The influence of flute form on drill design and performance

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THE INFLUENCE OF FLUTE FORM ON
DRILL DESIGN AND PERFORMANCE

by

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A Doctoral Thesis

Submitted in partial fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy
of the Loughborough University of Technology

July 1982

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I would like to express my gratitude to the Instituto Nacional de Investigação Científica - INIC - for the financial support that made this thesis possible.

I am also obliged to the following people:

Professor R J Sury, Head of the Department of Engineering Production and my Director of Research for the interest he took in my studies in England;

Dr D J Billau, my supervisor, for his constant encouragement, advice and assistance;

Osborn-Mushet Tools Limited, Sheffield, and Marsh Brothers and Co. Ltd, Engineers, Sheffield for the drills manufacture;

Mr D G Johnson, from the Department of Management Studies, for helping with the statistical design of the experiments;

Mr R E Phelps, from the Centre for Industrial Studies, for his assistance with the analysis and heat treatment of the materials;

Mr K Pugh and Mr M Frost for the photographs, and

All the other people, mainly in the Computer Centre and in CIS, who contributed to making this work come true.

The text was typed by Mrs J Smith whose help is also acknowledged.
"... an ordinary twist drill ... is extremely complex, geometrically".

Shaw and Oxford

"... when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind".

Lord Kelvin

THE INFLUENCE OF FLUTE FORM ON DRILL DESIGN AND PERFORMANCE
THE INFLUENCE OF FLUTE FORM ON DRILL DESIGN AND PERFORMANCE

SYNOPSIS

Many modifications have been made in the past to the conventional drill points and references to the better performance of curved lip drills when cutting cast iron can be found. Similar drill points do not seem to be as successful with steel.

The objective of this research was set to analyse drill design and to study the effect on drill performance of changing the drill conventional flute form when cutting steel.

Changing the conventional flute form has an immediate effect on the shape of the drill lip - it is no longer a straight cutting edge.

A new range of problems arises when the drill lip is a curved line as the available expressions in literature for drill cutting angles calculation are not valid except for straight lines. However, to be able to calculate and to predict the cutting angles with a non-conventional flute drill is a matter of necessity, especially if the new flute design is based or specified upon some condition relative to these angles.

The drill lip shape is also influenced by the flank surface. Thus the analysis of the drill lip shape and the calculation of the cutting angles cannot be made without studying both the flute and the flank surfaces.

Geometric surfaces are better dealt with by computing techniques and computers. Thus the shape of a drill lip - the intersection of the flute with the point flank - and the cutting angles, are analysed by means of computer design aids for both varying flute and point flank surfaces.
First, the conventional flute face design is revised as far as its design parameters and profiles normal to the drill axis are concerned. The flute heel is analysed and incorporated with the mathematical model for the flute face. Additionally, as a matter of interest for the flute cutter design, the flute sections normal to the flute direction are computed from the mathematical model for the flute.

The cylindrical grinding concept is analysed and mathematically modelled in order to simulate the capabilities of many cylindrical grinding machines in industry and the one available to the author. The name "extended cylindrical grinding" is proposed as the orthodox cylindrical grinding concept is extended to allow for free selection of all drill point features generally available with conical grinding.

A mathematical model for the extended cylindrical grinding is built up, the parameters defined, and the equations implemented in a computer program for the analysis of the effect of these parameters on the drill point features by numerical investigation, and by simulation by computer aided design.

To make possible the complete simulation of the drill point, the chisel edge - the intersection of two point flanks symmetric relatively to the drill axis - is also analysed.

The intersection of the modelled cylindrical flank surface with any modelled flute - conventional or non-conventional - yields the drill lip which is simulated for shape and analysed for the cutting angles such as rake angle, inclination angle, clearance angle and wedge angle.

By varying the flute form, the law to each cutting angle along the lip is altered. Reciprocally, to each pre-fixed law to some of the cutting angles along the drill lip corresponds to a different flute form.
One method to compute the flute form, given a law to the selected cutting angle along the drill lip, is presented, analysed and used for designing a new drill flute.

Based on the assumption that the effective rake angle is the important rake angle in cutting, and that it may be nearly unaltered when a decrease in the normal rake angle is compensated by an increase in the inclination angle, an attempt is made to increase drill life by designing a special flute with increased wedge angle (known as "heat sinking" at many workshops) at the outer corner.

Drills were manufactured according to the new flute design by drill manufacturers.

Tests were run with steel in order to compare the performance of a conventional fluted drill and the non-conventional design put forward.

The wear was measured at several points on the lips of the tested drills and appeared to be more uniform along the lips of the new design drill type than along the lips of the conventional one. Lip wear rate however, tended to be higher for the new design drill type than for the conventional one.

Comparing the drilling forces, the drilling thrust values for the new design drill type were smaller than for the conventional one; the drilling torque values however, were smaller for the conventional type than for the new design one.

Chips produced by both drill types were also analysed as a further aspect of drill performance.

The rigid body concept - a mechanics concept - was introduced for chip flow mathematically modelling and for computer aided analysis in order to study the influence of flute form on chip kinematics. The potential of this approach by the author for drilling chip analysis is shown by means of geometrical simulation, chip flow angle prediction
and chip length ratio prediction. This approach also allows for other predictions which correlate with experimental data already reported in literature.

The suggestion is made for drill design to be based on specifications established according to rigid body drilling chip production.
i) Notations

(BSj) British Standards specification number j
(C.j) Catalogue number j
[D.j] Definition number j
i.j Equation number j in Chapter i.
(j) Bibliographic reference number j.
(j,k) Bibliographic reference numbers j and k.
3D Three dimensional

ii) Vectors and Vectorial Operations

Vectors and vectorial operations are represented as in (78). A summary of those representations used throughout the present work is given in this section.

\( \mathbf{OP} \) - Vector with original point at \( O \) and terminal point at \( P \)
\( \mathbf{A} \) - Vector \( A \)
\( \mathbf{\hat{a}} \) - Unit vector \( a \)
\( A \) or \( |\mathbf{A}| \) - Magnitude of vector \( A \)
\( |\mathbf{\hat{a}}| = 1 \)
\( \mathbf{\hat{A}} \) - \( \mathbf{A} \mathbf{\hat{a}} = |\mathbf{A}| \mathbf{\hat{a}} \)
\( \mathbf{A} \cdot \mathbf{B} = |\mathbf{A}| |\mathbf{B}| \cos \theta \) - dot product of vectors \( A \) and \( B \); \( \theta \) is the angle between \( \mathbf{A} \) and \( \mathbf{B} \)
\( \mathbf{A} \times \mathbf{B} = |\mathbf{A}| |\mathbf{B}| \sin \theta \mathbf{c} \) - cross product of vectors \( A \) and \( B \); \( \theta \) is the angle between \( \mathbf{A} \) and \( \mathbf{B} \); \( \mathbf{c} \) is a unit vector perpendicular to vectors \( A \) and \( B \)
\( i,j,k \) - Unit vectors in the directions of the axes of a 3D rectangular coordinate system
\( \mathbf{\hat{a}} = (a_1, a_2, a_3) \) - components of vector \( a \) in the directions of the axes of a 3D rectangular coordinate system
\( \mathbf{i} = (1,0,0); \mathbf{j} = (0,1,0); \mathbf{k} = (0,0,1) \)
\[ \mathbf{\hat{a} \cdot \hat{b}} = |\mathbf{\hat{a}}| |\mathbf{\hat{b}}| \quad \mathbf{\hat{a} \times \hat{b}} = |\mathbf{\hat{a}}| |\mathbf{\hat{b}}| \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix} \]

\[ = |\mathbf{\hat{a}}| |\mathbf{\hat{b}}| \begin{pmatrix} a_2 b_3 - a_3 b_2 \\ a_3 b_1 - a_1 b_3 \\ a_1 b_2 - a_2 b_1 \end{pmatrix} \]

The following symbols are also used:

- \( \mathbf{\hat{t}} \) - unit vector tangent to a line or surface
- \( \mathbf{\hat{n}} \) - unit vector normal to a surface
- \( \mathbf{\hat{e}} \) - vector tangent to a cutting edge

### iii) List of Symbols

- **A, B, C, D, E, F, G, H, I, J** - coefficients to the equations of the surfaces representing the drill flanks
- **A_{h1}, B_{h1}, C_{h1}** - coefficients to the equation of the drill heel contour
- **b_1** - uncut chip width
- **b_2** - chip width
- **C_1, C_2, C_3, C_4** - coefficients to the equation of a plane in a 3D referential system
- **d_0** - drill diameter
- **d_0, v_g, e_g, k_g** - parameters to mathematical model of drill flank surface generated by cylindrical grinding
$D_{og}$, $V_g, Ex_g, RK_g$ - the same as $(d_{og}, v_g, ex_g, k_g)$ used in the FORTRAN computer programs (appendices)

$ex_g, Ex_g$ - see $d_{og}$ and $D_{og}$ entries, respectively

$k_1, k_2, \ldots$ - numerical constants

$\varepsilon$ - drill flute lead

$\varepsilon_1$ - uncut chip length

$\varepsilon_2$ - chip length

$r$ - radial distance on a drill

$r_c$ - radial distance on a chip

$r_e$ - cutting length ratio

$r_0, 2W', \gamma_f, \kappa$ - parameters to the conventional flute face mathematical model

$R_0, Web, H_0, R_k$ - equivalent to $(r_0, 2W', \gamma_f, \kappa)$ used in the FORTRAN computer programs (appendices)

$s$ - variable length measured along the drill lip

$t_1$ - uncut chip thickness

$t_2$ - chip thickness

$T, T_1, T_2, T_3$ - coordinate transformation matrices

$T_h$ - drilling thrust

$T_0$ - drilling torque

$V$ - cutting speed

$V_c$ - chip speed

$X_p, Y_p, Z_p$ - coordinates of point $P$ in a referential system with axes $X, Y$ and $Z$

$XCHI, YCHI, ZCHI$ - chisel edge coordinates used in the FORTRAN computer programs (appendices)

$X', Y', Z'$ - coordinates in auxiliary referential systems

$X'', Y'', Z''$ - coordinates in auxiliary referential systems

$X^*, Y^*, Z^*$ - coordinates in auxiliary referential systems

$W, W'$ - half web thickness and half lip spacing, respectively

$Z_{dc}$ - distance of chisel point (dead centre) to referential plane $XY$

$\alpha_n$ - normal clearance angle

$\beta_n$ - normal wedge angle

$\gamma_n, \gamma_e$ - normal and effective rake angle, respectively
\( \gamma_f \) - drill helix angle (at periphery) - refer to entry \( r_0 \)
\( \eta \) - chip flow angle
\( \kappa \) - half drill design point angle - refer to entry \( r_0 \)
\( \kappa_g \) - half drill ground point angle - refer to entry \( d_0 \)
\( \lambda \) - inclination angle
\( \mu, \chi \) - parameters to heel equation
\( \nu_g \) - refer to entry \( d_0 \)
\( \xi \) - rotation angle
\( \phi_{r,z} \) - cylindrical coordinates
\( \psi \) - chisel edge angle
\( \psi' \) - chisel edge angular distance to \( X \) axis of referential system

iv) Definitions

Writers in the area of drilling do not use always the same terms when referring to similar drill and drilling concepts. To avoid ambiguity, a glossary of the terms used throughout this work is presented in this section. Terms are given in alphabetical order.

[D.1] - Body - the part of the drill extending from the chisel edge to the shank end of the flute (3) (Figure 1.1)

[D.2] - Body clearance - the part of the body surface reduced in diameter to provide diametral clearance (3) (Figures 1.1 and 1.2)

[D.3] - Built up edge, BVE - a thin crusted layer on the tool face, adjacent to the cutting edge (4)

[D.4] - chip flow angle, \( \eta \) - Section 4.4
[D.5] - chip length ratio, \( \eta_1 \) - Section 8.6.3
[D.6] - chisel edge - Section 3.4
chisel edge angle, $\psi$ - the obtuse angle between the tangent to the projection of the chisel edge at the chisel point and the projection of the lips on a plane normal to the drill axis (67) (Figure 1.3).

clearance angle, lip, $\alpha_f$ - the same as nominal relief angle

clearance angle, normal, $\alpha_n$ - Section 4.3.2.

contact length, chip - length of tool - chip contact (79)

cylindrical grinding, extended - drill point grinding by generation of a cylinder surface which, for convenience, can be positioned in such a way that allows for free selection of all drill point features generally available with conical grinding

face, flute (rake) - part of the flute on which the chip impinges as it is cut from the work and which, together with the flank surface, determines the drill lip (Figure 1.1)

flank (surface) - the surface of a drill point which extends behind the lip to the following flute (Figure 1.2)

flute (surface) - Section 2.1

flute face, conventional - a flute face which is a ruled surface - Section 2.7

flute face, non-conventional - Section 2.7

heel flute (surface) - the surface which, together with the flute face completes the flute surface (Figure 1.1)

heel drill point contour - intersection of heel flute surface with flank surface (Figure 4.1)

inclination angle, $\lambda$ - Section 4.3.4

lands - the cylindrical ground surfaces on the leading edges of the drill flute (3) - (Figure 1.2)
v) Units

Where it is not referred to otherwise, the distances are measured in mm and the angles in degrees.
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"The complex nature of conventional twist drills and their cutting action has challenged research workers for many years"

Armarego

1. GENERAL INTRODUCTION
1.1 General Literature Survey

Drilling is one of the oldest (1,2) and most widely used operations (1,2,3,4,5,6,7,8,9,10) in the manufacturing process.

Kahng and Ham estimated hole-making to be more than 30% of the total metal cutting business (9). Billau quotes a PERA survey according to which 28.2% of the total general engineering industry in Britain consisted of work carried out on drilling machines (6). Ernst and Haggerty estimated about 20% of the machine tools in the USA were drilling machines (2). Drilling, however, can also be done on turning machines and other machine tools capable of providing a relative rotation of workpiece and cutting tool (8).

The drilling operation is affected by many factors (3) and its success depends mainly on the performance of the drilling tool.

To meet the requirements of the manufacturing process there are several types of drilling tools which may be as different as those referred to in Table 1.1.

The twist drill, Figure 1.1, a two lipped diametrically opposed helical fluted tool - is currently made of high speed steel and it is the most commonly used drilling tool (5).

According to Billau (11) the twist drill was invented in 1863 by Martignoni, and Wiriyacosol and Armarego (12) also refer to Morse as having patented a twist drill in 1863.

Twist drills have been produced since a century ago (10), and their development has been dependent on manufacturers incentives (6,10). However, for Billau, the development of alternative designs by drill manufacturers "has not proved fertile ground for the academic researcher" (6).

Specifications for the twist drill - also known as conventional drill (13), regular twist drill (14), standard drill (3) and orthodox
<table>
<thead>
<tr>
<th></th>
<th>Twist drill</th>
<th>Half-round drill</th>
<th>Pivot (micro)</th>
<th>Spade</th>
<th>Indexable insert drill</th>
<th>Gundrill</th>
<th>BTA system</th>
<th>Ejector drill</th>
<th>Trepanssion</th>
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</thead>
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<tr>
<td>Diameter typical range (mm)</td>
<td>0.51-51</td>
<td>0.15-6.35</td>
<td>0.025-0.51</td>
<td>25.4-152</td>
<td>15.9-76</td>
<td>2-25.4</td>
<td>11-203</td>
<td>19-57</td>
<td>44.5-254</td>
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<td>Depth/diameter ratio common maximum</td>
<td>5-10</td>
<td>&gt;10(horiz)</td>
<td>3-10</td>
<td>&gt;40(horiz)</td>
<td>2-3</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>

**TABLE 1.1:** Drilling Tools (8)
FIGURE 1.1: Twist drill [BS 328], with alterations

FIGURE 1.2: Twist drill point
drill (15) — have been issued by several national standard organizations (16, 17, 19, BS328).

A two fluted twist drill is generally considered to be geometrically complex (16, 20, 21, 22), and its main active surfaces are as follows (Figure 1.1 and Figure 1.2):

- two flanks (the surfaces produced by the drill user at the drill point)
- two flutes (the helical canals along the body of the drill)
- two margins (3,18) or lands (3, BS328) [they belong to the cylindrical (3) surface determining the leading edges of the flutes].

The intersection of the two flank surfaces yields the chisel edge.

Each flute comprises two parts:
- the face - the leading side where the chip formation occurs
- the heel - the trailing side which is the chip former.

Each flank intersects both flutes: the face of one flute and the heel of the other one. The intersections of the flank surfaces with the flute faces determine the lips (BS 328) or major cutting edges (BS 5533). The intersections of the flute faces with the margins determine the minor cutting edges (Figure 1.1) (BS 5533).

According to Armarego and Wright there are six features commonly specified in handbooks for twist drills (Figure 1.3) (16):

- the point angle, $\alpha_p$
- the chisel edge angle, $\alpha_f$
- the lip clearance angle at the outer corner, $\gamma_f$
- the web thickness, $W$
- the helix angle at the outer corner, $\gamma_f$
- the drill diameter, $d_o$.
Figure 1.3: Features of a conventional twist drill [after Armarego (15)] [expanded; symbols altered]
Three of the above listed features are determined at the manufacture stage: $d_0$, $2W$ and $\gamma_f$; the other three can be selected by the user at the drill point grinding stage.

For Shaw (discussion of paper 20), the important features are: the point angle, the helix angle and the web thickness.

As far as the point angle is concerned the author would prefer to make a distinction between the (conventional) flute design point angle, $[0.24]$, $2\beta$, and the actual ground point angle, $[0.25]$, $2\gamma_g$, for they may be different.

As shown in Chapter 2, it is necessary to define a point angle to design a conventional flute. If the ground point angle at the grinding machine is different to that for the flute design, the lips will be curve shaped (either convex or concave - Figure 1.4) as it is known in the workshop, and has been referred to, for instance, by Galloway (3).

To measure the actual drill point angle by measuring the angle of two curved lips becomes slightly ambiguous as it varies from point to point along the lips.

Also the relative position of the chisel edge to the curved lip ($\psi$, Figure 1.3) is open to reconsideration as the direction of the lip varies from point to point.

The web thickness, $2W$, is taken equal to the lip spacing $[D.23]$, $2W'$ (Figure 1.3), by several workers (3, 12, 16), however, the author did not find in the many works in literature any reference to the actual difference between $2W$ and $2W'$. Furthermore, the lip spacing feature is open to clarification too, when the lips are curved.

Most research work on twist drills was aimed at finding how drill performance correlates with the twist drill features, usually one at a time (23).
FIGURE 1.1: Conventional twist drill ground to three different point angles

(Refer to chapters 2 and 3 for parameters (and symbols))
The influence of point angle variation on drill life has been reported by Galloway (3) and PERA (24), for example. Its influence on drilling forces was studied by Galloway (3), Galloway and Morton (10), Wiriyacosol (12), Micheletti (23), Bhattacharyya and co-workers (25,26) and Oxford and Shaw (27). Micheletti (23) also quotes Codron, Bird and Fairfield.

The effect of the chisel edge angle on drilling forces was referred to by Micheletti (23).

The influence of the lip clearance angle [D.8] on drill life was investigated by Lorenz (28); on drill life and drilling forces, by Galloway and Morton (10) and PERA (24).

The web thickness has been reported to influence the drilling forces (3, 10, 20), and the helix angle to influence drill life (3, 29, 31, 32) and drilling forces (10, 27).

The effect of drill diameter on drilling forces has also been reported (10, 12, 27).

According to Micheletti (23), Tourret (32) would have reviewed most of the papers on drill performance published up to 1957.

Drill performance, according to many research workers in the drilling area, varies a great deal, for nominally similar twist drills, and for each set of cutting conditions. According to the same research workers such variation is due to the inaccuracies of drill geometry (3, 20, 28, 33, 34).

Inaccuracies of symmetry of the two fluted twist drill can occur at the manufacture stage (flute spacing inaccuracy, for example), and/or at the point grinding stage (flank positioning error, for example).

One frequently referred to error of twist drill symmetry is the relative lip height [D.22] (3, 9, 10, 33, 34, 35, 37, C.1) as it can diminish drill life. Some other errors of symmetry are:

- eccentricity of web (1, 17)
eccentricity of chisel edge (9, 35)
unequal lip spacing (1, 17)
defective drill straightness (17)

Many attempts to improve drill performance consisted of modifying the conventional drill point:

- spiral point (2, 17)
- four facets point (17)
- six facets point (17)
- double cone (17, 38)
- split point (2, 17)
- point thinning (3, 10, 17, 38, 39)

However, special flank surface shapes cannot be implemented except with special grinding machines and/or by expert toolmakers. Additionally, the performance improvement with these altered drill points is frequently limited to some drilling conditions, and some drill point forms alter the shape of the lips and are bound to affect the mechanics of cutting along these cutting edges (3).

Encouragement for the analysis of the drilling process to be made with a cutting mechanics approach has come from a great deal of workers who have suggested that there is no fundamental difference between the cutting process of complex tools such as drills and other simpler tools such as the single point cutting tool.

- Oxford and Shaw stated that an ordinary twist drill operates in the same way as a single point tool (27);
- Dagnell underlines the similarities between the drill lip action and the lathe single point cutting tool (40);
- Wiriyacoso1 and Armarego predicted some drilling performance characteristics by approaching the drill lip and the chisel edge to a certain number of elementary single point cutting tools (12);
- Kumar et al are of the opinion that the drill lip action is "more or less an inclined and oblique cutting process" (25).
The same opinion is shared by Bera and co-workers (26).

- Wu et al employed photoelastic techniques in the analysis of drill stress and found that at drill periphery their results suggested an action analogous to orthogonal cutting (41).

- Venkataraman attempted a theory of tool simulation consisting of one to one correspondence of the cutting angles along the drill lip with that of a shaper tool (42).

