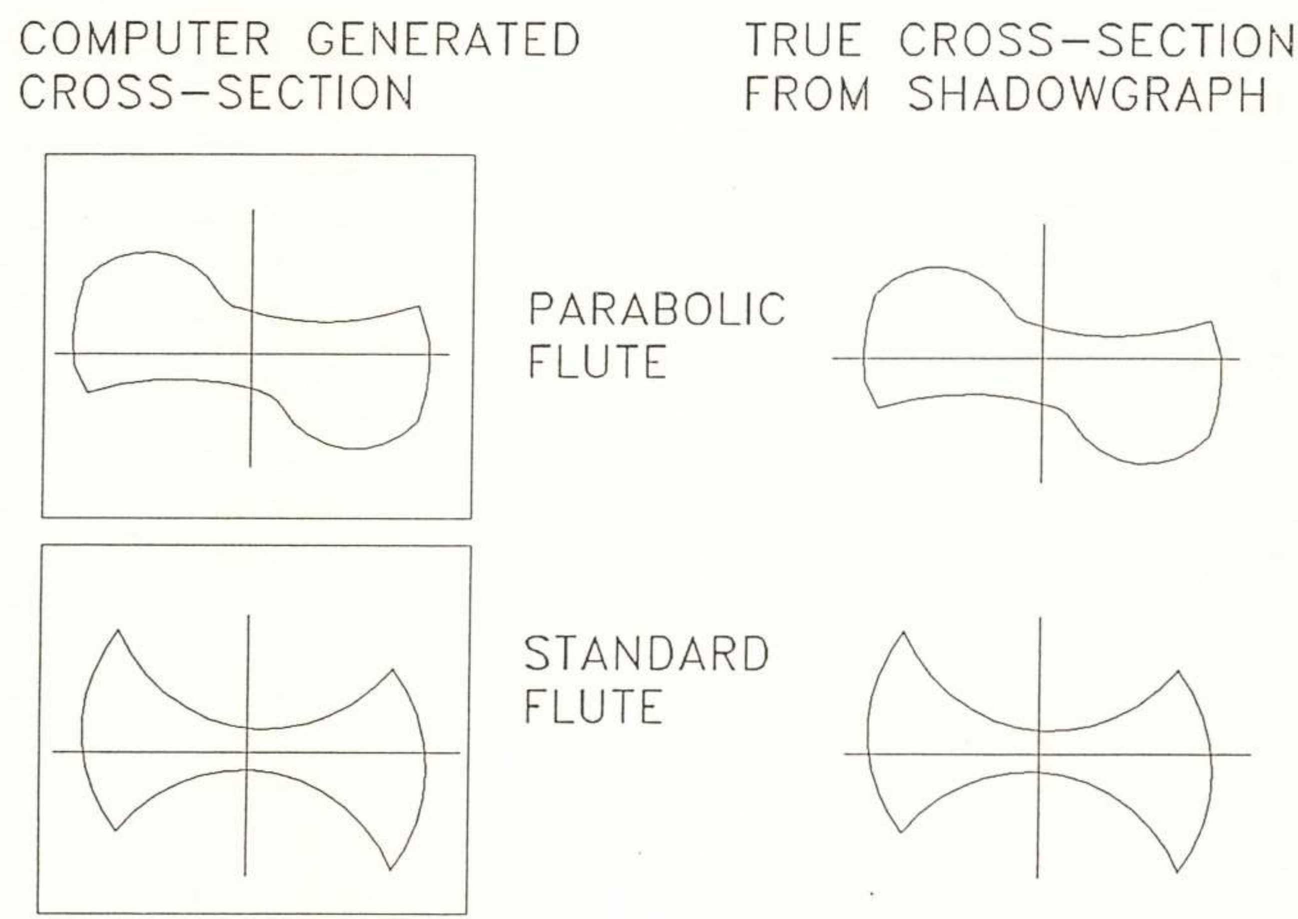


FIGURE 13: COMPARISON OF A COMPUTER GENERATED AND TRUE CROSS-SECTION