- Oxley and Palmer think that the shape of any tool is connected with the orthogonal cut case (43).

The influence of such angles as the rake angle [D.26, D.27] and/or the inclination angle [D.19], for example, on the mechanics of cutting has been emphasized by Merchant (44), Stabler (45, 81), Shaw (77, discussion of paper 20), Armarego and Brown (46), Lee and Shaffer (47), Hirota and Usui (48), Ramalingam (49), Catrina et al (50) and others (51, 52).

Some workers such as Galloway (3), Oxford (53), Williams (54) and Amaradasa (55) have presented expressions for the calculation of such angles as, the rake angle, the inclination angle and the clearance angle along the straight twist drill lips. These expressions are usually based on the features of the twist drills and the referred to cutting angles may be calculated for each point at a radial distance \( r \) selected on the straight drill lip.

By using the referred to expressions the following facts may be established for the straight lip of a conventional flute twist drill:

- normal rake angle [D.27] is maximum at the outer corner
- inclination angle [D.19] is minimum at the outer corner
- normal wedge angle [D.32] is minimum at the outer corner

It is also easy to find that:
- cutting speed is maximum at the outer corner
- the outer half of the drill removes 75% of the material from the hole.

Yokoyama and Watanabe made a thermal analysis of the drilling process and found calculated temperature to increase with radial distance on the drill lip and claimed good agreement with the experiments (56). Wu and co-workers have also analysed drill temperature distribution by numerical solutions (57) and found the higher values to be near the outer corner; they claimed good agreement with experiments too.

Oxford measured the chip flow angle along the drill lip and found the smaller values to be at the outer corner (20).

1.2 Statement and Approach to Problem

The outer corner (Figure 1.2) is the part of a conventional twist drill most subject to wear, according to Bhattacharyya (38, 58). Also Galloway (34) and Kanai and Kanda (33) referred to the wear near the outer corner and suggested it to be used as a drill life criterion.

The relatively quicker wear near the outer corner of a conventional drill may be attributed, at a first approach, to an unfavourable combination of high temperature and small wedge angle ("heat sink"), for, as suggested by Galloway (34), the amount of metal supporting the drill lips may influence drill life.

In an early preliminary numerical investigation on the expressions available in the literature, and measurements made by Amaradasa (55), the author found the wedge angle with conventional twist drills to vary from about 50° at the outer corner up to about 80° near the chisel corner.

The hypothesis is put forward that the flute face, which is produced at the manufacture stage, can possibly by changed in order to yield a more uniform wedge angle along the drill lip than that
with the conventional flute, and a more uniform wear along the new drill lip may be obtained while leaving the grinding process unaltered.

Drill lip wear may possibly be diminished at the outer corner by making the wedge angle bigger than that of a conventional flute drill, even at the expense of the normal rake angle. This would probably not impair drill efficiency as the effective rake angle \([D.26]\) - the angle that in the field of oblique cutting replaces the normal rake angle in orthogonal cutting, according to Shaw and co-workers (59) and Yokoyama and co-workers (56) - depends on the normal rake angle and inclination angle, according to Stabler (45), and a decrease in the normal rake angle can be compensated by an increase in the inclination angle (Figure 1.5).

Any departure from the conventional flute (rake) face \([D.15]\) - a ruled surface \([D.30]\) - has an immediate effect on the shape of the drill lip: it is no longer a straight cutting edge.

To deal with non-conventional flute faces \([D.16]\) or, in general, with non-straight drill lips, arises a new range of problems as the available expressions in the literature for drill lip cutting angles calculations are not valid except for straight lips.

The analysis of cutting variables such as rake angle, clearance angle and inclination angle along curved lips cannot be made without defining the surfaces which determine the drill lips - the flute face and the flank surface.

These two rather complex surfaces can be mathematically modelled and their properties and mutual intersections determining the cutting edges can be analysed by computer design aids.

A numerical investigation and geometrical simulation is to be performed in this work, as far as it is needed, for lip shape determination and cutting angles computation when the lips are not straight.
FIGURE 1.5: Effective rake angle computed from the normal rake angle and inclination angle.

[After Stabler (45); also Shaw (77) and others (25)]
To design a method for designing drill flutes specified by the cutting angles along the lip is also one of the author's purposes; especially to design a drill with such a flute that the lips would comply with the condition of uniform wedge angle.

The author's objectives can be summarised as follows:

- to analyse the influence of flute form on drill point design
- to design a new flute that hypothetically may improve drill performance
- to study the influence of flute form on drill performance (chips included) when cutting steel.

For these purposes the drill lip geometry is to be analysed by means of the cutting angles by computer aided design.
"It is ordinary thought that the shape of the drill flute should be such that the cutting lip will be a straight line"

Moore

2. CONVENTIONAL TWIST DRILL FLUTE DESIGN
2.1 Introduction

Galloway and Morton (10) defined the drill flute as a chip disposal groove extending from the drill point towards the shank. Tsai (5) points out the following functions to the flute:

i) form the cutting edges on the drill point
ii) allow the chip to escape
iii) cause the chips to curl
iv) permit cutting coolant to reach the cutting edges.

For Shaw and Oxford (27) the flute-shape details may be ignored for a "normally functioning drill". According to Cetim (17), the flute form affects the shape of the drilling chips. Shaw (21) refers to the influence of flute form on lip shape, chip flute space and drill torsional rigidity. Billau (11) also refers to the flute as providing a cutting lip after point grinding, assisting the removal of chips, and affecting drill rigidity.

2.2 Conventional Flute Face Design and Parameters

One half of the flute - the face - is commonly determined in order to yield a straight cutting edge (3, 20, 21, 60). The other half - the heel - is chosen in such a way that drill strength (3), drill rigidity (11, 21, 61) and space for chip conveyance (3, 21, 31) are at a compromise.

A straight line - the conventional drill main cutting edge - can be defined by two parameters relatively to an axis - the drill axis (Figure 2.1):

- $W'$ - the distance to the drill axis (half of drill lip spacing)
- $\kappa$ - angle to the drill axis (half of drill point angle)

An helical movement of this straight line around the drill axis generates a ruled surface - the conventional flute face. The locus of a point on the generating line, at a distance $r_0 (= d_o/2)$ from the drill axis, is an helical line with angle $\gamma_f$ - the drill helix angle.
$Z$ - drill axis
$f_1$ - Flute Face cross section
$Cc$ - chisel corner
$Oc$ - outer corner
$Cc-Oc$ - drill lip
$2\phi_0, \psi, \gamma_f, k$ - parameters to the conv. flute face model

FIGURE 2.1: Twist drill conventional flute face generation and parameters
The four parameters, \( r_0 \), \( W' \), \( \gamma_f \) and \( \kappa \) define mathematically the conventional drill flute face as no further parameters are needed.

Galloway (3) has already developed the parametric equations to the conventional flute face and from his analysis Tsai and Wu (60) deduced the mathematical model of the flute shape. As a matter of necessity the author presents the analysis by Galloway, further studied by Tsai, for the conventional flute mathematical model.

For the mathematical model reference, a coordinate system of rectangular cartesian axes is defined (Figure 2.1):

- \( Z \) - drill axis, pointing to the shank;
- \( XY \) - plane normal to the drill axis at the point where the distance from the drill axis to the flute generating line is measured;
- \( X \) - axis parallel to the projection of the flute generating line on the plane \( XY \), pointing to the same direction as that referred to projection;
- \( Y \) - axis in the plane \( XY \), normal to \( X \), orientated in such a way that the reference system \( XYZ \) is a right-hand coordinate system.

From Figure 2.1 it can be seen that:

\[
\kappa \phi = \kappa \phi_1 + \kappa \phi_2 \tag{2.1}
\]

where \( \kappa \phi_1 = \sin^{-1} \left( \frac{W'}{r} \right) \) \tag{2.2}

\[
\kappa \phi_2 = (r^2 - W'^2)^{\frac{1}{2}} \tan \gamma_f \cot \kappa / r_0 \tag{2.3}
\]

where \( r \) and \( \phi \) are the polar coordinates of a selected point on the flute profile in the plane \( XY \).
The flute cross-section can be determined numerically and/or geometrically if \( r_0, W', \gamma_f \) and \( \kappa \), or some relationships between them, are known.

2\( W' \) is close to the web thickness, as it will be shown, and the web thickness, \( 2W \), is usually specified according to the drill diameter, \( d_0 \), (17, 36, C.1). In (C.1) for instance, the recommended minimum web thickness reads approximately

\[
2W = 0.2 \left( d_0 \right)^{0.283}
\]

from a graphical relationship.

The classical helix angle, \( \gamma_f \), has been \( 27\frac{1}{2}^\circ \), according to Lorenz (29), and in his opinion this was inherited from the past when milling machines tables for flute cutting had a swivel of \( 55^\circ \).

For the parameter \( 2\kappa \), the point angle, \( 118^\circ \) is the most common value (3, BS 328).

The influence of the referred to parameters on the flute form is better shown graphically. For this purpose and according to one of the author's aims, a computer program, to be extended, is built up and its flow diagram shown in Figure 2.2.

Figure 2.3 shows the influence of the parameters to the conventional flute mathematical model on its cross-section.

2.3 Conventional Flute Face Mathematical Model

The flute cross-section at a distance \( \ell \) from the \( XY \) plane, equal to the drill lead, projects on this plane confounded with the cross-section in this plane. The projection of any cross-section between these two can be found by rotating the cross-section in the \( XY \) plane by an angle \( \zeta \) (Figure 2.4).

The angle of rotation, \( \zeta \), of two distinct flute normal cross-sections, distant \( Z \) from each other, can be obtained from the geometric
FIGURE 2.2: Flow diagram of the computer program segment to compute and plot (Figure 2.3) conventional flute (face) cross-sections
FIGURE 2.3: Computer analysis of the influence of the conventional flute design parameters on the flute face cross section.
analysis of helices (62):

\[ \zeta = \frac{\tan \gamma_f}{r_0} Z \]  

where \( \gamma_f \) is the helix angle at a radial distance \( r_0 \).

The angle, \( \phi_z \), for a point on the flute contour distant \( Z \) from the XY plane, at a radial distance \( r \) from the drill axis, can be computed from the angle, \( \phi \), for a point on the flute contour in the XY plane at the same radial distance, \( r \), from the drill axis as follows:

\[ \phi_z = \phi + \zeta \text{ or } \]

\[ \phi_z = \sin^{-1} \left( \frac{W'}{r} \right) + (r^2 - W'^2)^{\frac{1}{2}} \tan \gamma_f \cot \kappa/r_0 \]

\[ + \tan \gamma_f Z/r_0 \]

This equation, of the form \( f(r, \phi, Z) = 0 \), represents the points of the conventional flute face in cylindrical coordinates and it is the mathematical model to this surface.

2.4 Flute Heel Analysis

2.4.1 Flute heel mathematical model

For commodity, in the computer plots in Figure 2.3, the flute heel has been given the same law as the face of the flute. However, the drill cross-section influences the drill torsional rigidity and this affects drill life as referred by several workers (3, 6, 21, 31, 63, 64). It also affects the conveyance of drilling chips, and the design solution to the conflicting aspects of chip clogging properties and drill rigidity is usually based on a compromise between these two effects.
FIGURE 2.1: Two flute cross sections distant $z$, projected on a plane normal to the drill axis.

FIGURE 2.5: Comparing the heel designed according to the same law as to the flute face (i), to the heel designed according to a more realistic law (ii) [refer to FIG. 2.6]
According to Armarego (16), there is no full specification for the "drill point heel shape" (heel point contour- Figure 1.2) and the heel corner position.

For the purpose of mathematical modelling of the complete flute surface, the heel surface is approached in this work on a geometrical basis.

For simplicity, and because the heel is not critical (3), its cross-section in the XY plane is given, in this work, the law:

\[ Y = A_{h1} X^2 + B_{h1} X + C_{h1} \]  

which proved to describe satisfactorily the actual heel cross-sectiions produced, projected, magnified and studied by the author for all drills observed.

The flute normal cross-section resembles two circular sectors diametrically opposed (Figure 2.6i). From his observations the author found the contour heel corner, \( H_1 \) (Figure 2.5), to be 90°/95° apart of the contour face corner, \( F_1 \) (Figure 2.5), on the flute contour.

The heel design is approached in the following way:

i) the body clearance is neglected

ii) the heel contour corner, \( H_1 \), is determined from the face corner, \( F_1 \), on the basis of the empirical observations

iii) the heel contour joins the face contour at point \( H_2 \) (Figure 2.5) that originates the chisel corner, after grinding, by smooth transition.

iv) the heel contour in plane XY is represented by a second degree polynomial \( Y = h_1(X) \) such as it complies with the following conditions:
FIGURE 2.6 (i): Cross section (view from the drill point) of a conventional drill, normal to axis, with the following features:
\[ d_0 = 12.7 \text{ mm}, \quad 2w = 2.0 \text{ mm}, \quad \delta_f = 31^\circ, \quad \alpha_g = 60^\circ \]

FIGURE 2.6 (ii): Computer simulated cross section for a conventional Flute Face with the following values to the parameters:
\[ d_0 = 12.7 \text{ mm}, \quad 2w' = 2.0 \text{ mm}, \quad \delta_f = 31^\circ, \quad \alpha_g = 60^\circ, \]
and heel according to a second degree polynomial model.
a) contains point $H_1$

b) contains point $H_2$

c) has a common tangent with the flute face at point $H_2$

To determine numerically and geometrically the shape of the heel contour is to find $A_{h1}$, $B_{h1}$ and $C_{h1}$ to Equation 2.7.

The conditions established above lead to the following equations:

\[
\begin{align*}
A_{h1}X_1^2 + B_{h1}X_1 + C_{h1} - Y_1 &= 0 \\
A_{h1}X_2^2 + B_{h1}X_2 + C_{h1} - Y_2 &= 0 \\
2A_{h1}X_2 + B_{h1} - \frac{dY_2}{dX_2}h_2 &= 0
\end{align*}
\]

where $(X_1, Y_1)$ and $(X_2, Y_2)$ are the coordinates of point $H_1$ and point $H_2$ respectively and $\frac{dY_2}{dX_2}h_2$ is the slope of the tangent to the flute face at point $H_2$.

Figure 2.5(ii) shows a flute heel profile plotted after being computed according to the above introduced criterion compared to the one that follows the same law as the conventional flute face profile.

An actual flute profile is shown in Figure 2.6(i). Figure 2.6(ii) shows the computer plot of the flute profile simulated according to the mathematical approach presented above and according to the specifications referred to in Figure 2.6(i).

The heel surface, like the face, is an helical surface and it is better represented by cylindrical coordinates, $r$, $\phi$ and $z$, which can be written in parametric form

\[
r = (Y^2 + X^2)^{\frac{1}{2}} = ((A_{h1}X^2 + B_{h1}X + C_{h1})^2 + X^2)^{\frac{1}{2}}
\]

2.8
\[ \phi = \tan^{-1} \left( \frac{Y}{X} \right) + \left( \frac{\gamma_f}{r_0} \right) \mu = \tan^{-1} \left( \frac{(A_{h1}X^2 + B_{h1}X + C_{h1})}{X} \right) \]

\[ + \left( \frac{\gamma_f}{r_0} \right) \mu \]  

\[ Z = \mu \]  

where \( \mu \) and \( X \) are the parameters to the coordinates \( r, \phi \) and \( Z \).

### 2.4.2 Web thickness

Oxford (53) defines the web as "the minimum section of metal between the two flutes".

Figure 2.3 (face and heel profiles computed from equations 2.1 to 2.3) suggests that the web thickness, \( 2W \), is measured along one of the axes of the flute profile. Analysis of equations 2.1 to 2.3 shows that the minimum radial distance for the points of the flute occurs for \( \phi = 90^0 \) and therefore \( 2W = 2W' \).

Figure 2.5(ii), representing a more realistic heel contour than Figure 2.3, suggests that \( 2W' \) might be different from \( 2W \).

According to the definition, \( W \) can be found by determining the minimum distance from the heel to the drill axis:

\[ r = (X^2 + Y^2)^{\frac{3}{2}} \]  

where \( Y = A_{h1}X^2 + B_{h1}X + C_{h1} \).

From the condition \( \frac{dr}{dX} = 0 \) it results:

\[ X = -\frac{B_{h1}}{A_{h1} + \lambda} \]  

and \( W \) can be computed.

Numerical investigation revealed that \( 2W \) is slightly higher than \( 2W' \) and the difference seems to be irrelevant for many purposes.
As an example, the web thickness was computed for the conditions

\[ 2W' = 2 \text{ mm}; \quad \gamma_f = 30^\circ; \quad \kappa = 59^\circ; \quad d_o = 12.7 \text{ mm} \]

and it was found \( 2W = 2.008 \text{ mm} \), i.e. a difference of less than 1%.

2.5 Flute Contour in a Plane Normal to the Helical Direction of Drill Flute

The flute cutter design is better dealt with if the cross-section of the flute profile perpendicular to its helical direction is known.

A method for determining such a section should be available if a new flute form is to be designed and manufactured.

The solution to this problem is approached as follows:

i) A plane \( P_1 \) (Figure 2.7) normal to the helical direction of the flute is defined and represented by:

\[ C_1X + C_2Y + C_3Z + C_4 = 0 \]  \hspace{1cm} 2.13

in the coordinate system \((X, Y, Z)\).

ii) For each point \( P \) (Figure 2.7) of the flute contour in the plane \( XY \), a point \( Q \) belonging to the same helical line on the flute surface as \( P \), and on the plane \( P_1 \), is found by computing the intersection point of the helical line with plane \( P_1 \).

iii) The set of points \( Q \) belonging to the flute surface and to the plane \( P_1 \) are better represented in graphical form if a new coordinate system \((X', Y', Z')\), is defined such as the plane \( X'Y' \) coincides with the plane \( P_1 \) (Figure 2.7).
FIGURE 2.7: Flute cross section in a plane normal to the flute helical direction.
iv) The coordinates of each point \( Q, (X_Q, Y_Q, Z_Q) \) are transformed into the new coordinates \( (X_Q', Y_Q', Z_Q') \).

Note: Transformations of coordinates are dealt with in Chapter 3, Section 3.2.1. To avoid repetitions and as the subject is analysed in the referred to section no further details are given here. (See Figure 2.8 for flow diagram of computer program segment).

The flow diagram of the computer program segment (see Appendix 1) for the computation of the above referred to sections is shown in Figure 2.8.

Cross-sections perpendicular to the helical direction of the flute, for several values of the parameters of the conventional flute and heel mathematical models are shown in Figure 2.9.

### 2.6 Some Alterations to Conventional Flutes

Many works in literature refer to some deviations from the conventional flutes, usually due to manufacture inaccuracies and/or manufacturing variations. Some variations are introduced for the purpose of creating special drilling characteristics such as the ones to implement a stronger chip breaking effect than that yielded by the regular flute (Figure 2.10).

Drill flute variations have been referred to by Galloway (3, 34), Galloway and Morton (10) and Lorenz (29), for instance. Arshinov and Alekev (4) also refer to flute deviations and point a cause for them. According to these workers, for each set of the drill flute features, \( r_0, 2W', \gamma_f \) and \( \kappa \), a proper flute profile cutter should be designed and used. This, however, would require a great many cutters for cutting the flutes of a given range and the manufacturers frequently use the same flute cutter within a certain drill diameter range. The influence of these flute deviations on the cutting angles such as the normal rake angle inclination angle, for instance, will be shown later when a method for finding the drill lip cutting geometry is presented.
Main program

Read number of points, NPOINT, to be selected on the flute face and heel surface

Read interval (PHSEC1, PHSEC2) where the first point of the desired section is expected to lay and read the accuracy to the desired numerical solution. Read other values for NAG subroutine call

Compute the direction-cosines of the direction of the flute to which the sectioning plane \( p \) (see text) is to be perpendicular

Compute the transformation matrix for \( (X,Y,Z) \rightarrow (X',Y',Z') \)
Coordinate transformation

\[ I = 1 \]

Compute coordinates, \((XP, YP, ZP)\) - refer to text - of the Ith point \( P \) on the flute face or heel surface in plane XY

FIGURE 2.8 (continued)
Compute coordinates, \((X_0, Y_0, Z_0)\) - refer to text - of the \(I\)th point \(Q\) on the sectioning plane \(p_1\) (Figure 2.7) and on the same helical line as \(P\)

- NAG subroutine
- successive bisections of interval \((PHSEC1, PHSEC2)\)

Compute a new internal \((PHSEC1, PHSEC2)\) for the computation of the \((I+1)\)th point \(Q\) from the computed \(I\)th point \(Q\)

Compute the coordinates, \((X'_Q, Y'_Q, Z'_Q)\)

\((X', Y', Z')\)

\[ I = NPOINT \]

\(\text{No} \rightarrow 4\)

\(\text{Yes}\)

Plot curves made of \(NPOINT\) points from the flute face and \(NPOINT\) points from the heel surface \((X', Q')\)

Main program

FIGURE 2.8: Flow diagram of the computer program (refer to Appendix 1) for the computation of the flute cross-section perpendicular to the helical direction of the flute
Central set of parameters:

<table>
<thead>
<tr>
<th>$2r_0$</th>
<th>2w</th>
<th>$\gamma_f$</th>
<th>2k</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.7</td>
<td>1.5</td>
<td>30</td>
<td>118</td>
</tr>
</tbody>
</table>

FIGURE 2.9 (continued)
FIGURE 2.9: Computer analysis of the flute sections normal to the flute helical direction by varying the conventional flute model parameters. [refer to previous page].
FIGURE 2.10: Modified Flutes:

(i) Chip breaking grooves (15,38)
(ii) Typical chip breaking drill (15,17)
(iii) Self-thinned heavy duty drill (21,38)
(iv) Crisp design chip breaker (21,38)
2.7 Flute Design Classification

The flutes which are ruled surfaces generated as shown above, according to the parameters $r_0$, $2W'$, $\gamma_f$ and $\alpha$ are designated in this work by conventional flutes. The conventional flutes for which $2\kappa = 118^\circ$ are designated standard flutes as this is the point angle specified in (BS 328).

Any flute which is not designed to comply with the condition to yield a straight lip is called non-conventional flute.

The following classification of drill flutes is proposed:

- conventional flutes: designed to be ruled surfaces
- non-conventional flutes: designed according to other criterion rather than yielding a straight lip

- standard flutes:
  $2\kappa = 118^\circ$
- non-standard flutes:
  $2\kappa \neq 118^\circ$

2.8 Chapter Closure

The conventional drill flute is determined on the basis of a very simple condition: the linearity of the drill lip.

It seems fortunate that such a criterion could serve the many different drilling conditions - drill sizes, feeds, speeds and materials, for example - and has succeeded for the many years the conventional drills have been used in industry.

The flute face, however, is curved and it has never been proved that a straight lip is better than any other shape. Furthermore, reports are found from time to time referring to the improved performance of drills ground to curved lips as for drilling cast iron.
Nearly all research work took this flute form for granted and has generated an important body of information data that applies only to such forms.
"The effects of the grinding parameters on the drill geometry are complex"

Fujii

3. MATHEMATICAL MODEL TO ANY-DRILL POINT

YIELDED BY CYLINDRICAL GRINDING
3.1 Introduction

For complete determination of the drill point geometry and cutting lip geometry it is necessary to define the flank surfaces.

The drill surfaces are usually machine produced. In some cases, in industry, the drill points are manually ground, however, this is uncommon in drilling research. The author came across in the literature just one case, by Lorenz (7), where drills manually ground were compared, for drill performance, against drills ground at a drill grinding machine.

Assessing drill sharpening methods and proposing "acceptable grinder criteria", Armarego (16) compares three drill grinding points: 'conical flank', 'cylindrical flank' and the 'plane flank'.

The conical grinding method was first (65) dealt with by Galloway (3) and further analysed by Fujii and co-workers (65,66), Tsai and Wu (60) and Armarego and Rotenberg (22, 66, 68).

A cylindrical drill grinding machine was available to the author and many similar machines are used in industry.

It is unfortunate that the cylindrical grinding method is scarcely dealt with in the literature; and, according to Armarego (16), this method is "unsuitable for general purpose drill point sharpening".

At the time the author started his work, the paper by Armarego (16, Annals of CIRP 29/1/1980) was not available to him. Later, when the paper was available, the author found the analysis of Armarego to be a particular case, with a major simplification, of the one made by the author. In fact the analysis of the author considers four parameters while Armarego considers only three. However, the analysis by the author further aims at:

- building a mathematical model for drill cylindrical grinding;
- including in this model all setting possibilities usually available in current practice of drill cylindrical grindings;
implementing the mathematical model in a computer program in order that it can be analysed by computer aided design.

3.2 Cylindrical Grinding Analysis

In a previous work (11), Billau manufactured a perspex model representing the mechanism of the type of the grinding machine available to the author (Figure 6.4) and has shown that the flank point surface is of cylindrical form.

In this work the author approaches the cylindrical grinding in an analytical way, in order to build up a mathematical model to be dealt with by computing methods and computer design aids.

3.2.1 Setting parameters

From the study of the work by Billau (11, 69) and further analysis of the referred to grinding machine, the following grinding setting parameters were established by the author (Figure 3.1):

- \( d_{og} \) - \((= 2 r_{og})\) diameter of the cylinder generated by grinding
- \( v_g \) - angle for the position of the flute relative to the generated cylinder by grinding
- \( e_{xg} \) - distance between the axis of the generated cylinder by grinding and the drill axis
- \( \kappa_g \) - angle between the axis of the cylinder generated by grinding and the drill axis.

3.2.2 Mathematical model for cylindrical flank surface

For reference of the mathematical model, referential systems are needed.

One referential system \((X, Y, Z)\), has already been defined in the previous chapter, for flute and drill reference. This will always be, for consistency, the ultimate reference system (Figure 3.2).
FIGURE 3.1: Drill setting parameters for cylindrical grinding: \( \text{dog} = 2r_{og} \), \( v_g \), \( e_{exg} \), \( k_g \) [extended cylindrical grinding]

- \( a_g \) - axis of grinding cylinder
- \( a_d \) - axis of drill
FIGURE 3.2: coordinate reference systems

$X'Y'Z'$ - Drill holding device reference system

$XYZ$ - Drill reference system
However, for analysis simplicity, other referential systems are also considered.

The cylinder generated by grinding is firstly referred to an auxiliary referential system \((X', Y', Z')\) attached to the drill holding device (Figure 3.2).

For clarity, the generated cylinder by grinding and system \((X', Y', Z')\) attached to it are further represented in Figure 3.3.

From Figure 3.3 the cylindrical surface can be described as follows:

\[
(X' - ex)^2 + Y'^2 = r^2_{og}
\]

\(Z'\) any real number

For consistency, this cylinder surface - one drill flank surface - shall be referred to the referential system \((X, Y, Z)\). To help with the coordinates transformation, two auxiliary referential systems, \((X'', Y'', Z'')\) and \((X*, Y*, Z*)\), are introduced. The referred to four systems are shown in Figure 3.4 which shows also their geometrical relationships.

The system \((X*, Y*, Z*)\) has its \(X*\) axis coincident with the axis \(X'\) of system \((X', Y', Z')\); \(Y*\) and \(Z*\) are in the same plane as the \(Y'\) and \(Z'\) axes but rotated \(\kappa_g\) - the grinding point angle - relatively to these axes.

From Figure 3.4:

\[X' = X*\]
\[Y' = Y* \cos \kappa_g = Z* \sin \kappa_g\]
\[Z' = Y* \sin \kappa_g + Z* \cos \kappa_g\] or, in other form:
FIGURE 3.3: Generated grinding cylinder of axis ag
[refer to FIG 3.1 and FIG 3.2]

FIGURE 3.4: Drill referential system (X,Y,Z); Drill holding device referential system
(X',Y',Z'); Auxiliary referential systems
(X'',Y'',Z'') and (X'',Y'',Z'').
\[
\begin{align*}
X' & = 1 & 0 & 0 & X^* & = X* \\
Y' & = 0 & \cos K \sigma & -\sin K \sigma & Y^* & = T_l Y* \\
Z' & = 0 & \sin K \sigma & \cos K \sigma & Z^* & = Z*
\end{align*}
\]

where \( T_l \) is the coordinates transformation matrix:

\[
T_l = \begin{bmatrix}
1 & 0 & 0 \\
\cos K \sigma & -\sin K \sigma & 0 \\
\sin K \sigma & \cos K \sigma & 0
\end{bmatrix}
\]

The system \((X'', Y'', Z'')\) is a translation of system \((X^*, Y^*, Z^*)\) and they are apart from the distance \(Z_0\) (distance from 0 to 0') measured either along \(Z''\) or \(Z^*\):

\[
\begin{align*}
X^* & = X'' \\
Y^* & = Y'' \\
Z^* & = Z'' - Z_0 \quad \text{or, in other form,}
\end{align*}
\]

\[
\begin{align*}
X^* & = 1 & 0 & 0 & X'' & = 0 & X'' & = 0 \\
Y^* & = 0 & 1 & 0 & Y'' + 0 & = T_2 & Y'' + 0 & = 3.3 \\
Z^* & = 0 & 0 & 1 & Z'' & -Z_0 & Z'' & -Z_0
\end{align*}
\]

Finally, the referential system \((X, Y, Z)\) attached to the drill has its \(Z\) axis coincident with \(Z''\); the \(XY\) plane is the same as the plane \(X''Y''\) and \(X\) axis is rotated \(\psi_g\) relatively to the \(X'\) axis.

From Figure 3.4:
\[ X'' = X \cos \nu g - Y \sin \nu g \]
\[ Y'' = X \sin \nu g + Y \cos \nu g \]
\[ Z'' = Z \]

or:
\[
\begin{bmatrix}
X'' & \cos \nu g & -\sin \nu g & 0 & X & X \\
Y'' & \sin \nu g & \cos \nu g & 0 & Y & T_3 & Y \\
Z'' & 0 & 0 & 1 & Z & Z
\end{bmatrix}
\]

The cylindrical surface can now be expressed in terms of X, Y and Z. In fact from 3.3 and 3.4:
\[
\begin{bmatrix}
X' \\
Y' \\
Z'
\end{bmatrix} =
\begin{bmatrix}
T_1 & T_2 & T_3 \\
T_1 & 0 & 3.5 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
-Z_0
\end{bmatrix}
\]

and this leads to
\[
X' = X \cos \nu g - Y \sin \nu g
\]
\[
Y' = (X \sin \nu g + Y \cos \nu g) \cos \kappa g - (Z - Z_0) \sin \kappa g
\]
\[
Z' = (X \sin \nu g + Y \cos \nu g) \sin \kappa g + (Z - Z_0) \cos \kappa g.
\]

Substituting \(X'\) and \(Y'\) in Equation 3.1 it results an equation of the form:
\[
f_{a1}(X,Y,Z) = AX^2 + BY^2 + CZ^2 + DXY + EXZ + FYZ +
+ GX + HY + IZ + 0
\]

where:
\[
A = \cos^2 \nu g + \sin^2 \nu g \cos^2 \kappa g
\]
\[
B = \sin^2 \nu g + \cos^2 \nu g \cos^2 \kappa g
\]
\[
C = \sin^2 \kappa g
\]
$D = -2 \cos \theta \sin \gamma + 2 \sin \theta \cos \gamma \cos^2 \kappa \gamma$

$E = -2 \sin \kappa \gamma \cos \kappa \gamma \sin \gamma$

$F = -2 \sin \kappa \gamma \cos \kappa \gamma \cos \gamma$

$G = 2 \sin \kappa \gamma \cos \kappa \gamma \sin \gamma Z_0 - 2 \varepsilon x \gamma \cos \gamma$

$H = 2 \sin \kappa \gamma \cos \kappa \gamma \cos \gamma Z_0 + 2 \varepsilon x \gamma \sin \gamma$

$I = -2 Z_0 \sin^2 \kappa \gamma$

$J = \varepsilon x^2 + Z_0^2 \sin^2 \kappa \gamma - r_0^2$

$Z_0 = (r_0^2 - (\varepsilon x^2 - \theta W)^2)^{1/2}/\sin \kappa \gamma$

This equation represents the model of one flank whose parameters are, $r_0$, $\gamma$, $\varepsilon x$ and $\kappa \gamma$ which determine completely the coefficients A to J of function $f_{al}$.

A two-fluted drill point is made of two similar flanks and one flank substitutes the other when the drill is rotated $180^\circ$. For each point $P_1 = (X,Y,Z)$ on the flank represented by equation $f_{al}$, there is a diametrically opposed point $P_2 = (-X,-Y,Z)$ on the other flank. The equation $f_{al2}$ for this flank can be found from $f_{al1}$ by substituting $X$ for $-X$ and $Y$ for $-Y$:

$f_{al2} = AX^2 + BY^2 + CZ^2 + DXY - EXZ - FYZ -$

$- GX - HY + IZ + J = 0$
3.3 Computing Approach

The equations dealt with in the previous sections can be easily dealt with by computing methods.

The implementation of these equations in a computer program do not present any particular problem and the respective flow diagram is omitted from this writing.

The segment computer program relative to the drill flank point can be seen in the computer program shown in Appendix 1.

Figures 3.5 to 3.8 show computer plotted cross-sections through both flank surfaces, normal to the drill axis. Each figure shows the effect of one of the four grinding parameters on the size or on the position of the flank surface relative to the referential system attached to the drill.

3.4 The Chisel Edge

The intersection of the two flank surfaces forms the chisel edge. To find the chisel edge is to find the common solution to \( f_{a1} \) and \( f_{a2} \) at the drill point region.

The chisel edge can be found geometrically and numerically from the successive cross-sections on both flank surfaces yielded along the drill axis: Figures 3.5 to 3.8.

The chisel edge intersects the drill axis at the chisel point (dead centre), \((0, 0, Z_{dc})\), where \(Z_{dc}\) can be found from either \(f_{a1}\) or \(f_{a2}\) by making \(X = Y = 0\). In doing so, \(Z_{dc}\) is found from the equation:

\[
CZ_{dc}^2 + IZ_{dc} + J = 0
\]

which results from \(f_{a1}(0, 0, Z) = f_{a2}(0, 0, Z) = 0\).
Grinding - cylindrical

$D_{og} = 20.00$
$V_{g} = 90.00$
$E_{xg} = 2.00$
$R_{kg} = 59.00$

Grinding - cylindrical

$D_{og} = 28.00$
$V_{g} = 90.00$
$E_{xg} = 2.00$
$R_{kg} = 59.00$

FIGURE 3.5: Computer plotted cross sections of the flank surfaces normal to the drill axis.
Effect of $D_{og}$
FIGURE 3.6: Computer plotted cross sections of the flank surfaces normal to the drill axis.
Effect of $V_g$
Grinding - cylindrical

D0g = 24.00
Vg = 90.00
Exg = 2.00
Rkg = 59.00

FIGURE 3.7: Computer plotted cross sections of the flank surfaces normal to the drill axis.
Effect of Exg
Grinding - cylindrical

$D_Og = 24.00$
$V_g = 90.00$
$E_xg = 2.00$
$R_{kg} = 50.00$

Grinding - cylindrical

$D_Og = 24.00$
$V_g = 90.00$
$E_xg = 2.00$
$R_{kg} = 70.00$

FIGURE 3.8: Computer plotted cross sections of the flank surfaces normal to the drill axis. Effect of $R_{kg}$
The direction of the chisel edge at the chisel point is given by the tangent to the chisel edge at this point.

Let $S_{a1}$ be the flank surface represented by equation $f_{a1}$; from geometry, the normal vector, $\vec{n}_1^+$, to surface $S_{a1}$ at one point $(X, Y, Z)$ is in the same direction as the vector $(af_{a1}/\partial X, af_{a1}/\partial Y, af_{a1}/\partial Z)$:

$$N_1 \vec{n}_1^+ = (af_{a1}/\partial X, af_{a1}/\partial Y, af_{a1}/\partial Z) \quad 3.9$$

In the same way, for flank $S_{a2}$:

$$N_2 \vec{n}_2^+ = (af_{a2}/\partial X, af_{a2}/\partial Y, af_{a2}/\partial Z) \quad 3.10$$

At the chisel edge, $\vec{n}_1^+$ and $\vec{n}_2^+$ are both normal to the tangent to this line; then the tangent to the chisel edge is in the direction of vector $\vec{n}_1^+ \times \vec{n}_2^+$, that is, normal to both $\vec{n}_1^+$ and $\vec{n}_2^+$.

At the chisel point, $(0, 0, Z_{dc})$,

$$N_1 \vec{n}_1^+ = (EZ_{dc} + G, FZ_{dc} + H, 2CZ_{dc} + I) \quad 3.11$$

$$N_2 \vec{n}_2^+ = (-EZ_{dc} - G, -FZ_{dc} - H, 2CZ_{dc} + I) \quad 3.12$$

$$N_1 N_2 \vec{n}_1^+ \times \vec{n}_2^+ = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ EZ_{dc} + G & FZ_{dc} + H & 2CZ_{dc} + I \\ -EZ_{dc} - G & -FZ_{dc} - H & 2CZ_{dc} + I \end{vmatrix} \quad 3.13$$

where $\hat{i}$, $\hat{j}$ and $\hat{k}$ are the unit vectors associated with the axes of the referential system $(X, Y, Z)$. 
Grinding - cylindrical

$D_0g = 25.40$
$V_g = 90.00$
$E_{xg} = 2.50$
$R_{kg} = 59.00$

FIGURE 3.10: Effect of $V_g$ on the chisel edge angle

Grinding - cylindrical

$D_0g = 25.40$
$V_g = 90.00$
$E_{xg} = 2.50$
$R_{kg} = 59.00$

FIGURE 3.9: Effect of $D_0g$ on the chisel edge angle
Grinding - cylindrical

DOg = 25.40
Ug = 90.00
Exg = 2.50
Rkg = 59.00

FIGURE 3.11: Effect of Exg on the chisel edge angle

Grinding - cylindrical

DOg = 25.40
Ug = 90.00
Exg = 2.50
Rkg = 59.00

FIGURE 3.12: Effect of Rkg on the chisel edge angle
\[ N_1 N_2 n_1^\rightarrow \times n_2^\rightarrow = (E Z + G)(2(FZ_{dc} + H)(2CZ_{dc} + I), - 2(FZ_{dc} + H)(2CZ_{dc} + I), 0) \]

As expected, the \( n_1^\rightarrow \times n_2^\rightarrow \) vector is normal to the drill axis (third component null), i.e. the tangent to the chisel edge at the drill chisel point is normal to the drill axis.

This tangent makes an angle \( \psi' \) (Figures 3.9 to 3.12) with the \( X \) axis, which is the same as the chisel edge angle, \( \psi \), when the drill lip is a straight line.

Let \( \hat{c} \) be the unit vector in the direction of \( N_1 N_2 n_1^\rightarrow \times n_2^\rightarrow \), or, in the chisel edge direction; let \( \hat{t} \) be the unit vector along the \( X \) axis:

\[ \hat{c}.\hat{t} = |\hat{c}|.|\hat{t}|. \cos \psi' = \cos \psi' \]

The variation of angle \( \psi' \) with the flank model parameters is shown in Figures 3.9 to 3.12 which reveal the parameter \( v_g \) to have in general a greater influence than the other parameters.

Numerical investigation, not included in this work, also revealed the direction of the tangent along the chisel edge to vary very little: less than 1% at a point 1 mm away from the chisel point.

3.5 Chapter Closure

In building up the novel model of the cylindrical grinding and implementing it in a computer program, the author aimed at designing a 'tool' to be used in flute design. Thus the analysis was carried out just up to the stage that was needed for that purpose. However, the analysis has been brought to a point that makes easy any further numerical and geometrical investigation on the cylindrical flank surfaces.
"The drill is geometrically the most complex tool to be found in the workshop and offers a real challenge to anyone attempting to visualize the effective rake angle or other quantities of fundamental importance."

Milton Shaw

4. **DRILL POINT GEOMETRIC SIMULATION AND CUTTING ANGLES ALONG ANY SHAPED DRILL LIP**
4.1 Introduction

In attempting to design a new drill flute based on the pre-fixed values of the cutting angles along a drill lip, the author found himself committed to the task of devising and designing analytical and computing 'tools' not available so far. Designing, developing and implementing these 'tools' has been a major task in his work to achieve the main purpose, and, as a result, an extensive, quite complex computer program was built up.

One objective with this computer program was to design it in order that it could simulate any drill point either for any flute form or for any set of the setting parameters of a drill point cylindrical grinding machine.

Simulation of the drill point by computer aided design presents the following advantages:

- it is an additional design aid in drill design;
- it allows for visualization of drill point before flute manufacture and/or actual drill point grinding;
- it can offer an overall view of the drill point configuration represented by its complete contour, for example;
- it allows for elimination of undesired configurations;
- it eliminates trial and error grindings for a set of desired features;
- it reveals design details not immediately available from the traditional set of features used to characterize a drill point;
- it offers a useful approach in unusual situations as the one referring to non-conventional flute design;
- it allows for finding, by comparison with the actual drill points, the error and/or deviations of the flute form and/or the ground surfaces.
4.2 Drill Point Geometric Simulation

The geometry of the drill point is determined by the flutes and flanks and their mutual intersections. The drill surfaces are designated as follows (Figure 4.1):

- $S_{\alpha 1}$ - represented by a function $f_{\alpha 1}$ - is the flank surface extending towards the positive semi-axis $X$

- $S_{\alpha 2}$ - represented by a function $f_{\alpha 2}$ - is the flank surface extending towards the negative semi-axis $X$ and symmetric to $S_{\alpha 1}$ relative to the drill axis ($Z$ axis)

- $S_{\gamma 1}$ - represented by a function $f_{\gamma 1}$ - is the flute face which, with $S_{\alpha 1}$, determines the lip 1

- $S_{\gamma 2}$ - represented by a function $f_{\gamma 2}$ - is the flute face which, with $S_{\alpha 2}$, determines the lip 2

- $S_{h 1}$ - represented by a function $f_{h 1}$ - is the heel surface that, together with $S_{\gamma 1}$, completes one flute surface

- $S_{h 2}$ - represented by a function $f_{h 2}$ - is the heel surface that, together with $S_{\gamma 2}$, completes the second flute surface

- $S_{af}$ - represented by a function $f_{af}$ - is the drill external cylindrical surface

For the sake of simplicity and without any relevant loss of geometric information, the drill body clearance is not considered and therefore the drill margin (land) is not simulated.

The flow diagram of the computer program segment for drill point simulation is presented in Figure 4.2. The computer program itself, to which belong the referred to segment and other segments already referred to in previous chapters, is presented in Appendix 1 and has been the source for other computer programs the author developed and used throughout his work.
FIGURE 4.1: Drill point surfaces and drill point contour lines.
Flute faces, $f_{\gamma 1}$, $f_{\gamma 1}$, already determined

Flute heels $f_{h1}$, $f_{h2}$, already determined

Flank surfaces $f_{\alpha 1}$, $f_{\alpha 2}$, already determined

Read number, NPOINT, of points to be considered for each curve computation

Read interval (ZOUT1, ZOUT2) where the outer corner is expected to fall

Compute guess point to chisel corner CORN(1), CORN(2), CORN(3) from WEB value

Read tolerance values for desired accuracy of the outer corner and chisel corner computations and other values for NAG subroutine call

FIGURE 4.2 (continued)
Call subroutine to compute outer corner of lip 1. (Common solution to $f_{a1}$ and $f_{a1}$ at radial distance $R_0$ - refer to text)

Write: outer corner computed

Call subroutine to compute chisel corner: the common point to 3 surfaces: $S_{a1}$, $S_{a2}$ and $S_{y1}$, or, the common solution to $f_{y1}$, $f_{a2}$, and $f_{y1}$ (refer to text)

Write: chisel corner computed

Divide flute face cross-section from the points which originate the chisel corner and the outer corner into NPOINT intervals

$I = 2$

$I = I + 1$

Compute an interval ($RSTANN$, $RSTANZ$) for the computation of the $I$th point on the drill lip

Call subroutine to compute the $I$th point on the lip

NAG subroutine - successive bisections of interval ($ZOUT1$, $ZOUT2$)

NAG subroutine - a program based on the minimization of a residuals function

NAG subroutine - successive bisections of interval ($RSTANN$, $RSTANZ$)
Write: lip computed

Drill chisel point already computed

Divide distance from drill chisel point up to chisel corner into NPOINT intervals

\[ K = 2 \]

Compute ZCHI from the chisel corner and from the chisel point for the Kth point

Compute YCHI2 from equation derived from \( f_{\alpha 1} \) and \( f_{\alpha 2} \) after elimination of \( X \) (refer to text)

\[ K = NPOINT \]

Write: chisel edge computed
Read interval \((ZCLE1, ZCLE2)\) for heel corner computation

\[ L = 1 \]

Call subroutines to compute heel corner on the flank surface \(S_{h1}\) from the point on the flute heel \(S_{h2}\) at radial distance \(r_0\) from drill axis.

Divide angular distance from heel corner on flute 2 \((S_{h2})\) to outer corner in flute 1 \((S_{y1})\) into \(NPOINT\) intervals.

Call subroutine to compute the \(L\)th point on the flank corner on the cylindrical drill surface.

\[ L = L + 1 \]

Yes

Write: flank contour on the cylindrical drill surface computed

No

\[ L = NPOINT \]

NAG subroutine - successive bisections of interval \((ZCLE1, ZCLE2)\)

NAG subroutine - successive bisections of interval \((ZCLE1, ZCLE2)\)
Divide heel surface (cross-section from point originating the chisel corner up to the point originating the heel corner into NPOINT intervals

\[ M = 2 \]

Compute an interval \((RHEEL_1, RHEEL_2)\) for the computation of the \(M\)th point on the heel drill point contour

Call subroutine to compute the \(M\)th point on the heel surface \(S_h\) and on the flank point surface \(S_{a2}\) (refer to text)

\(M = M+1\)

\(\text{No}\)

\(M = N\)\text{POINTER}\?

\(\text{Yes}\)

Write: heel drill point contour computed

Plot drill point. Write coordinates of drill point contour lines

**Main program**

FIGURE 4.2: Flow diagram of computer program segment for drill point geometric simulation
From the computer program implemented numerical model for the drill point, many simulations either numeric (Table 4.1) or geometric (Figure 4.3) were done with two purposes:

i) numerical and geometrical investigation
ii) for comparison with actual drill points produced on the grinding machine available to the author, with drills mainly from the shelf.

Figure 4.3 shows a simulated drill point of a 19.05 mm (3") diameter conventional flute drill for which the cylindrical grinding parameters were selected as follows:

\[ d_{og} = 38 \text{ mm}; \quad \theta_g = 65^0; \quad e_{xg} = 3 \text{ mm}; \quad \kappa_g = 59^0 \]

Figure 4.4 shows the actual drill point, after grinding, of a conventional flute drill without margins which has been manufactured for research purposes, with the features used for the simulation shown in Figure 4.3.

Figures 4.5 to 4.10 are presented to illustrate drill point simulation for one conventional flute ground to three different point angles. The effect of the other cylindrical grinding parameters and the conventional flute design parameters is illustrated in Appendix 2.

4.3 Lip Geometry Related Cutting Angles Along Any Shape Drill Lip

Drill features, as presented in Chapter 1, are inadequate to take account of the differences between flute forms which influence the length and shape of the lips and the chisel edge length together with the cutting angles along the lips.

Lip length and chisel edge length can be put in evidence from the computations presented in the previous section (Table 4.1 and geometric simulations).
**TABLE 4.1:** Computer printout for drill point (an example)

(Ref to FIGURES 1.3 and 1.1)

1 - Radial distance and coordinates along the drill lip (From the outer corner)

2 - Distance along the drill lip (From the outer corner)

3 - Half-chisel edge coordinates (From the chisel corner to the chisel point)

4 - Circumferential drill flank contour coordinates and angle (From heel corner)
Flute - Grinding -
conventional cylindrical

R₀ = 9.52  D₀g = 38.00
Web = 3.00  U₀ = 65.00
H₀ = 30.00  Exg = 3.00
Rk = 65.00  Rkg = 59.00

FIGURE 4.3: Computer simulated drill point
[Compare with FIG 4.1 for actual drill point]
Flute - conventional
Grinding - cylindrical

R0 = 9.52  D0g = 38.00
Web = 3.00  Ug = 65.00
H0 = 30.00  Exg = 3.00
Rkg = 59.00

FIGURE 4.4: Actual drill point
[Compare with FIG 4.3 for computer simulated drill point]
FIGURE 4.5: Computer simulation of drill point.

Flute - conventional
Grinding - cylindrical

\[ R_0 = 6.00 \quad D_{og} = 26.00 \]
\[ \text{Web} = 1.80 \quad \text{Ug} = 90.00 \]
\[ H_0 = 27.50 \quad \text{Exg} = 2.50 \]
\[ R_k = 59.00 \quad R_{kg} = 59.00 \]
Flute - Grinding
conventional cylindrical

\[ RO = 5.00 \quad DOg = 26.00 \]
\[ Web = 1.80 \quad Vg = 90.00 \]
\[ Ho = 27.50 \quad Exg = 2.50 \]
\[ Rk = 59.00 \quad Rkg = 48.00 \]

[Compare with FIG 4.5 for ground point angle]

FIGURE 4.6: Computer simulation of drill point.
Flute - \textit{Grinding-conventional cylindrical}

- $R_0 = 6.00$  \hspace{1cm} $D_0g = 26.00$
- Web$ = 1.80$  \hspace{1cm} $V_g = 90.00$
- $H_0 = 27.50$  \hspace{1cm} $E_{xg} = 2.50$
- $R_k = 59.00$  \hspace{1cm} $R_{kg} = 68.00$

[Compare with FIG 4.5 for ground point angle]

\textbf{FIGURE 4.7:} Computer simulation of drill point.
FIGURE 4.8: Comparing similar views of computer simulated
drill points ground to three different point
angles (refer to FIG 4.5 to FIG 4.7).
FIGURE 1.9: Comparing similar views of computer simulated drill points ground to three different point angles (refer to FIG 1.5 to FIG 1.7).
Flute - conventional
R₀ = 6.00
Web = 1.80
H₀ = 27.50
Rk = 59.00

Grinding-cylindrical
D₀g = 26.00
Vg = 90.00
Exg = 2.50
Rkg = 48.00

Grinding-cylindrical
D₀g = 26.00
Vg = 90.00
Exg = 2.50
Rkg = 59.00

Grinding-cylindrical
D₀g = 26.00
Vg = 90.00
Exg = 2.50
Rkg = 68.00

FIGURE 4.18: Comparing similar views of computer simulated drill points ground to three different point angles (refer to FIG 4.5 to FIG 4.7).
For a more complete knowledge of a drill cutting capability, the cutting geometry along its edges must be known.

Single point cutting tools are usually dealt with in terms of rake angles, inclination angle and clearance angle, for example. These angles are the concepts which eventually should be used in comparing such different tools as drills and single point cutting tools.

To design new drill flutes according to prefixed conditions such as a uniform wedge angle along the drill lip, it is not possible before a method is available to compute such an angle along the cutting edge.

Galloway (3) and others presented expressions to calculate some basic cutting angles along the drill lips. These expressions are not valid except for straight lips.

Drill curved lips are reported from time to time to perform better than the straight ones, at least in special cases - with cast iron, for instance.

Approaching the cutting angles of curved edges could be made, according to Stabler (45), in the same way as for straight cutting edges by taking the tangent at the selected point to the curved cutting edge. This approach is considered in the following analysis and computations.

4.3.1 Rake angle

The rake angle has always received a great deal of attention which is expressed in the number of papers which deal with this particular variable, and in the many designations used with the same basic concept.

The many designations used with the rake angle derive mainly from the oblique cutting case as for this case the definition of rake is dependent on the selection of the reference plane and measurement plane.
The normal rake angle is a basic angle, for the many works reporting on its influence upon cutting performance and for being a basic variable for the calculation of other rake angles such as the velocity rake and the effective rake.

The normal rake angle (Figure 4.11), \( \gamma_n \), is measured in a plane perpendicular to the cutting edge, \( p_n \), between the face \( (S_{y1} \text{ or } S_{y2}) \) and the normal to the plane defined by the cutting edge and the cutting velocity.

The vector simultaneously normal to the cutting edge vector, \( \tilde{e} \), and velocity vector, \( \tilde{v} \), is designated by \( \hat{n}_m \) (Figures 4.11 and 4.12). The vector on the rake face, normal to the cutting edge is designated by \( \tilde{t}_{y1} \).

From Figure 4.11:

\[
\hat{n}_m \cdot \tilde{t}_{y1} = |\hat{n}_m| \cdot |\tilde{t}_{y1}| \cos \gamma_n = \cos \gamma_n
\]

4.1

Computing \( \hat{n}_m \) and \( \tilde{t}_{y1} \):

From Figure 4.12:

\[
N_n \hat{n}_m = \tilde{e} \times \tilde{v}
\]

4.2

\[
\tilde{v} = (- \sin \phi, \cos \phi, 0)
\]

4.3

where \( N_m = |\tilde{e} \times \tilde{v}| \)

Vector \( \tilde{v} \) is normal to radial vector \( \tilde{r} \) and parallel to the XY plane (Figure 4.12). Vector \( \tilde{e} \) is computed from the vector, \( \hat{n}_{a1} \), normal to the flank at point \( P \), and from the vector \( \hat{n}_{y1} \), normal to the rake face (Figure 4.13):

\[
\tilde{e} = \hat{n}_{y1} \times \hat{n}_{a1}
\]

4.4
\( \vec{t}_{R1} \) - vector tang to rake face at point P

\( \vec{n}_m \) - vector \perp to cutting velocity and to cutting edge at point P

**FIGURE 4.11:** Normal rake angle definition

\[ \vec{r} = (\cos \phi, \sin \phi, 0) \]

\[ \vec{v} = (-\sin \phi, \cos \phi, 0) \]

\[ \vec{v} \perp \vec{r} \]

[Refer also to FIG 4.11]

**FIGURE 4.12:** Definition of vector normal to the cutting edge and to cutting velocity, \( \vec{n}_m \)
\[ \vec{n}_{x1} \rightarrow \text{vector} \parallel \text{Flute Face} \]

\[ \vec{n}_{k1} \rightarrow \text{vector} \parallel \text{Flank} \]

\[ \vec{e} \perp \vec{n}_{x1} \]

\[ \vec{e} \perp \vec{n}_{k1} \]

\[ \vec{t}_f \parallel \vec{e} \]

\[ \vec{t}_h \parallel \vec{e} \]

\[ \vec{t}_f \rightarrow \text{vector} \parallel \text{Flute tang} \]

\[ \vec{t}_h \rightarrow \text{vector} \parallel \text{Flute tang} \]

**FIGURE 1.13:** Determination of vector \( \vec{e} \) and cutting edge direction.

\( F \rightarrow \text{normal Flute cross section} \)

\( h \rightarrow \text{helical line on Flute Face} \)

**FIGURE 1.14:** Determination of vector, \( \vec{n}_{r1} \), normal to the rake face.

[Refer to previous FIGS.].
where \( E = |\hat{n}_{\gamma l} \times \hat{n}_{\alpha l}| \)

and \( N_{\alpha l} \cdot \hat{n}_{\alpha l} = (a f_{\alpha l}/aX, a f_{\alpha l}/aY, a f_{\alpha l}/aZ) \) \hspace{1cm} 4.5

where \( f_{\alpha l} \) is the expression for the mathematical model of flank \( S_{\alpha l} \) and \( N_{\alpha l} \) is the length of the vector on the right side of the equation.

Vector \( \hat{n}_{\gamma l} \) is computed from the vector, \( \hat{t}_h \), tangent to the helix containing \( P \), and from the vector, \( \hat{t}_f \), tangent to the flute cross-section at point \( P \) (Figure 4.14).

From Figure 4.14:

\[ N_{\gamma l} \cdot \hat{n}_{\gamma l} = \hat{t}_h \times \hat{t}_f \] \hspace{1cm} 4.6

where \( N_{\gamma l} = |\hat{t}_h \times \hat{t}_f| \)

The vector \( \hat{t}_h \), tangent to helix \( h \) (Figure 4.15) can be computed from vector, \( \hat{v} \), normal to \( \hat{r} \) at \( P \) and from the helix angle \( \gamma_h \) at point \( P \).

From Figure 4.15:

\[ T_h \cdot \hat{t}_h = \hat{v} + \cot \gamma_h \hat{r} \] \hspace{1cm} 4.7

Vector \( \hat{t}_f \) can be computed as shown in Figure 4.16:

\[ \hat{t}_f = (-\cos(\tan^{-1}(dY/dX)_{Z=0} - \xi), -\sin(\tan^{-1}(dY/dX)_{Z=0} - \xi),0) \] \hspace{1cm} 4.8

Finally, \( \hat{t}_{\gamma l} \) is computed from \( \hat{n}_{\gamma l} \) and \( \hat{e} \) (Figure 4.13):

\[ T_{\gamma l} \cdot \hat{t}_{\gamma l} = \hat{n}_{\gamma l} \times \hat{e} \] \hspace{1cm} 4.9
FIGURE 1.15: Determination of tangent to helix $h$, $\mathbf{t}_h$, from the normal to radial vector and from the helix angle.

\[
\mathbf{t}_f = (\cos(\tan^{-1}(dY/dX)_{Z=0} - \pi), \sin(\tan^{-1}(dY/dX)_{Z=0} - \pi), 0)
\]

FIGURE 1.16: Determination of tangent $\mathbf{t}_f$, to flute cross section at point $P$. 

\[\mathbf{f}(X,Y) = 0\]

\[\tan^{-1}(dY/dX)_{Z=0}\]
where $T_{\gamma_1} = |\hat{n}_{\gamma_1} \times \hat{e}|$

$\dot{v}$, $\hat{n}_{\alpha_1}$, $\hat{t}_h$ and $\hat{t}_f$ are computed directly from Equations 4.3, 4.5, 4.7 and 4.8 respectively. From $\dot{v}$, $\hat{n}_{\alpha_1}$, $\hat{t}_h$ and $\hat{t}_f$, the algorithm to compute the normal rake angle is devised as follows:

$\hat{t}_f$, $\hat{t}_h + \hat{n}_{\gamma_1}$  \hspace{1cm} (Equation 4.6)

$\hat{n}_{\gamma_1}$, $\hat{n}_{\alpha_1} + \hat{e}$  \hspace{1cm} (Equation 4.4)

$\hat{e}$, $\dot{v} + \hat{n}_m$  \hspace{1cm} (Equation 4.2)

$\hat{n}_{\gamma_1}$, $\hat{e} + \hat{t}_{\gamma_1}$  \hspace{1cm} (Equation 4.9)

$\hat{t}_{\gamma_1}$, $\hat{n}_m + \gamma_n$  \hspace{1cm} (Equation 4.1)

For computing purposes the variables which are vectors must be represented by their components in a referential system, as shown in Section 'Nomenclature'.

The flow diagram of the computer program (Appendix 1) segment to compute the normal rake angle is given in Figure 4.17.

The above presented method was tested, for straight lips, against the expression for the normal rake angle, $\gamma_n$, given by Galloway (3):

$$\tan \gamma_n = \frac{(\sigma^2 - \omega^2 \sin^2 \kappa)}{(\rho^2 - \omega^2)^{\frac{3}{2}} \sin \kappa} \tan \gamma_f - \frac{\sigma \cos \kappa}{(\rho^2 - \omega^2)^{\frac{3}{2}}} \hspace{1cm} 4.10$$

where $\rho = \frac{r}{r_0}$ and $\sigma = \frac{W'}{r_0}$
Main program

Flute faces $f_{\gamma 1}, f_{\gamma 2}$ already determined

Flank surfaces, $f_{\alpha 1}, f_{\alpha 2}$ already determined

Read number, NPOINT, of points to be considered along the drill lip

$I = 1$

Compute cylindrical coordinates at point I on the drill lip

FIGURE 4.17 (continued)
Compute vector v components parallel to XV plane and normal to radial direction (refer to text).

Compute components of vector, n, normal to flank point surface at point I (refer to text).

Compute components of vector, t, tangent to helix at point I (refer to text).

Compute slope of tangent to flute cross-section in plane XY for a point at the same radial distance as I point.

Compute angle of rotation of flute cross-section at point I on the lip relative to flute cross-section in referential plane XY.
FIGURE 4.17: Flow diagram of computer program segment to compute the normal rake angle
The normal rake angle, \( \gamma_n \), was calculated both with the formulae by Galloway and with the algorithm by the author for the case of straight lips. Large ranges of parameters, \( r_0 \), \( W' \), \( \kappa \) and \( \gamma_f \) and varying radial distances, \( r \), were investigated and the results were coincident.

The need and advantage of the present method refers mainly to the cases where the lips are curved and for which Equation 4.10 cannot be applied.

The present algorithm allows for numerical and graphical investigation of the normal rake angle for any practical range of the grinding parameters - \( d_{og} \), \( \gamma_g \), \( ex_g \), \( Kg \) - for any practical range of the conventional flute parameters - \( r_0 \), \( W' \), \( \gamma_f \), \( \kappa \) - and for other flutes defined by their cross-sections in the XY plane.

In Figure 4.18 it is shown the variation of the normal rake angle with the radial distance for three different conventional flutes; the flutes have different design point angles and are ground accordingly (Figure 4.5 and Appendix 2).

In Figure 4.19 it is shown the variation of the normal rake angle with the radial distance for one conventional flute and three different ground point angles (Figures 4.5, 4.6 and 4.7).

One curve from Figure 4.18 - \( 48^0 \) design point angle flute and \( 48^0 \) ground point angle - is compared with one curve from Figure 4.19 - \( 59^0 \) design point angle flute and \( 48^0 \) ground point angle - in Figure 4.20.

The influence of the conventional flute design parameters other than \( \kappa \), and the influence of the cylindrical grinding parameters other than \( Kg \) on the normal rake angle is shown in Appendix 3.
Flute - conventional

Grinding - cylindrical

\[ R_0 = 6.00 \]
\[ \text{Web} = 1.80 \]
\[ H_0 = 27.50 \]
\[ R_k = 27.50 \]
\[ R_k = R_{kg} \]

\[ \text{R}_k = 48.0 \text{(i)} \]
\[ \text{R}_k = 59.0 \text{(ii)} \]
\[ \text{R}_k = 68.0 \text{(iii)} \]

FIGURE 1.18: Normal rake angle for three different design point angles ground accordingly.

[Refer to FIG 1.5 and Appendix 2]
Flute - conventional
Grinding-cylindrical

R₀ = 6.00  D₀g = 26.00
Web = 1.80  Vg = 90.00
H₀ = 27.50  Exg = 2.50
Rk = 59.00  Rkg

Rkg  48.0 (i)
59.0 (ii)
68.0 (iii)

radial distance, mm

FIGURE 4.19: Normal rake angle for one flute design and three different ground point angles.
(Refer to FIG 4.5, 4.6 and 4.7).
FIGURE 4.20: Normal rake angle for one ground point angle value (i) and two different conventional flutes. Refer to Fig. 4.18 and 4.19.
4.3.2 Clearance angle

The space between the flank of a cutting tool and the machined surface is usually measured by the clearance angle.

To produce a cutting edge with an excessive clearance angle weakens the lip (10); to make it minute increases interference between tool and machined surface (17).

The clearance angle may be measured in a number of different measurement planes through the cutting edge, and several definitions of clearance angle are possible. As for the rake angle, all possible definitions can usually be referred to and calculated from the normal clearance angle.

The normal clearance angle, (Figure 4.21), \( \alpha_n \), is measured in a plane perpendicular to the cutting edge, \( p_n \), between the flank (\( S_{\alpha_1} \) or \( S_{\alpha_2} \)) and the plane defined by the cutting edge and the cutting velocity (Figure 4.21).

From Figure 4.21

\[
\vec{t}_m \cdot \vec{t}_{a_1} = |\vec{t}_m| |\vec{t}_{a_1}| \cos \alpha_n = \cos \alpha_n
\]  \hspace{1cm} \text{(4.11)}

where \( \vec{t}_m \) and \( \vec{t}_{a_1} \) are both normal to the cutting edge, the first being tangent to the machined surface and the second being tangent to the flank.

\( \vec{t}_m \) can be computed from \( \vec{e} \) and from \( \vec{n}_m \) (Figure 4.22) which have already been determined:

\[
\vec{T}_m \vec{t}_m = \vec{n}_m \times \vec{e}
\]  \hspace{1cm} \text{(4.12)}

where \( \vec{T}_m = |\vec{n}_m \times \vec{e}| \)
\[ \hat{t}_{m} \] - vector tangent to flank at point P
\[ \hat{n}_{m} \] - vector normal to machined surface at point P
\[ \hat{n}_{\alpha_{1}} \] - vector normal to flank \((S_{\alpha_{1}})\) at point P

**FIGURE 4.21:** Normal clearance angle definition

\[ \hat{t}_{m} \perp \hat{n}_{m} \]

\[ \hat{t}_{m} \perp \hat{e} \]

\[ \hat{e} \] - vector tangent to \(ce\)
\[ \hat{v} \] - velocity vector
\[ \hat{t}_{\alpha_{1}} \perp \hat{e} \]

**FIGURE 4.22:** Determination of vector, \(\hat{t}_{m}\), tangent to the machined surface.

[Refer to FIG 4.12 and 4.21]
FIGURE 1.23: Normal clearance angle and the effect of the grinding parameter Exg. [Refer to Appendix 4 for the other parameters]
FIGURE 4.21: Normal clearance angle and the effect of the grinding point angle, Rkg. (Refer to Appendix 4 for the other parameters)
FIGURE 4.25: Comparing the normal clearance to the relief angle.
\[ \hat{t}_{a1} \] can also be computed from \( \hat{e} \) and \( \hat{n}_{a1} \) which have been determined too:

\[ T_{a1} \hat{t}_{a1} = \hat{e} \times \hat{n}_{a1} \]  \hspace{1cm} (4.13)

where \( T_{a1} = |\hat{e} \times \hat{n}_{a1}| \)

Computation of the normal clearance angle was carried out according to a similar method as for the normal rake angle. Thus the author thinks it unnecessary to repeat an identical flow diagram to that in Figure 4.17 of the computer program segment (refer to Appendix 1) for this computation.

Figure 4.23 shows the influence of the grinding parameter \( e \times g \) (refer to Appendix 2 for simulated drill points) on the normal clearance angle. This grinding parameter, as the author found from numerical investigation, has a strong effect on the clearance angle without influencing so strongly the other drill point features.

The influence of the ground point angle, \( k_g \), on the normal clearance angle is also shown in Figure 4.24 (refer to Appendix 2 for simulated drill point).

The influence of the other cylindrical grinding parameters and the influence of the conventional flute design parameters is shown in Appendix 4.

The nominal relief angle, as defined by Galloway \([D.28]\) is compared with the normal clearance angle in Figure 4.25.

### 4.3.3 Wedge angle

The wedge angle is a measure of the amount of metal supporting the cutting edge.
FIGURE 4.26: Definition of the normal wedge angle

[Refer to FIG 4.11 and 4.21]

FIGURE 4.27: Definition of the inclination angle
FIGURE 1.28: Normal wedge angle for one flute and three different ground point angles. [Refer to Fig 4.5 to 4.7]
The normal wedge angle, $\beta_n$, is measured in a plane normal to the cutting edge between the face and the flank (Figure 4.26).

From Figure 4.26:

$$\hat{t}_{\gamma 1} \cdot \hat{t}_{a 1} = |\hat{t}_{\gamma 1}| |\hat{t}_{a 1}| \cos \beta_n = \cos \beta_n$$  \hspace{1cm} (4.14)

where $\hat{t}_{\gamma 1}$ and $\hat{t}_{a 1}$ have already been defined in the previous sections. Also: (BS 5533):

$$\beta_n = \pi/2 - \gamma_n - \alpha_n$$  \hspace{1cm} (4.15)

Computing $\beta_n$ from equation 4.14 serves as a verification for the computations with equation 4.15.

Figure 4.28 shows the variation of the normal wedge angle along the drill lip when one conventional flute is ground to three different point angles (refer to Figures 4.5 to 4.7 for drill point simulation).

4.3.4 Inclination angle

The angle of inclination has received a great deal of attention since Stabler (45). It has a major influence upon the chip flow and affects the cutting efficiency in several ways.

The inclination angle is measured in the plane determined by the cutting edge and the cutting velocity, between the normal to the velocity in this plane and the cutting edge (Figure 4.27).

From Figure 4.27:

$$\hat{v} \cdot \hat{n} = |\hat{n}| |\hat{v}| \cos (90^\circ - \lambda),$$

$$\hat{v} \cdot \hat{n} = \sin \lambda$$  \hspace{1cm} (4.16)
FIGURE 1.29: Inclination angle for one conventional drill flute and three different ground point angles. [Refer to FIG 1.5 to 1.7]
FIGURE 4.30: Effect of the grinding parameter \( V_g \) on the inclination angle.

[Refer to Appendix 2: varying \( V_g \)]
Figure 4.29 shows the inclination angle variation with the radial distance for the same conventional flute drill, ground to three different point angles.

The influence of the grinding parameter $V_g$ is also shown in Figure 4.30 where it can be seen to be relatively small.

The influence of other cylindrical grinding parameters other than $V_g$ and $V_g$ and the influence of the conventional flute design parameters is shown in Appendix 5.

4.4 Chip Flow Angle

The chip flow angle, as the inclination angle, has received a lot of attention since the paper (45) by Stabler. Workers such as Colwell (51), Spaans (73), Usui and Hirota (48) and others (46, 70, 71, 72) have also dealt with this variable for the oblique cutting.

Apart from the need for the effective rake angle calculation, the importance of the chip flow angle arises from the interest in chip flow control.

As the author will refer to the chip flow angle, later in this work, some laws are revised in the present section.

The chip flow angle is measured on the rake face, between the normal to the cutting edge and the chip flow velocity (16) - Figure 4.31.

Several methods to determine the chip flow angle have been reviewed and shortly discussed by Venuvinod and Shing (74). Prediction rules (45, 48, 51) have also been reported.

The most well known prediction rule is the one due to Stabler, for the number of papers referring to it and for the number of reported experiments carried out to test it. This is an empirical rule and reads:
FIGURE 4.31: Definition of chip flow angle.

- ce - cutting edge
- \( \vec{v}_c \) - chip velocity
- \( \vec{v} \) - cutting velocity
- \( \lambda \) - inclination angle
- \( \eta \) - chip flow angle
- \( b_1 \) - uncut chip width
- \( b_2 \) - chip width
\[ \eta = \lambda \]  

4.17

where \( \eta \) - chip flow angle
\( \lambda \) - inclination angle

According to Stabler (75), the rule expressed by equation 4.17 has been challenged by Shaw, Cook and Smith, Rapier and Wilkinson, among others.

Stabler himself, after further experimental work, later proposed an alteration to the previous rule which should now read (75):

\[ \eta = K\lambda \]  

4.18

where \( K \) is a constant: 0.9 \( \leq \) 0.95.

Spaans, in a recent doctoral thesis (73), found that \( K \) could vary from 0.6 to 1.4 and Rapier and Wilkinson, according to Russell and Brown (70), reported that \( \eta \) is often greater than \( \lambda \).

Spaans (73) also found that if the rake angle and/or the inclination angle differ from zero, the chip flow angle is material dependent.

Armarego and Cheng (72) suggested that chip flow angle is either entirely dependent on the inclination angle and slightly influenced by the normal rake angle. Brown and co-workers (46), Russell and co-workers (70) and Armarego and Cheng (72) found the expression

\[ \eta = \tan^{-1} (\tan \lambda \cos \gamma) \]  

4.19

to correlate satisfactorily with the results of some experiments.

Very recently, Usui and Hirota (48) approached the mechanics of oblique cutting from the point of view of the theory of plasticity.
FIGURE 1.32: Chip Flow angle against inclination angle along a drill lip, according to laws to oblique cutting, by three workers.
in a similar way as Lee and Shaffer (47) did for the orthogonal cutting, and derived the following expression for the chip flow angle:

\[ n = \tan^{-1}\left(\frac{\tan \lambda}{\sin \gamma_n + \cos \gamma_n}\right) \]  

4.20

The laws by Stabler, by Brown and by Usui if used with a drill lip would result in the curves shown in Figure 4.32.

4.5 Effective Rake Angle

As referred to in the general introduction, some authors believe that with oblique cutting the effective rake angle replaces the normal rake angle as used with orthogonal cutting.

The effective rake angle, \( \gamma_e \), can be computed from the normal rake angle, the inclination angle and the chip flow angle. The geometrical relationship between these variables has been referred to by Stabler (45), Oxford (20) and Armarego and co-workers (46) and reads:

\[ \sin \gamma_e = \sin \lambda \sin \gamma_n + \cos \lambda \cos \gamma_n \sin \gamma_n \]  

4.21

Equation 4.21 shows that, for a given cutting edge, the effective rake angle, \( \gamma_e \), depends on the chip flow angle, \( n \).

Figure 4.33 shows the variation of the effective rake angle with the radial distance, computed according to three chip flow angle laws referred to in the previous section.
For chip flow angle according to:

i - Equation 4.19 (Brown)

ii - Equation 4.17 (Stabler)

iii - Equation 4.20 (Usui)

FIGURE 4.33: Effective rake angle for several chip flow laws
4.6 **Chapter Closure**

For all the drill points ground according to the parameters utilised for geometric simulation, the author found very good agreement between the predicted contour and the actual drill point contour. Very small observed deviations, however, may be attributed to flute manufacture deviations and/or very small errors in setting the grinding machine, together with measurement errors.

A very well known drill point error, nearly always present, is the relative lip height. The simulation here presented is rigorously symmetric and does not take any account of this error, or web eccentricity, or other drill errors such as those referred to in the general introduction. The author could easily simulate these errors with his computing approach by introducing assymetrics either in the flutes shapes or in the flank point surfaces and simulating accordingly. This however is not included in this project as it is out of purpose.

An extensive piece of work could be set, in another project, for assessing the significance of the small deviations between the actual drill points and the simulated ones in order to gain information on the accuracy of the drill grinding machine type available to the author. In the same work the objective could be set to find the relative influence of each parameter upon the different types of deviations.
"The flute geometry behind the cutting edge mainly influences the conveyance of chips and assumes an important role only when chips tend to jam in the flutes".

Shaw and Oxford.

5. AN APPROACH TO NON-CONVENTIONAL DRILL

FLUTE DESIGN
5.1 Introduction

As referred to in Chapter 2, the flute profile is usually designed in order to yield a straight cutting edge. However, some workers (13, 58, 76) have reported on the better performance of the drill curved lips - as those yielded by grinding the drill to a point angle different to the one relative to the flute design (refer to Chapter 4, Figure 4.6).

The condition for the drill lip to be straight seems to stem from tradition and from empirical grounds.

The specifications for drill flute design may be given in terms of the cutting angles along the drill lip.

This chapter deals with the problem of designing a drill flute which, together with the flank surface, yields a lip with uniform wedge angle.

5.2 General Mathematical Approach to Flute Design

As in the previous chapters, the symbol $S_{a1}$ is used for the flank surface and the symbol $S_{y1}$ for the flute face. Also the equations expressing the properties of the coordinates for each surface are designated by $f_{a1}$ and $f_{y1}$ respectively.

$f_{a1}$ has been dealt with in Chapter 3. $f_{y1}$ is to be found according to the specifications to the drill lip.

Let a current point on the cutting edge, Q, be represented by $(x, y, z)$ - Figure 5.1 - and any point on $S_{a1}$, or $S_{y1}$, to be represented by $(X, Y, Z)$.

As the drill lip is one intersection of surfaces $S_{y1}$ and $S_{a1}$, the equations:
\[ f_{\gamma 1}(X,Y,Z) = 0 \]
\[ f_{\alpha 1}(X,Y,Z) = 0 \]

have a common solution for the points \((x, y, z)\).

The unit vector tangent to the drill lip is represented by:

\[ \vec{e} = (e_1, e_2, e_3) \]

and the perpendicular to \(S_{\alpha 1}\) is represented by

\[ \hat{n}_{\alpha 1} = (n_{\alpha 11}, n_{\alpha 12}, n_{\alpha 13}) \]
\[ = (\frac{\partial f_{\alpha 1}}{\partial X}, \frac{\partial f_{\alpha 1}}{\partial Y}, \frac{\partial f_{\alpha 1}}{\partial Z}) \]

where \(f_{\alpha 1}\) is a continuous function of \(X\), \(Y\) and \(Z\) (Chapter 3).

The condition for \(\vec{e}\) to be tangent to \(S_{\alpha 1}\) is:

\[ \vec{e} \cdot \hat{n}_{\alpha 1} = 0 \]

5.1

If \(s\) is chosen to represent the length from a reference point on the drill lip to \((x, y, z)\), measured along the lip, vector \(\vec{e}\) may be further represented by:

\[ \vec{e} = (dx/ds, dy/ds, dz/ds) \]

where \(x = x(s)\), \(y = y(s)\) and \(z = z(s)\) are the parametric equations for the coordinates of point \((x, y, z)\).
Equation 5.1 may be rewritten as follows:

\[
\left(\frac{af_{l}}{ax}, \frac{af_{l}}{ay}, \frac{af_{l}}{az}\right)_{x,y,z} (dx/ds, dy/ds, dz/ds) = 0
\]

or

\[
\left[\frac{af_{l}}{ax}\right]_{x,y,z} \cdot \frac{dx}{ds} + \left[\frac{af_{l}}{ay}\right]_{x,y,z} \cdot \frac{dy}{ds} + \left[\frac{af_{l}}{az}\right]_{x,y,z} \cdot \frac{dz}{ds} = 0
\]

where:

\[
(dx/ds)^2 + (dy/ds)^2 + (dz/ds)^2 = 1
\]

A third relationship independent of the above two is needed for finding points \((x, y, z)\) of the cutting edge. This will be given by considering the vector \(\vec{v}\) with the same direction as the cutting velocity:

\[
\vec{v} = (v_1, v_2, v_3)
\]

By definition of inclination angle (equation 4.16):

\[
\vec{v} \cdot \hat{e} = \sin \lambda \quad \text{(Equation 4.16), or}
\]

in other notation:

\[
(v_1, v_2, v_3) \cdot (dx/ds, dy/ds, dz/ds) = \sin \lambda
\]
The tangent to the cutting edge is tangent to the flank surface and makes an angle $\pi/2 - \lambda$ with the cutting velocity, so, the components

$$(e_1, e_2, e_3) = (dx/ds, dy/ds, dz/ds),$$

of the unit vector in the direction of the tangent to the cutting edge must be a solution to the following equations:

$$\begin{align*}
&\left[\frac{\partial f_1}{\partial x}\right]_{x,y,z} \frac{dx}{ds} + \left[\frac{\partial f_1}{\partial y}\right]_{x,y,z} \frac{dy}{ds} + \left[\frac{\partial f_1}{\partial z}\right]_{x,y,z} \frac{dz}{ds} = 0 \\
&V_1 \frac{dx}{ds} + V_2 \frac{dy}{ds} + V_3 \frac{dz}{ds} = \sin \lambda \\
&(\frac{dx}{ds})^2 + (\frac{dy}{ds})^2 + (\frac{dz}{ds})^2 = 1
\end{align*}$$

5.1, 4.16

The points $(x,y,z)$ on the cutting edge can be found by integration of $dx/ds$, $dy/ds$ and $dz/ds$.

5.3 Computation of a Non-conventional Drill Flute Profile

5.3.1 Analysis for computation

The drill specifications for the drill with a new flute design are as follows:

- body
  - $d_0$ - drill diameter (12.7 mm) ($\frac{1}{2}$")
  - $2W$ - web thickness (2 mm)
  - $\gamma_f$ - helix angle at drill periphery (30°)
FIGURE 5.1: Geometric elements for the analysis of the drill lip.

FIGURE 5.2: Specification parameters and geometric reference elements for the new flute design.
- point (cylindrical grinding parameters)
  
  \( d_{og} \) - grinding cylinder diameter (28 mm)
  
  \( v_g \) - grinding cylinder rotation (90°)
  
  \( e_{xg} \) - distance from grinding cylinder axis to drill axis (3 mm)
  
  \( 2\alpha_g \) - grinding point angle (118°)
  
- flute
  
  face - designed in order to yield, together with the flank point, a uniform wedge angle
  
  heel - determined as for the conventional flute (Chapter 2)

The flute to be designed will be referred to as a referential system of Cartesian coordinates \((X, Y, Z)\).

The outer corner, \( O_c \), of the new design drill is defined as if it belonged to a conventional flute drill with the following design parameters: \( d_o \), \( 2W \), \( \gamma_f \) and \( \kappa \) (Figures 5.2 and 5.3). For reference, the chisel corner, \( C_c \), that would be yielded with such a conventional flute drill is also considered (Figure 5.2).

Let \( Q(x,y,z) \) be a point on the lip of the new design drill such that it is on the same helix as \( P(X,V,0) \) of the new flute profile in the plane \( XY \) (Figure 5.3).

Let \( \vec{v} = (v_1, v_2, 0) \) to be parallel to the rotational velocity at point \( Q \) and

\[ |\vec{v}| = 1 \]

From Figure 5.3

\[ \phi_1 = \tan^{-1} \left( \frac{y}{x} \right) \]

\[ r = \sqrt{x^2 + y^2} \]
FIGURE 5.3: Geometric elements for the analysis of a new flute design.
\[ z = r_0 \phi_2 / \tan \gamma_f \]  

where \( \phi_1, r \) and \( z \) are the cylindrical coordinates of point \( Q \).

Also from Figure 5.3:

\[ v_1 = \sin \phi_1 \]  
\[ v_2 = \cos \phi_1 \]  
\[ v_3 = 0 \]

where \((v_1, v_2, 0)\) is in the direction of the rotational velocity at point \( Q \).

Equation \( f_{\alpha_1} = 0 \) has already been dealt with in Chapter 3:

\[ f_{\alpha_1}(X, Y, Z) = AX^2 + BY^2 + CZ^2 + DXY + EZ + FYZ + GX + HY + IZ + J = 0 \]

where coefficients from \( A \) to \( J \) depend on the grinding parameters \( d_{og}, v_g', e_x, g \) and have also been given.

From equation 3.6:

\[ \left[ \frac{\partial f_{\alpha_1}}{\partial X} \right]_{X,Y,Z} = 2Ax + Dy + Ez + G \]  
\[ \left[ \frac{\partial f_{\alpha_1}}{\partial Y} \right]_{X,Y,Z} = 2By + Dx + Iz + H \]  
\[ \left[ \frac{\partial f_{\alpha_1}}{\partial Z} \right]_{X,Y,Z} = 2Cz + Ex + Fy + I \]

All terms in the system of equations, Equations 5.1", 4.16" and 5.2, except \( \lambda \), have been expressed in terms of the coordinates \((x, y, z)\) of point \( Q \) on the drill lip.
To express the inclination angle, $\lambda$, immediately in terms of the coordinates $(x, y, z)$, $\lambda = \lambda(x, y, z)$, is not possible as, in the present situation, the lip is not specified in terms of the normal wedge angle. One solution however, is to proceed by successive approximations, by investigating different laws to the angle $\lambda$, till the desired values for the normal wedge angle are arrived at. This procedure can be implemented in a computer program and quickly and properly done by computers.

A relationship between the inclination angle, $\lambda$, and the point Q position along the cutting edge may be expressed as

$$\lambda = \lambda(K_1, K_2, K_3, \ldots, r)$$

where $K_1, K_2, K_3, \ldots$ are constants and $r$ is the radial distance from Q to the drill axis.

As $\lambda$ enters in Equation 4.16" under the form of $\sin \lambda$ it appears more reasonable to think of a relationship with the form

$$\sin \lambda = \lambda(K_1, K_2, K_3, \ldots r)$$

or, rather,

$$r \sin \lambda = \lambda(K_1, K_2, K_3, \ldots r)$$

as, by doing $\lambda(K_1, K_2, K_3, \ldots r) = \text{const}$, the law

$$r \sin \lambda = \text{const}$$

is similar to

$$r \sin \lambda = W \sin \kappa = \text{const}$$

for a conventional drill.

As a matter of simplicity and as the result of computer aided numerical investigation, the polynomial law
was selected. If \( r \neq 0 \) this equation becomes:

\[
\sin \alpha = K_1 r^2 + K_2 r + K_3 + \frac{K_4}{r} \quad (5.11')
\]

5.3.2 Non-conventional drill flute profiles

In order to solve numerically the problem above analysed, a computer program was designed and built.

The flow diagram for this computer program is presented in Figure 5.4 and the program itself is shown in Appendix 6.

For the purpose of the computation, the cylindrical grinding surface was selected, as it would be for grinding a regular conventional drill point.

In order to decide the range of wedge angles that could be reasonably selected for the present computation, the wedge angle for a 12.7 mm (½") diameter conventional drill with the same parameters \( R_o, 2W, \gamma_f \), as for the non-conventional flute, and the standard point \( 118^\circ \) was analysed - Figure 5.5.

Several wedge angle values, mainly within the range falling in the middle of curve in Figure 5.5, were tested by means of the computer program referred to above. As an example, Figures 5.6 and 5.7 show the computer plots for flutes yielding a \( 65^\circ \) and \( 60^\circ \) normal wedge angle respectively.

Observing the computer plots as shown in Figures 5.6 and 5.7 it can be noticed a "gap" between the special flute (a) and the heel (c) near the point that yields the chisel corner. This "gap" increases with the selected wedge angle, and the modification to be made to the flute at this area in order to bridge the flute face with the heel surface, for manufacture, becomes larger.
Start

Read parameters for drill body and drill point architecture

Read number of points, NPOINT, to be considered along the lip

Flank surface, f already determined

Compute conventional flute profile for comparison with profile being designed

Compute reference points: outer corner, chisel corner and chisel point from flank equations

Read value for the desired wedge angle

Read to a guess a set of values (C12) to law to Sin(λ), SEN01, and STEP for successive corrections of these values for finding an acceptable solution

FIGURE 5.4 (continued)
Read tolerance for the solution, maximum number of iterations and other parameters for NAG subroutines call.

Call subroutine and compute: UU1, UU2 - the components of the rotation unit vector; DFDX, DFDY, and DFDZ - the components of the normal to flank; CE1, CE2 and CE3 - the components of the tangent to the cutting edge at point I; and the points of the profile generated according to values (C12).

Compute the wedge angle.

If I < NPOINT, go to step 1; otherwise, call subroutine to compute the deviations of the wedge angle from the desired value, comparing successive residuals of a function for different sets, (C12), of parameters to the inclination angle law.

FIGURE 5.4 (continued)
FIGURE 5.4: Flow diagram for the computer program for finding a non-conventional flute
FIGURE 5.5: Normal wedge angle for conventional drill
a - new flute (65° wedge angle)
b - conventional flute
c - heel

Flute -

Grinding-cylindrical

$R_0 = 6.35$
$\text{Web} = 2.00$
$H_0 = 30.00$

$\text{D}0g = 28.00$
$V_g = 90.00$
$E_xg = 3.00$
$R_kg = 59.00$

FIGURE 5.6: Computer plots of conventional and new design flutes.
a - new flute (60° wedge angle)

b - conventional flute

c - heel

Flute - Grinding-
cylindrical

R0 = 6.35  D0g = 28.00
Web = 2.00  Vg = 90.00
H0 = 30.00  Exg = 3.00
Rkg = 59.00

FIGURE 5.7: Computer plots of conventional and new design flutes.
From his numerical investigations and his observations, the author decided to select the wedge angle to be 60°, as it is well above the wedge angle at the outer corner of the conventional drill (Figure 5.5) and it yields a flute face (Figure 5.7) for which the normal wedge angle is nearly constant (Figure 5.8). Additionally, the inclination angle (Figure 5.9) and the normal rake angle (Figure 5.10) are such that the effective rake angle, after Stabler (45), is very close to the one to the conventional drill (Figure 5.11). Finally, the alteration necessary to be made to the flute face, for manufacture, in order to bridge it with the heel surface at the region of the chisel corner is small (Figure 5.7).

5.4 Drill Prototype Manufacture

Drill prototype manufacture involved the collaboration of drill manufacturers and was not controlled by the author.

The drill normal cross-section design, after the computer plot shown in Figure 5.7, is presented in Figure 5.12.

The geometric simulation of the drill point according to new design (Figure 5.12) is shown in Figure 5.14.

The flute cross-section, normal to flute helical direction, for flute cutter design (at the drill's manufacture) is shown in Figure 5.13.

The author has had two lots of prototypes of the new drill design build, one after the other, from two different drill manufacturers.

Drills belonging to one lot presented a web weakness and some of them split into pieces, after a few dozen holes. Drills belonging to the other lot have been made by another drill manufacturer, and they have shown (Figures 5.15, 5.16 and 5.17) to be closer to the design by the author (Figure 5.12) than the ones from the first batch.
FIGURE 5.8: Normal wedge angle for the new flute design.
FIGURE 5.9: Inclination angle for the new flute design.
Flute -\new  
Grinding- cylindrical

\begin{itemize}
\item \text{R0} = 6.35
\item \text{Web} = 2.00
\item \text{H0} = 30.00
\end{itemize}

\begin{itemize}
\item \text{D0g} = 28.00
\item \text{Vg} = 90.00
\item \text{Exg} = 3.00
\item \text{Rkg} = 59.00
\end{itemize}

\textbf{FIGURE 5.10:} Normal rake angle for the new flute design.
FIGURE 5.11: Effective rake angle computed for chip flow angle law according to Stabler's rule for oblique cutting.
FIGURE 5.12: Drill cross section designed after FIG 5.7

FIGURE 5.13: Flute cross section normal to the flute helical direction for the new flute design
[FIG 5.12]
FIGURE 5.14: Computer geometric simulation of drill point according to design shown in FIG 5.12
FIGURE 5.15
New design drill cross section - view from the drill point

FIGURE 5.16
Computer simulated cross section after manufactured new design drill (FIG 4.15) - view from the drill point

FIGURE 5.17
As in FIG 5.16 - view from the drill shank
Flute - new

Grinding-
cylindrical

R0 = 6.35
Web= 2.00
H0 = 33.00

D0g= 28.00
Ug = 90.00
Exg = 3.00
Rko = 59.00

FIGURE 5.18: Computer geometric simulation of drill point as manufactured. (Refer to FIG 5.16 and 5.17)
Drills belonging to the referred to second lot will be designated by new design drills, or new flute drills and the simulation for this actual new design drill point is shown in Figure 5.18.
"No man ought to be discouraged if the experiments he puts in practice answer not his expectations; for what succeeds pleases more, but what succeeds not many times informs no less".

Bacon

6. PERFORMANCE TESTS - COMPARING LIP WEAR ON CONVENTIONAL AND NEW DESIGN DRILL
6.1 Introduction

6.1.1 Review of drill performance concept

The author did not find in the literature a generally accepted drill performance measure. He rather found that the drill performance concept comprehends several aspects. For convenience some drill performance aspects will be revised concisely.

For Waller (31) the aspect of drill performance most emphasized in the past was drill life. Lorenz (28,29) also refer to drill life when he reports on drill performance. Valery (82) reported upon durability of drills.

Micheletti and Levi (23) restrained the analysis of drill performance to the study of drilling forces, and so did Fujii and co-workers (37).

Billau (11) emphasized the hole quality with the double margin drill. Burant and Skingle (83) looked for high metal-removal rates when testing different drills for the determination of optimum drilling conditions for an Al-Si alloy.

Ernest and Haggerty (2) investigated drill performance by considering the following aspects: (i) torque and thrust, (ii) drill life and (iii) hole oversize.

Galloway and Morton (10) have listed the main objectives of drill users:

i) high rate of penetration;
ii) long drill life;
iii) accuracy of holes;
iv) high drilling efficiency.

Later, Galloway (3) considered drilling performance criteria as follows:

i) rate of penetration;
ii) drill life;
iii) efficiency of metal removal;
iv) hole accuracy;
v) hole surface finish.

Kanai and Kanda (33), in a contribution for the development of a standardized drill test, recommended the wear at the drill outer corner to be measured and to be used as a drill performance index.

Farnworth (84) defined a drilling performance index based on economic factors where drill life is one of the variables accounting for the index calculation.

Nakayama (66), Arshinov and Aleksev (4), CETIM (85) and others (83) referred to chip geometry in assessing machining performance.

6.1.2 Drill life

In spite of being very frequently used as a performance criterion, drill life definition is still open to discussion.

According to Singpurwalla and Kuebler (86) drill life could mean different things to different people. Galloway and Morton (10) found it difficult to recommend means to determine the end of drill life but based on personal judgement. Also Valery (82) stated that drill life is somewhat vague and Williams and McGilchrist (87) referred that no current drill life criterion provides a unique measure of drill failure. Burant and Skingle (83) referred to the fact that drill life was determined more or less subjectively.

The author found in some reports (86,87) the writer's referring that they relied on the personal opinions of drilling operators rather than on any objective criterion to judge upon the end of drill life.

Frequently, squeaking (82,88), crying (86), screaming (89) and screeching (11,35) during drill is taken as an indication of drill failure. Singpurwalla and Kuebler (86) and PERA (24) determined the end
of drill life by a change in sound during drilling. Iwata and Moriwaki (90) and Weller and co-workers (91) studied acoustic emission from the cutting process in order to find some useful information about the cutting state.

The change in colour of the drill during drilling has also been suggested by Singpurwalla and Kuebler (86) as a (subjective) method for drill life criterion.

Drilling torque and thrust have been suggested by Galloway (3), Galloway and Morton (10) and others (89), as indicators of drill dulling. Also (BS 5623) refers to the cutting forces used as a basis for tool life criterion in scientific research and in adaptive control systems. However, some doubts on the methods based upon the use of dynamometers and upon the variations of drilling forces in assessing drill life have been put forward by Oxford (discussion of paper (3)), Williams and McGilchrist (87) and Billau (35).

6.1.3 Drill wear

To allow a drill to reach the state of complete failure can lead to irreparable damages or long lasting regrinding operations. Thus Oxford (92) and others (93) recommended that excessive drill wear should be avoided as a matter of cost effectiveness.

Frequently drill life (and in general tool life) is associated with flank wear by some workers. (Billau (35) found the "wear rate"/"life" to correspond favourably with the "screech"/"life" for the drills and conditions he tested. For Valery (82), the end of drill life appears to be related to an area of wear at the drill lip. Burant and Skingle (83) decided that drill life would be ended at the point at which the "wear pattern changes to an increasing rate". Soloja and Toko (64) also based drill life upon wear criteria. Subramanian and Cook (94) reported that the limit of the economical life of a tool is determined by the extent of wear on the tool, and according to Tseng and Noujaim (95) the wear land width "is considered by many to be the most dependable guide of tool life".
Frequently tool life is defined in terms of a pre-determined wear land width (Figure 6.1) (1, 88, 95, 97, 98, BS 5623), and one great advantage of such a method consists of not being dependent on individual judgement.

Subramanian and Cook (94) and Kanai and Kanda (33) find the drill flank wear to be relatively easy to measure, however, Lorenz (88), considers that it is very time consuming.

Billau (11), Subramanian and Cook (94), among others, established that drill lip flank wear develops in three stages (Figure 6.2);

A - rapid and non-linear increase of the wear land width due to the removal of the sharp edge.
B - slow, long and uniform rate of wear.
C - accelerated wear rate leading to increase of noise and drill failure.

In order to monitor and to assess as objectively as possible the decreasing ability of drill lips to cut, as drilling progresses, the drills dealt with in this work will be tested for wear.

6.2 Experimental Design

The aim for the experiments to be made is to compare two drill types - conventional and new design - for wear at the neighbourhood of the drill outer corner with the number of holes drilled.

6.2.1 Drill test type

A great selection of drilling speeds and feeds are usually available to drilling researchers and drill users. Lorenz (28), Lenz (99), Galloway and Morton (10), Valery (82), Williams (87), Singpurwalla and Kuebler (86) and Billau (35), among others, reported on the influence of speed and feed on drill life and they found the drill life to decrease with increasing speeds and feeds.
FIGURE 6.1: Geometry of a worn cutting edge

FIGURE 6.2: Drill lip wear pattern (11)
[Refer to text for phases A, B and C]
As a matter of economy and because resources to researchers are usually scarce, tests should be as short as possible. However, there is no general agreement on the acceptance of accelerated life testing (100). Some workers (101) argue that the same phenomena (thermic, dynamic, structural) are present during cutting, either during slow or accelerated cutting; others (10) think that the mechanism of drill failure or wear varies with the cutting conditions.

Drilling tests may be divided into three types (3,10):

- short duration tests - up to approximately 30 holes, each two diameters deep
- medium duration tests - up to approximately 40-140 holes, each two diameters deep
- long duration tests - more than 150 holes, each two diameters deep.

A literature survey revealed that many reported drilling tests (3, 5, 28, 29, 87, 88, 89, 94) are medium duration tests as they are frequently roughly centred at 100 holes. For Galloway (3), the knowledge gained through medium-duration life tests could be used in the workshop.

In view of the above, the author decided to perform medium duration drilling tests.

6.2.2 Factors selection

The author thought it to be necessary to investigate the two different flute designs response to the variation of (i) speed, (ii) feed and (iii) point angle as these are the variables with a major influence on drill performance and over which the user has usually a wide control. Limitations to these variables may be imposed by the available range of speeds and feeds in the drilling machine and by the maximum point angle that can be set in the grinding machine.
FIGURE 6.3: Radial arm drilling machine
The very limited amount of experience on the new design drill and also the limited resources available to the author prevented the inclusion of a larger number of variables.

6.2.3 Equipment

The drilling machine, the coolant, other equipment, the drills and other factors were involved in close control.

6.2.3.1 Drilling machine

A radial drilling machine (Figure 6.3) was used for all drilling tests relating to this project. Its features are as follows:

Manufacturer: Archdale Limited
Type: 6 ft radial arm
Power: 5 HP motor
Spindle: 2.5 inch diameter - No 5 internal Morse taper
Speeds: 60 85 110 140 197 260
        350 490 640 820 1140 1500 rev/min
Penetration: 30 45 70 103 157 240 rev/in
Coolant supply: 5 l/min (= 1.1 gallons/minute)

To produce a portal frame-like structure an adjustable brace was fixed to the free end of the arm.

The machine was checked for alignment. The speeds were checked with a stroboscope device and the feeds by a dial gauge.

6.2.3.2 Drill grinding machine

A Dormer model 84 drill grinding machine was used in this work for the preparation and regrinding of the drill points (Figure 6.4).

Billau (11) has investigated with a perspex model the shape of the flank face produced by this grinding machine and found it to be of a cylindrical form.
The relevant technical data for this machine is as follows:

Grinding wheel, diameter: 203 mm  
width: 25 mm  
bore: 102 mm  
Maximum peripheral speed: 30 m/sec  
Range of drill diameters: 3 mm - 32 mm  
Maximum overall length of drill: 420 mm  
Range of point angles: 90° - 140°

With the machine available to the author, the point angle could not be larger than about 135°.

6.2.3.3 Drill geometry measurement machine

Much of the drill geometrical accuracy depends on the careful control of quality during the manufacture stage. Careful drill point grinding however is as much important as the manufacture.

The drills reported in this work have been manufactured under special control and the drill grinding by the author has been made and controlled in the most careful way. For the control of the geometrical drill features, before any test, a Dormer model 94 goniometer drill inspection unit was used (Figure 6.5). The angles can be measured to the 5’ and the distances to the 0.01 mm.

For proper positioning of the drill in the goniometer and for more accurate results, the main vee block as from the manufacturer was provided with a clamping system in order the drill could be properly set and held during measurement (Figure 6.5).

6.2.3.4 Microscope

For the wear measurement on the flank face of the drills a Hilger and Watts microscope provided with a table operated by two perpendicular micrometer screws was used. The normal eyepiece of the microscope was replaced by a micrometer graticule type of eyepiece (Figure 6.6).
FIGURE 6.6: Hilger and Watts microscope adapted for drill lip wear measurement
The position of the points on the cutting edge and the position of the points on the line determining the wear land on the flank were measured relatively to a reference line etched on the flank (Section 6.3.1). Measurements were made at five equally spaced points near the outer corners, on both lips of each drill (Section 6.3.1).

6.2.4 Preliminary life tests for selection of values of factors

In order to establish the cutting conditions for the main wear testing the author: (i) surveyed technical data available for the conventional drills (mainly reports on drill life), (ii) ran preliminary tests with both drill types.

The preliminary tests were run to determine the penetration rates which would lead to medium-duration tests (see Section 6.2.1). The results were used to select the cutting speed and drilling feed values shown in the next section.

6.2.5 Statistical design of experiments

In designing the experimental work for the drill wear tests the following objectives were considered:

- investigate the difference (if any) between the conventional and the new design drill when speed, feed and point angle are varied

- design the experiments in order that statistical analysis can be exercised with the data collected

- plan statistically the experimental sequence and the combination of factors for each experiment

- provide for conclusions relating to the interaction between factors
make the series of experiments as economical as possible

The advantages of statistical design of experiments have been emphasized in many works by statisticians (103, 104, 105) and by some researchers in the drilling area (87, 88).

Each drill type is tested for combinations of some values of the factors referred to in Section 6.2.2: (i) cutting speed, (ii) drilling feed and (iii) point angle.

As a matter of efficiency, a factorial design experiment will be used in the present investigation, and for statistical analysis the experiments relating to the same drill type are arranged in separate blocks.

According to the factorial design, each factor is given two values: one conventionally called low and the other high. To use a special notation similar to the one frequently found in books on statistics (102, 105) the symbols shown in Table 6.1 were adopted.

**TABLE 6.1: Symbols for Factor Levels**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (S)</td>
<td>1</td>
<td>s</td>
</tr>
<tr>
<td>Feed (F)</td>
<td>1</td>
<td>f</td>
</tr>
<tr>
<td>Point angle (κ)</td>
<td>1</td>
<td>κ</td>
</tr>
</tbody>
</table>

The following factors levels were considered:

- Speed 1 - 32.72 m/min (820 rpm)
- s - 45.48 m/min (1140 rpm)
Feed 1 - 0.106 mm/rev (240 RPI)
f - 0.162 mm/rev (157 RPI)
Point 1 - 118°
κ - 134°

The different combinations of the above factors levels for wear testing are shown in Table 6.2.

**TABLE 6.2: Combination of Factors Levels for Wear Testing**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>S (rpm)</th>
<th>F(RPI)</th>
<th>κ(deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>l</td>
<td>820</td>
<td>240</td>
<td>118</td>
</tr>
<tr>
<td>s</td>
<td>1140</td>
<td>240</td>
<td>118</td>
</tr>
<tr>
<td>f</td>
<td>820</td>
<td>157</td>
<td>118</td>
</tr>
<tr>
<td>κ</td>
<td>820</td>
<td>240</td>
<td>134</td>
</tr>
<tr>
<td>sf</td>
<td>1140</td>
<td>157</td>
<td>118</td>
</tr>
<tr>
<td>sκ</td>
<td>1140</td>
<td>240</td>
<td>134</td>
</tr>
<tr>
<td>fκ</td>
<td>820</td>
<td>157</td>
<td>134</td>
</tr>
<tr>
<td>sfκ</td>
<td>1140</td>
<td>157</td>
<td>134</td>
</tr>
</tbody>
</table>

### 6.3 Drill Wear Testing

#### 6.3.1 Testing procedure

The aim of the wear testing was to compare the performance of two drill types differing by the flute form. For the purpose of eliminating the effect of any difference between drills other than the flute profile shape, only one drill of each type was used. To use more than one drill of each type would introduce additional geometric differences such as minor flute shape differences among the drills of the same type as well as differences in web thickness, web eccentricity, relative lip height and drill straightness which would affect the variability of the results of the drilling tests (Chapter...
To use only one drill was found in literature (3, 87) to be acceptable.

Two drills, one of each type, were selected with the most approximate web thicknesses, helix angles and drill diameters (Section 6.3.2).

The decreasing length of the drills with the successive drill regrindings could be compensated by a special drill holder (Figure 6.7) that allows for control of drill projection length.

To keep to a minimum any discrepancies from drill regrindings, the tests were run first for one point angle. After completion of these tests the grinding machine was set for the other angle and this set-up was kept until all the tests had been run.

After each drill regrinding the web thickness and the drill diameter of each drill were checked for differences due to possible web taper and to the negligible drill diameter taper (Tables 6.3 and 6.4). The differences were found to be within the measurement error for the drill length removed by regrinding during all drilling tests.

After each test the drills were observed for any change of colour that could affect drill material hardness and structure and drill regrinding was made carefully as recommended in (35) to avoid drill burning. Drill hardness was measured on the drill margins after each regrinding and was found to be within the measured values as received (Section 6.3.2).

Each hole was 3 drill diameters deep and the drill wear was measured at five points, on both lips of each drill, numbered as shown in Figure 6.8. Point 5 is coincident with the outer corner and each point is 0.508 mm (0.02") distant to the next one.

With this procedure, not only the wear at the outer corner but also along a length of about 1/3 of the whole lip length was measured, and in this way it will be possible to monitor and to compare the pattern of wear in the neighbourhood of the outer corner for both drill types.
FIGURE 6.7: Bristol Erickson chuck for variable drill length projection
FIGURE 6.8: Wear measurement points on drill lips in the neighbourhood of the outer corner.

FIGURE 6.9: Etched line on the drill Flank surface for wear measurement reference.
The wear was measured after the fifth, tenth, fifteenth, and twentieth holes and each ten holes after the twentieth. Wear measurements were carried out until the drill failed, or, until the 150th hole if failure had not occurred before.

For measurement reference, etched lines were produced on the flanks, parallel to the line defined by the outer corner and the chisel corner (Figure 6.9).

For reading accuracy three readings were taken at each measurement point.

6.3.2 Drill features

As it has already been referred to, the tests were run with two types of drills: conventional and new design. For this purpose, together with the new design drills, some conventional drills were also manufactured from the same lot of material and according to the same production and treatment processes, in a way that only the differences in the flute geometries would be expected (Figure 6.10).

The drills were manufactured from the same lot of M2 high speed steel whose nominal composition is:

<table>
<thead>
<tr>
<th>C(%)</th>
<th>W(%)</th>
<th>Mo(%)</th>
<th>Cr(%)</th>
<th>V(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.83</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

The drills were heat treated as follows:

- Pre-heat: 800 - 850°C
- High heat: 1220 - 1240°C
- Temperature: 550 - 560°C - one hour twice
- Steam temperature: 470°C - for half an hour

All the drills, especially manufactured, both conventional and new design, are straight shank drills and are held in a Bristol Erikson chuck (Figure 6.7).
FIGURE 6.10: Cross sections of conventional (i) and new design (ii) drill - view from the drill point.
Drill hardness was measured on the drill margins, near the drill point, in a Vickers Armstrong pyramid hardness testing machine and all results were found to be within the interval 64-66 HRc (Rockwell C scale)

Drill nominal relief angle $[\theta_{20}]$, chisel edge angle and heel corner elevation (height of the heel corner relative to the outer corner), were the same as for the design of the new drill (Chapter 5) (Tables 6.3 and 6.4).

The point angle was selected for two values: $118^\circ$ and $134^\circ$; the first being the standard point angle (BS 328), and the second being the maximum possible within the grinding machine available to the author.

Two drills of each type were chosen and their cross-sections projected and magnified. For each drill type the differences found between the two sections were within the measurement errors.

For the new design drill, the differences between the designed profile and the profile as manufactured were found to be small (Chapter 5). However, for drill point geometric simulation and for all other computing purposes, as a matter of accuracy, the new drill flute profile as manufactured is used instead of the designed one.

For the purpose of mathematical representation of the profile as manufactured, a set of points with coordinates $(X,Y)$ was taken by superimposing a graticule to the projected profile. This set of points was further represented by a polynomial law that better fitted their coordinates in order that the profile could be mathematically dealt with as a continuous curve.

The conventional drill profiles as manufactured were also compared to the conventional computed profiles and appeared to be similar.

Simulations for both drill types and both drill point angles are shown from Figures 6.11 to 6.14 and the actual features as measured are shown in Tables 6.3 and 6.4.
### TABLE 6.3: Drill Specification for Drills Used with Tests for 118° Nominal Point Angle

<table>
<thead>
<tr>
<th>Grinding Parameters</th>
<th>$d_{og}(\text{mm})$</th>
<th>$\gamma_g(\text{deg})$</th>
<th>$\text{exg(\text{mm})}$</th>
<th>$\kappa_g(\text{deg})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28</td>
<td>90</td>
<td>3.0</td>
<td>59</td>
</tr>
</tbody>
</table>

### DRILL SPECIFICATION

<table>
<thead>
<tr>
<th>Item</th>
<th>Conventional Drill</th>
<th>New Design Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shank</td>
<td>Straight</td>
<td>Straight</td>
</tr>
<tr>
<td>Overall length (mm) (before first test for 118° point)</td>
<td>150.5</td>
<td>151.0</td>
</tr>
<tr>
<td>Flute length (mm) (before first test) for 118° point</td>
<td>101.0</td>
<td>102.0</td>
</tr>
<tr>
<td>Drill diameter (mm)</td>
<td>12.70</td>
<td>12.70</td>
</tr>
<tr>
<td>Web thickness (mm)</td>
<td>1.95</td>
<td>1.95</td>
</tr>
<tr>
<td>Helix angle (deg)</td>
<td>33.0</td>
<td>33.2</td>
</tr>
<tr>
<td>Point angle - outer corner/chisel corner line (deg)</td>
<td>118.1</td>
<td>117.8</td>
</tr>
<tr>
<td>Nominal relief angle (deg)</td>
<td>14.2</td>
<td>14.6</td>
</tr>
<tr>
<td>Chisel edge angle - outer corner/chisel corner line (deg)</td>
<td>113.6</td>
<td>112.0</td>
</tr>
<tr>
<td>Width of margin (mm)</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Back taper at margin (%)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Elevation of the heel corner relative to the outer corner (mm)</td>
<td>0.48</td>
<td>0.54</td>
</tr>
<tr>
<td>Lip length - outer corner/chisel corner distance (mm)</td>
<td>6.85</td>
<td>6.75</td>
</tr>
<tr>
<td>Chisel edge length (mm)</td>
<td>2.10</td>
<td>2.40</td>
</tr>
<tr>
<td>Eccentricity of chisel (mm)</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Lip height difference (mm)</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Flute spacing</td>
<td>&lt;5'</td>
<td>&lt;5'</td>
</tr>
</tbody>
</table>
### TABLE 6.4: Drill Specification for Drills Used with Tests for 134° Nominal Point Angle

<table>
<thead>
<tr>
<th>Grinding Parameters</th>
<th>( d_{og} ) (mm)</th>
<th>( \nu_g ) (deg)</th>
<th>( exg ) (mm)</th>
<th>( \kappa_g ) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>34</td>
<td>100</td>
<td>3.8</td>
<td>( \approx 67 )</td>
</tr>
</tbody>
</table>

**DRILL SPECIFICATION**

<table>
<thead>
<tr>
<th>Item</th>
<th>Dimension</th>
<th>Conventional Drill</th>
<th>New Design Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shank</td>
<td></td>
<td>Straight</td>
<td>Straight</td>
</tr>
<tr>
<td>Overall length (mm) (before first test for 134° point)</td>
<td>144.5</td>
<td>145.5</td>
<td></td>
</tr>
<tr>
<td>Flute length (mm)</td>
<td>95</td>
<td>96.5</td>
<td></td>
</tr>
<tr>
<td>Drill diameter (mm)</td>
<td>12.70</td>
<td>12.70</td>
<td></td>
</tr>
<tr>
<td>Web thickness (mm)</td>
<td>1.95</td>
<td>1.95</td>
<td></td>
</tr>
<tr>
<td>Helix angle (deg)</td>
<td>33.0</td>
<td>33.2</td>
<td></td>
</tr>
<tr>
<td>Point angle - outer corner/chisel corner line (deg)</td>
<td>133.8</td>
<td>133.5</td>
<td></td>
</tr>
<tr>
<td>Nominal relief angle (deg)</td>
<td>13.6</td>
<td>13.8</td>
<td></td>
</tr>
<tr>
<td>Chisel edge angle - outer corner/chisel corner line (deg)</td>
<td>117.5</td>
<td>116.2</td>
<td></td>
</tr>
<tr>
<td>Width of margin (mm)</td>
<td>0.90</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Back taper at margin</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Elevation of the heel corner relative to the outer corner (mm)</td>
<td>0.65</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>Lip length - outer corner/chisel corner line (mm)</td>
<td>6.35</td>
<td>6.40</td>
<td></td>
</tr>
<tr>
<td>Chisel edge length (mm)</td>
<td>2.10</td>
<td>2.35</td>
<td></td>
</tr>
<tr>
<td>Eccentricity of chisel (mm)</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Lip height difference (mm)</td>
<td>0.01</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Flute spacing (deg)</td>
<td>( &lt;5' )</td>
<td>( &lt;5' )</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 6.11: Computer geometric simulation of conventional flute drill point. (Refer to TABLE 6.3)
FIGURE 6.12: Computer geometric simulation of new design Flute drill point. [Refer to TABLE 6.3]

| Flute - | Grinding-
<table>
<thead>
<tr>
<th>new</th>
<th>cylindrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO = 6.35</td>
<td>D0g= 28.00</td>
</tr>
<tr>
<td>Web= 1.95</td>
<td>Vg = 90.00</td>
</tr>
<tr>
<td>H0 = 33.20</td>
<td>Exg= 3.00</td>
</tr>
<tr>
<td></td>
<td>Rkg= 59.00</td>
</tr>
</tbody>
</table>

[scale - 4.5 / 1]
FIGURE 6.13: Computer geometric simulation of conventional Flute drill point. (Refer to TABLE 6.1)
Flute - new

Flute - new

Grinding-
cylindrical

R0 = 6.35
Web = 1.95
H0 = 33.20

D0g = 34.00
Vg = 100.00
Exg = 3.80
Rkg = 67.00

[scale - 4.5 / 1]

FIGURE 6.14: Computer geometric simulation of new design flute drill point. [Refer to TABLE 6.4]
6.3.3 Material

Selection of the testing material was limited to existing stocks in CIS (Centre for Industrial Studies, Loughborough University).

152 mm x 152 mm x 77 mm (6" x 6" x 3") blocks of EN43 steel in the normalised condition were used for the wear tests. The nominal chemical composition for this steel is:

<table>
<thead>
<tr>
<th>C(%)</th>
<th>Si(%)</th>
<th>Mn(%)</th>
<th>S(%)</th>
<th>P(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45/0.50</td>
<td>0.05/0.35</td>
<td>0.7/1.0</td>
<td>0.06 Max</td>
<td>0.06 Max</td>
</tr>
</tbody>
</table>

A sample analysis indicated that the material was within the chemical specifications.

The blocks were machined on both faces for parallelism and surface roughness uniformity. The hardness was measured on all blocks, on both faces and it was found that approximately 90% of the readings fall in the interval 180 HB - 190 HB.

The blocks were drilled on both faces.

6.4 Wear Tests Results

The "screech" many times referred to in literature (Section 6.1.2) and observed in the workshop was the criterion to decide that the drilling operation should not be continued.

When "screech" occurred the bottom of the hole presented radial marks of the type already referred to by Singpurwalla and co-workers (86), and the electric power input to the drilling machine increased by a significant amount as also reported in (89).
"Screech" occurred in the following cases:

- **118° x 1140 rpm x 240 RPI**
  - Conventional drill - 90 holes
  - New design drill - 84 holes

- **118° x 1140 rpm x 157 RPI**
  - Conventional drill - 77 holes
  - New design drill - 60 holes

- **134° x 1140 rpm x 240 RPI**
  - Conventional drill - 50 holes
  - New design drill - 69 holes

- **134° x 1140 rpm x 157 RPI**
  - Conventional drill - 31 holes
  - New design drill - 42 holes

The results for the wear loss (Figure 6.1) at point 1 (Figure 6.8) against the number of holes drilled, for each set of drilling conditions, and for both drill types are shown from Figure 6.15 to Figure 6.22. Similar results for the outer 4 points selected along the drill lips are shown in Appendix 7.

The variation of the wear loss with point position along each lip of each drill type, at the neighbourhood of the outer corner, at the end of the 150th hole, or shortly before drill failure, is represented from Figures 6.23 to 6.30 for all sets of drilling conditions tested.

### 6.5 Analysis of the Results

The wear curves shown in Figures 6.15 to 6.22 and in Appendix 7 appear to fit phases A and B of the typical wear curve shown in Figure 6.2. Phase C of the referred to typical curve hardly could be noticed with point 5 (Appendix 7) for one experiment leading to drill failure (134° x 1140 rpm x 157 RPI).
FIGURE 6.15: Wear loss at point 1 of each drill lip

- Conventional Flute
- New Flute

118 deg point
820 RPM
240 RPM
FIGURE 6.16: Wear loss at point 1 of each drill lip
FIGURE 6.17: Wear loss at point 1 of each drill lip
Figure 6.18: Wear loss at point 1 of each drill lip.
FIGURE 6.19: Wear loss at point 1 of each drill lip

- o conventional Flute
- + new Flute

134 deg point
820 RPM
210 RPI
FIGURE 6.20: Wear loss at point 1 of each drill lip
FIGURE 6.21: Wear loss at point 1 of each drill lip
FIGURE 6.22: Wear loss at point 1 of each drill lip
FIGURE 6.23: Wear loss at five points along each drill lip
FIGURE 6.24  Wear loss at five points along each drill lip
FIGURE 6.25: Wear loss at five points along each drill lip
FIGURE 6.26: Wear loss at five points along each drill lip
FIGURE 6.27: Wear loss at five points along each drill lip
FIGURE 6.28: Wear loss at five points along each drill lip
FIGURE 6.29: Wear loss at five points along each drill lip
FIGURE 6.30: Wear loss at five points along each drill lip
There is an immediate detectable difference between the wear profiles referring to the new design drill and those for the conventional one: the initial phase A for the conventional drills portrays a more intense wear than that for the new design drill, especially with points 3, 4 and 5 (Appendix 7). For point 5, for instance, the wear loss relative to phase A of the wear curves is 2 to 3 times bigger with the conventional drill than with the new design drill.

Phase B is longer than phase A and it is expected to reflect more consistently the wear performance of each drill type.

To compare the wear performance of both drill types, the wear rate, measured by the slope of the straight line that better fits phase B of each wear curve (Figures 6.15 to 6.22 and Appendix 7), was computed and averaged for each pair of lips of each drill and for each set of drilling conditions. The results are shown in Table 6.5.

With few exceptions, all values shown in Table 6.5 appear to be higher for the new design drill than for the conventional one, for the same drilling conditions. Comparing the values for the new design drill with those for the conventional drill shown in Table 6.5, the minimum ratio was found to be 0.51 and the maximum 2.52. However, on average, the values of the wear rate for the new design drill are approximately 50% higher than those for the conventional drill, for the same speed, feed and point angle.

In order to test the statistical significance of the differences between the values shown in Table 6.5 an analysis of variance has been carried out on these values.

The results of the tests are arranged in two separate blocks: one referring to the conventional drill and another to the new design drill.

The results for point 1 (Figure 6.8) on the lips are taken from Table 6.5, multiplied by 10 for convenience of the calculations, and
TABLE 6.5: Wear Rate
In optical divisions per hole (Average for two lips. After Figures 6.15 - 6.22 and Appendix 7)

<table>
<thead>
<tr>
<th>Drill Type</th>
<th>Point Angle (deg)</th>
<th>RPI</th>
<th>RPM</th>
<th>Point 1</th>
<th>Point 2</th>
<th>Point 3</th>
<th>Point 4</th>
<th>Point 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>118</td>
<td>240</td>
<td>820</td>
<td>0.071</td>
<td>0.053</td>
<td>0.066</td>
<td>0.088</td>
<td>0.350</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1140</td>
<td>0.230</td>
<td>0.250</td>
<td>0.298</td>
<td>0.316</td>
<td>0.345</td>
</tr>
<tr>
<td>Conventio-</td>
<td>157</td>
<td>820</td>
<td>0.168</td>
<td>0.180</td>
<td>0.194</td>
<td>0.159</td>
<td>0.350</td>
<td></td>
</tr>
<tr>
<td>nal</td>
<td></td>
<td></td>
<td>1140</td>
<td>0.335</td>
<td>0.380</td>
<td>0.391</td>
<td>0.436</td>
<td>0.465</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>820</td>
<td>0.036</td>
<td>0.052</td>
<td>0.048</td>
<td>0.066</td>
<td>0.370</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1140</td>
<td>0.233</td>
<td>0.278</td>
<td>0.348</td>
<td>0.308</td>
<td>0.645</td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>820</td>
<td>0.114</td>
<td>0.132</td>
<td>0.132</td>
<td>0.128</td>
<td>0.355</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1140</td>
<td>0.387</td>
<td>0.446</td>
<td>0.551</td>
<td>0.756</td>
<td>1.275</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>820</td>
<td>0.044</td>
<td>0.068</td>
<td>0.087</td>
<td>0.121</td>
<td>0.465</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1140</td>
<td>0.375</td>
<td>0.407</td>
<td>0.464</td>
<td>0.550</td>
<td>0.660</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td>240</td>
<td>0.176</td>
<td>0.207</td>
<td>0.276</td>
<td>0.289</td>
<td>0.415</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1140</td>
<td>0.371</td>
<td>0.468</td>
<td>0.614</td>
<td>0.690</td>
<td>0.720</td>
</tr>
<tr>
<td></td>
<td>157</td>
<td>820</td>
<td>0.064</td>
<td>0.084</td>
<td>0.104</td>
<td>0.146</td>
<td>0.325</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1140</td>
<td>0.292</td>
<td>0.342</td>
<td>0.390</td>
<td>0.456</td>
<td>0.440</td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>240</td>
<td>0.186</td>
<td>0.248</td>
<td>0.280</td>
<td>0.322</td>
<td>0.340</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1140</td>
<td>0.590</td>
<td>0.639</td>
<td>0.608</td>
<td>0.664</td>
<td>0.650</td>
</tr>
<tr>
<td></td>
<td>157</td>
<td>820</td>
<td>0.064</td>
<td>0.084</td>
<td>0.104</td>
<td>0.146</td>
<td>0.325</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1140</td>
<td>0.292</td>
<td>0.342</td>
<td>0.390</td>
<td>0.456</td>
<td>0.440</td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>240</td>
<td>0.186</td>
<td>0.248</td>
<td>0.280</td>
<td>0.322</td>
<td>0.340</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1140</td>
<td>0.590</td>
<td>0.639</td>
<td>0.608</td>
<td>0.664</td>
<td>0.650</td>
</tr>
</tbody>
</table>
presented in Table 6.6 (refer to Section 6.2.5 for the meaning of the symbols).

**TABLE 6.6: Wear Rate (x 10)**

<table>
<thead>
<tr>
<th>Point 1 on the lips</th>
<th>Block C (Conventional drill)</th>
<th>Block N (New design Drill)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment (drilling condition)</td>
<td>Yield (wear rate x 10)</td>
<td>Treatment (drilling condition)</td>
</tr>
<tr>
<td>(1)</td>
<td>0.71</td>
<td>(1)</td>
</tr>
<tr>
<td>s</td>
<td>2.30</td>
<td>s</td>
</tr>
<tr>
<td>f</td>
<td>1.68</td>
<td>f</td>
</tr>
<tr>
<td>sf</td>
<td>3.35</td>
<td>sf</td>
</tr>
<tr>
<td>κ</td>
<td>0.36</td>
<td>κ</td>
</tr>
<tr>
<td>sk</td>
<td>2.33</td>
<td>sk</td>
</tr>
<tr>
<td>fk</td>
<td>1.14</td>
<td>fk</td>
</tr>
<tr>
<td>sfκ</td>
<td>3.87</td>
<td>sfκ</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>15.74</strong></td>
<td><strong>Total:</strong></td>
</tr>
</tbody>
</table>

Total Sum: 15.74 + 20.98 = 36.72
TABLE 6.7: Sum of Squares (Ref to Table 6.6)

Point 1 on the lips

<table>
<thead>
<tr>
<th>Block C</th>
<th>Block N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>Yield</td>
</tr>
<tr>
<td>(l)</td>
<td>0.504</td>
</tr>
<tr>
<td>s</td>
<td>5.290</td>
</tr>
<tr>
<td>f</td>
<td>2.822</td>
</tr>
<tr>
<td>sf</td>
<td>11.222</td>
</tr>
<tr>
<td>k</td>
<td>0.130</td>
</tr>
<tr>
<td>sk</td>
<td>5.429</td>
</tr>
<tr>
<td>fk</td>
<td>1.300</td>
</tr>
<tr>
<td>sfk</td>
<td>14.977</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>41.674</td>
</tr>
</tbody>
</table>

Sum of squares (Table 6.7):

Sum of squares within Block C:

\[ 41.674 - \frac{(15.74)^2}{8} = 10.706 \]

Sum of squares within Block N:

\[ 78.325 - \frac{(20.98)^2}{8} = 23.305 \]

Total sum of squares = 41.674 + 78.325 - \frac{(36.72)^2}{16} = 35.727

Between blocks sum of squares:

\[ \frac{(15.74)^2}{8} + \frac{(20.98)^2}{8} - \frac{(36.72)^2}{16} = 1.716 \]
Total sum of squares within blocks:

\[10.706 + 23.305 = 34.011\]

Analysis of variance between and within blocks is shown in Table 6.8.

**TABLE 6.8: Analysis of Variance**

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between blocks</td>
<td>1.716</td>
<td>1</td>
</tr>
<tr>
<td>Within blocks</td>
<td>34.011</td>
<td>14</td>
</tr>
<tr>
<td>Total:</td>
<td>35.727</td>
<td>15</td>
</tr>
</tbody>
</table>

**TABLE 6.9: Treatment Sum of Squares (refer to Table 6.6)**

Point 1 on the lips
Block C + Block N

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield C + Yield N</th>
<th>(Yield C + Yield N)^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(l)</td>
<td>1.15</td>
<td>1.3225</td>
</tr>
<tr>
<td>s</td>
<td>6.05</td>
<td>36.6025</td>
</tr>
<tr>
<td>f</td>
<td>3.44</td>
<td>11.8336</td>
</tr>
<tr>
<td>sf</td>
<td>7.06</td>
<td>49.8436</td>
</tr>
<tr>
<td>k</td>
<td>1.00</td>
<td>1.0000</td>
</tr>
<tr>
<td>sk</td>
<td>5.25</td>
<td>27.5625</td>
</tr>
<tr>
<td>fk</td>
<td>3.00</td>
<td>9.0000</td>
</tr>
<tr>
<td>sfk</td>
<td>9.77</td>
<td>95.4529</td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td>232.6176</td>
</tr>
</tbody>
</table>
Treatment sum of squares (Table 6.9):

\[
\frac{232.6176}{2} - \frac{(36.72)^2}{16} = 32.036
\]

Table 6.10 shows the sum of squares relative to residual treatments and between blocks.

**TABLE 6.10: Analysis of Variance**

Point 1 on lips

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between blocks</td>
<td>1.716</td>
<td>1</td>
</tr>
<tr>
<td>Treatments</td>
<td>32.036</td>
<td>7</td>
</tr>
<tr>
<td>Residual</td>
<td>1.975</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>35.727</strong></td>
<td><strong>15</strong></td>
</tr>
</tbody>
</table>

According to a common algorithm (105, 124) the effect of factor S, for instance, can be represented as follows:

\[(s - (1)) (f + (1)) (k + (1)) = sfk + sf + sk - f - k - (1)\]

Similar "expressions" can be used for the other cases. The effects of the different combinations of factors are presented in Table 6.11. In Table 6.12 is presented the analysis of variance for all factors and their interactions.

Proceeding in a similar way as for point 1 for the analysis of variance of the wear rate at points 2, 3, 4 and 5, the effects of the different factors and their interactions were computed and presented in Tables 6.13, 6.14, 6.15 and 6.16 respectively.
TABLE 6.11: Treatment Effect
Point 1 on the lips

<table>
<thead>
<tr>
<th>Effect of</th>
<th>s_fK</th>
<th>f</th>
<th>s_K</th>
<th>f_K</th>
<th>s</th>
<th>f</th>
<th>k</th>
<th>(l)</th>
<th>Total</th>
<th>Square</th>
<th>Sum of Squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>9.77</td>
<td>+7.06</td>
<td>+5.25</td>
<td>-3.00</td>
<td>+6.05</td>
<td>-3.44</td>
<td>-1.00</td>
<td>-1.15</td>
<td>19.54</td>
<td>381.812</td>
<td>23.863</td>
</tr>
<tr>
<td>F</td>
<td>9.77</td>
<td>+7.06</td>
<td>-5.25</td>
<td>+3.00</td>
<td>-6.05</td>
<td>+3.44</td>
<td>-1.00</td>
<td>-1.15</td>
<td>9.82</td>
<td>36.432</td>
<td>6.027</td>
</tr>
<tr>
<td>SF</td>
<td>9.77</td>
<td>+7.06</td>
<td>-5.25</td>
<td>-3.00</td>
<td>-6.05</td>
<td>-3.44</td>
<td>+1.00</td>
<td>+1.15</td>
<td>1.24</td>
<td>1.5383</td>
<td>0.096</td>
</tr>
<tr>
<td>k</td>
<td>9.77</td>
<td>-7.06</td>
<td>+5.25</td>
<td>+3.00</td>
<td>-6.05</td>
<td>-3.44</td>
<td>+1.00</td>
<td>-1.15</td>
<td>1.32</td>
<td>1.742</td>
<td>0.109</td>
</tr>
<tr>
<td>sK</td>
<td>9.77</td>
<td>-7.06</td>
<td>+5.25</td>
<td>-3.00</td>
<td>-6.05</td>
<td>+3.44</td>
<td>-1.00</td>
<td>+1.15</td>
<td>2.50</td>
<td>6.25</td>
<td>0.391</td>
</tr>
<tr>
<td>Fk</td>
<td>9.77</td>
<td>-7.06</td>
<td>-5.25</td>
<td>+3.00</td>
<td>+6.05</td>
<td>-3.44</td>
<td>-1.00</td>
<td>+1.15</td>
<td>3.22</td>
<td>10.368</td>
<td>0.648</td>
</tr>
<tr>
<td>SFK</td>
<td>9.77</td>
<td>-7.06</td>
<td>-5.25</td>
<td>-3.00</td>
<td>+6.05</td>
<td>+3.44</td>
<td>+1.00</td>
<td>-1.15</td>
<td>3.80</td>
<td>14.44</td>
<td>0.902</td>
</tr>
</tbody>
</table>

TOTAL 32.036
TABLE 6.12: Analysis of Variance (Refer to Tables 6.10 and 6.11)
Point 1 on the lips

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Mean Square</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i)</td>
<td>(ii)</td>
<td>(iii)</td>
<td>(iv) = (ii)/(iii)</td>
<td>(v)</td>
</tr>
<tr>
<td>Between Blocks</td>
<td>1.716</td>
<td>1</td>
<td>1.716</td>
<td>6.09</td>
</tr>
<tr>
<td>Treatments</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>23.863</td>
<td>1</td>
<td>23.863</td>
<td>84.62</td>
</tr>
<tr>
<td>f</td>
<td>6.027</td>
<td>1</td>
<td>6.027</td>
<td>21.37</td>
</tr>
<tr>
<td>k</td>
<td>0.109</td>
<td>1</td>
<td>0.109</td>
<td>0.39</td>
</tr>
<tr>
<td>sf</td>
<td>0.096</td>
<td>1</td>
<td>0.096</td>
<td>0.34</td>
</tr>
<tr>
<td>sk</td>
<td>0.391</td>
<td>1</td>
<td>0.391</td>
<td>1.39</td>
</tr>
<tr>
<td>fx</td>
<td>0.648</td>
<td>1</td>
<td>0.648</td>
<td>2.30</td>
</tr>
<tr>
<td>sfk</td>
<td>0.902</td>
<td>1</td>
<td>0.902</td>
<td>3.20</td>
</tr>
<tr>
<td>Residual</td>
<td>1.975</td>
<td>7</td>
<td>0.282</td>
<td>1.00</td>
</tr>
<tr>
<td>Total:</td>
<td>35.727</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** Significant at 0.1% level (highly significant (105))
**  Significant at 1% level  (significant (105))
*   Significant at 5% level  (probably significant (105))
n.s. Not significant at 5% level (non-significant(105))
TABLE 6.13: Analysis of Variance

Point 2 on the lips

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares (i)</th>
<th>Degrees of Freedom (iii)</th>
<th>Variance Estimate Mean Square (iv)(=)(i)/(iii)</th>
<th>Variance Ratio (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between blocks</td>
<td>2.993</td>
<td>1</td>
<td>2.993</td>
<td>14.29</td>
</tr>
<tr>
<td>Treatments</td>
<td>39.942</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>29.866</td>
<td>1</td>
<td>29.866</td>
<td>142.63</td>
</tr>
<tr>
<td>f</td>
<td>8.497</td>
<td>1</td>
<td>8.497</td>
<td>40.58</td>
</tr>
<tr>
<td>k</td>
<td>0.270</td>
<td>1</td>
<td>0.270</td>
<td>1.29</td>
</tr>
<tr>
<td>sf</td>
<td>0.133</td>
<td>1</td>
<td>0.133</td>
<td>0.64</td>
</tr>
<tr>
<td>sk</td>
<td>0.230</td>
<td>1</td>
<td>0.230</td>
<td>1.10</td>
</tr>
<tr>
<td>fk</td>
<td>0.397</td>
<td>1</td>
<td>0.397</td>
<td>1.90</td>
</tr>
<tr>
<td>sfk</td>
<td>0.548</td>
<td>1</td>
<td>0.548</td>
<td>2.62</td>
</tr>
<tr>
<td>Residual</td>
<td>1.466</td>
<td>7</td>
<td>0.209</td>
<td>1.00</td>
</tr>
<tr>
<td>Total:</td>
<td>44.401</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** Significant at 0.1% level (highly significant (105))

** Significant at 1% level (significant (105))

n.s. Not significant at 5% level (non-significant (105))
### TABLE 6.14: Analysis of Variance

Point 3 on the lips

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares (i)</th>
<th>Degrees of Freedom (ii)</th>
<th>Variance Estimate Mean Square (iv)=(ii)/(iii)</th>
<th>Variance Ratio (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between Blocks</strong></td>
<td>4.050</td>
<td>1</td>
<td>4.050</td>
<td>16.09 **</td>
</tr>
<tr>
<td><strong>Treatments</strong></td>
<td>48.852</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>38.657</td>
<td>1</td>
<td>38.657</td>
<td>153.57 ***</td>
</tr>
<tr>
<td>f</td>
<td>9.471</td>
<td>1</td>
<td>9.471</td>
<td>37.63 ***</td>
</tr>
<tr>
<td>κ</td>
<td>0.041</td>
<td>1</td>
<td>0.041</td>
<td>0.16 n.s.</td>
</tr>
<tr>
<td>sf</td>
<td>0.059</td>
<td>1</td>
<td>0.059</td>
<td>0.23 n.s.</td>
</tr>
<tr>
<td>sk</td>
<td>0.201</td>
<td>1</td>
<td>0.201</td>
<td>0.80 n.s.</td>
</tr>
<tr>
<td>fk</td>
<td>0.107</td>
<td>1</td>
<td>0.107</td>
<td>0.43 n.s.</td>
</tr>
<tr>
<td>sfk</td>
<td>0.316</td>
<td>1</td>
<td>0.316</td>
<td>1.26 n.s.</td>
</tr>
<tr>
<td><strong>Residual</strong></td>
<td>1.762</td>
<td>7</td>
<td>0.252</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>54.664</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** Significant at 0.1% level (highly significant (105))

** Significant at 1% level  (significant (105))
n.s. Not significant at 5% level (non-significant (105))
TABLE 6.15: Analysis of Variance

Point 4 on the lips

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate Mean Square</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i)</td>
<td>(ii)</td>
<td>(iii)</td>
<td>(iv)=(ii)/(iii)</td>
<td>(v)</td>
</tr>
<tr>
<td>Between Blocks</td>
<td>6.015</td>
<td>1</td>
<td>6.015</td>
<td>9.22</td>
</tr>
<tr>
<td>Treatments</td>
<td>66.769</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>51.015</td>
<td>1</td>
<td>51.015</td>
<td>78.17 ***</td>
</tr>
<tr>
<td>f</td>
<td>12.128</td>
<td>1</td>
<td>12.128</td>
<td>18.58 **</td>
</tr>
<tr>
<td>κ</td>
<td>0.243</td>
<td>1</td>
<td>0.243</td>
<td>0.37 n.s.</td>
</tr>
<tr>
<td>sf</td>
<td>1.205</td>
<td>1</td>
<td>1.205</td>
<td>1.85 n.s.</td>
</tr>
<tr>
<td>sκ</td>
<td>0.219</td>
<td>1</td>
<td>0.219</td>
<td>0.33 n.s.</td>
</tr>
<tr>
<td>fκ</td>
<td>0.975</td>
<td>1</td>
<td>0.975</td>
<td>1.49 n.s.</td>
</tr>
<tr>
<td>sfκ</td>
<td>0.984</td>
<td>1</td>
<td>0.984</td>
<td>1.51 n.s.</td>
</tr>
<tr>
<td>Residual</td>
<td>4.568</td>
<td>7</td>
<td>0.653</td>
<td>1.00</td>
</tr>
<tr>
<td>Total</td>
<td>77.352</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** Significant at 0.1% level (highly significant (105))

** Significant at 1% level  (significant (105))

* Significant at 5% level  (probably significant (105))

n.s. Not significant at 5% level  (non-significant (105))
TABLE 6.16: Analysis of Variance
Point 5 on the lips

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares (i)</th>
<th>Degrees of Freedom (iii)</th>
<th>Variance Estimate (iv) = (ii)/(iii)</th>
<th>Variance Ratio (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Blocks</td>
<td>0.056</td>
<td>1</td>
<td>0.056</td>
<td>0.01</td>
</tr>
<tr>
<td>Treatments</td>
<td>59.692</td>
<td>7</td>
<td>32.348</td>
<td>7.27</td>
</tr>
<tr>
<td>s</td>
<td>32.348</td>
<td>1</td>
<td>32.348</td>
<td>1.20</td>
</tr>
<tr>
<td>f</td>
<td>5.348</td>
<td>1</td>
<td>5.348</td>
<td>0.64</td>
</tr>
<tr>
<td>κ</td>
<td>2.848</td>
<td>1</td>
<td>2.848</td>
<td>1.75</td>
</tr>
<tr>
<td>sf</td>
<td>7.770</td>
<td>1</td>
<td>7.770</td>
<td>1.31</td>
</tr>
<tr>
<td>sk</td>
<td>5.820</td>
<td>1</td>
<td>5.820</td>
<td>0.80</td>
</tr>
<tr>
<td>fk</td>
<td>3.563</td>
<td>1</td>
<td>3.563</td>
<td>0.45</td>
</tr>
<tr>
<td>sfk</td>
<td>1.995</td>
<td>1</td>
<td>1.995</td>
<td>n.s.</td>
</tr>
<tr>
<td>Residual</td>
<td>31.167</td>
<td>7</td>
<td>4.452</td>
<td>1.00</td>
</tr>
<tr>
<td>Total:</td>
<td>90.915</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant at 5% level (probably significant (105))

n.s. Not significant at 5% level (non-significant (105))
TABLE 6.17: Summary of Tables 6.12 to 6.16 for Statistical Analysis of Significance

<table>
<thead>
<tr>
<th>Factors</th>
<th>Point 1</th>
<th>Point 2</th>
<th>Point 3</th>
<th>Point 4</th>
<th>Point 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill type</td>
<td>*</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>n.s.</td>
</tr>
<tr>
<td>Drilling speed</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>Drilling feed</td>
<td>**</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>n.s.</td>
</tr>
<tr>
<td>Drill point</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Intersection of factors</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

*** Significant at 0.1% level (highly significant (105))

** Significant at 1% level (significant (105))

* Significant at 5% level (probably significant (105))

n.s. Not significant at 5% level (non-significant (105))
For the ranges of the drilling factors tested, the analysis of tables 6.12 to 6.16 reveals that the difference between the drill types is significant (1% level) for points 2 and 3; the difference is probably significant (5% level) for points 1 and 4. For point 5, the probability of the difference between drill types to occur by chance is greater than 5% and it can be considered non-significant.

For the ranges of the drilling factors tested, the effect of speed is highly significant (0.1% level) for points 1, 2, 3 and 4 (Tables 6.12 to 6.15) and probably significant (5% level) for point 5 (Table 6.16). The effect of drilling feed is highly significant (0.1% level) for points 2 and 3 (Tables 6.13 and 6.14), is significant (1% level) for points 1 and 4 (Tables 6.12 and 6.15) and non-significant for point 5 (Table 6.16).

These results are summarised in Table 6.17.

Surprisingly, the effects of the drilling factors (Table 6.17) do not mirror significantly at point 5, the outer corner, with the exception of drilling speed (probably significant). This might be taken, on a purely statistical basis, as meaning that the wear rate at the outer corner is independent of the drilling factors tested (except for drilling speed). However, this is not true as it is known by the workers in the drilling area. The reason for this result should be looked for in the residual for point 5 (Table 6.16) which is much higher than those for the other points 1, 2, 3 and 4 and reflects a large variability in the wear rate at this point. Therefore, inner points to the outer corner on the drill lip must be selected when wear rate performance measurement is intended.

The above analysis of the drill wear results reveals that the expectations built upon the hypothesis of better drill wear performance, with a new flute yielding a better "heat sink" while maintaining approximately the same effective rake angle as the conventional one, did not succeed. However, the observation of Figures
6.23 to 6.30 shows a more uniform wear for the new design drill than for the conventional one as, for the majority of cases, the transition from point 4 to point 5, for the wear curves, is smoother for the first drill type than for the second one.

It can also be noted that for the tests which ended with "screech", the wear loss is greater for the conventional drill than for the new design drill at point 5 (outer corner), where the wear is shown to vary from approximately 0% (118° x 1140 rpm x 240 RPI) to more than +50% (134° x 1140 rpm x 157 RPI) relatively to the new design drill (Appendix 7). The reverse appears to happen with the other points, especially points 3 and 4, for which the wear loss with the new design drill varies from approximately 0% (point 4, 118° x 1140 rpm x 157 RPI) to more than +20% (point 4, 118° x 1140 rpm x 240 RPI) (Appendix 7).

The tests reported in this chapter have been set to investigate the drills wear performance, however, on the basis of reported work in literature (35) on drill life, and on the higher wear rate for the new drill design, a shorter life, according to the "screech" criterion (Section 6.1.2), might be expected with the new design drill. Nevertheless, the tests which ended with "screech" (Section 6.4) do not allow such a definitive statement.
"Mechanical efficiency in drilling operations can be expressed in terms of torque and total thrust on the drill".

Galloway

7. PERFORMANCE TESTS - COMPARING DRILLING FORCES ON CONVENTIONAL AND NEW DESIGN DRILL
7.1 Introduction

Many papers (3, 12, 17, 23, 24, 25, 26, 27, 106, 107) report on drilling forces measurement.

The importance of drilling forces derives from the need to compute drilling power consumption and stress and/or strain on working elements such as the components being drilled, component holders, drill holders and drilling machine spindle. Drilling forces can also be important in comparing drill performance for different drill designs.

It is usual to measure drilling torque and thrust and many drilling variables have been investigated for their influence on drilling forces.

Drilling forces have been studied for the variation of helix angle (3, 23, 27, 42), point angle (3, 17, 23, 42), clearance angle (3, 23), point shape (2, 17), chisel edge length (3), drill diameter (3, 5, 27, 42), feed (5, 23, 27, 42, 53, 99), speed (42), workpiece material (3, 5, 23, 27, 42, 53), depth of hole (42) and number of holes (3) and with and without pilot holes (25).

7.2 Experimental Design

The author aimed at designing an experiment to compare, for drilling forces, 12.7 mm (½") drills of two types - a conventional drill and the new flute design drill. To define the number and the range of the variables to be tested was one of his targets.

To exclude the cutting speed as a testing factor was justified on the basis of the reports of some workers who found the influence of the cutting speed on drilling forces to be negligible (27), insignificant (12) or null (107).

7.2.1 Factors selection

Each drill type is to be tested for the drilling forces with varying drill point angle and drilling feed.
As a result of the conditions fixed for the wear tests, and the drilling feeds range available in the drilling machine used by the author, the combinations of drilling factors shown in Table 7.1 were selected for testing.

**TABLE 7.1:**
Drilling Factors Combinations Used with the Drilling Forces Tests

<table>
<thead>
<tr>
<th>Drill Type</th>
<th>Drill point angle, deg</th>
<th>Revolutions per inch penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>118</td>
<td>240 157 103 70</td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>240 157 103 70</td>
</tr>
<tr>
<td>Wear design</td>
<td>118</td>
<td>240 157 103 70</td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>240 157 103 70</td>
</tr>
</tbody>
</table>

7.2.2 Equipment

The drilling machine, the grinding machine and the geometry measurement machine have already been described in Chapter 6 (Section 6.2.3).
7.2.2.1 **Dynamometer**

A Kistler two-component measuring platform type 9271A was used in this work (C.2).

This measuring platform is a piezoelectric transducer which measures simultaneously a force parallel to the transducer axis, $F_Z$, and a moment in the plane normal to the line of application of the force, $M_Z$ (Figure 7.1).

Each channel comprises a charge amplifier and a galvo-amplifier, driving a recording galvanometer in an ultraviolet oscillograph. The charge amplifier converts the electrical charge into a proportional voltage, taking into account the individual transducer sensitivity, so that the output voltage is an even scale of N/V. In addition, the desired range can be selected over four decades in steps of 1, 2, 5. The set up is shown in Figure 7.2.

The technical specification for the dynamometer is as follows:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum measuring range: $F_Z$</td>
<td>- 5000 to 20,000N</td>
</tr>
<tr>
<td></td>
<td>$M_Z$: ± 100 Nm</td>
</tr>
<tr>
<td>Overload capacity:</td>
<td>± 50%</td>
</tr>
<tr>
<td>Resolution:</td>
<td>$F_Z$: 0.02 N</td>
</tr>
<tr>
<td></td>
<td>$M_Z$: 0.0002 Nm</td>
</tr>
<tr>
<td>Cross sensitivity:</td>
<td>$F_Z \rightarrow M_Z \leq \pm 0.0002$ Nm/N</td>
</tr>
<tr>
<td></td>
<td>$M_Z \rightarrow F_Z \leq \pm 1.0$ N/Nm</td>
</tr>
<tr>
<td>Linearity:</td>
<td>$\leq \pm 1%$ full scale output</td>
</tr>
<tr>
<td>Hysteresis:</td>
<td>$\leq \pm 0.5%$ full scale output</td>
</tr>
<tr>
<td>Resonant frequency:</td>
<td>= 3.5 KHz</td>
</tr>
<tr>
<td>Rigidity:</td>
<td>$F_Z$: =6500 N/\mu$m</td>
</tr>
<tr>
<td></td>
<td>$M_Z$: =0.5 Nm/\mu$rad</td>
</tr>
<tr>
<td>Sensitivity:</td>
<td>$F_Z$: 2.0 pc/N</td>
</tr>
<tr>
<td></td>
<td>$M_Z$: 150 pc/Nm</td>
</tr>
<tr>
<td>Working temperature range:</td>
<td>0° to 70°C</td>
</tr>
<tr>
<td>Mass:</td>
<td>2.9 Kg</td>
</tr>
</tbody>
</table>
FIGURE 7.1: Kistler thrust (Fz) and torque (Mz) measuring platform
The oscillograph was a Southern Instruments direct reading ultra-violet unit series M1300 with the following specifications:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvanometer</td>
<td>SMI/N 100 c/s</td>
</tr>
<tr>
<td>Number of data channels:</td>
<td>10</td>
</tr>
<tr>
<td>Datum traces:</td>
<td>2</td>
</tr>
<tr>
<td>Writing speed:</td>
<td>762 mm/s</td>
</tr>
<tr>
<td>Max. deflection:</td>
<td>152 mm</td>
</tr>
<tr>
<td>Recording material:</td>
<td>Kodak linagraph direct print paper 120 mm wide</td>
</tr>
<tr>
<td>Paper speeds:</td>
<td>3.8, 7.6, 12.7, 25.4, 38.1, 76.2, 254, 762, 1270, 2540 mm/s</td>
</tr>
<tr>
<td>Speed stability:</td>
<td>better than ±5%</td>
</tr>
<tr>
<td>Timing lines:</td>
<td>0.01, 0.1, or 10s</td>
</tr>
</tbody>
</table>

**Galvanometer specification:**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural frequency:</td>
<td>1000 c/s</td>
</tr>
<tr>
<td>Terminal resistance</td>
<td>35Ω</td>
</tr>
<tr>
<td>d.c. sensitivity:</td>
<td>0.05 mA/mm, 1.75 mV/mm</td>
</tr>
<tr>
<td>Maximum safe current:</td>
<td>50 mA</td>
</tr>
<tr>
<td>Maximum safe voltage</td>
<td>1.75V</td>
</tr>
</tbody>
</table>

**Calibration of the dynamometer:**

The dynamometer was calibrated by directly applying a proving ring in the axial direction and loading a lever arm for the calibration of the torque component as reported in (84). A torsion balance was also used for moment calibration, as indicated by the manufacturer [C.2], and similar results as for the arm were obtained.

Calibration charts and calibration set-up pictures are not presented for dynamometer calibration procedures for drilling forces measurement are already well established (3, 5, 35, 84, 125).
7.2.3 Preliminary work

The purpose of the experiments reported in this chapter was to test the effect of flute form on drilling forces with steel.

The author considered, as for the wear tests, two point angles - 118° and 134° - and tested the whole range of drilling feeds available with the drilling machine.

Some tests were performed with two materials: EN3 and EN8 steels.

The results of the experiments with EN3 steel with the conventional drill appeared to be unexpectedly much higher than the values predicted by the simplified formula equations 7.1 and 7.2 after Oxford and Shaw (27):

\[
T_o = 0.087 \text{HB} f^0 \cdot 8 \quad d_o^{1 \cdot 8} \quad 7.1
\]

\[
T_h = 0.195 \text{HB} f^0 \cdot 8 \quad d_o^{0 \cdot 8} + 0.0022 \text{HB} \quad d_o^{2} \quad 7.2
\]

where
- \( T_o \) = drilling torque, lb.in
- \( T_h \) = drilling thrust, lb
- \( \text{HB} \) = workpiece hardness, psi
- \( f \) = drilling feed, in/rev
- \( d_o \) = drill diameter, in
(Units as given in (27)).

Close inspection of the drill after drilling EN3 steel revealed the presence of an important built-up-edge (BUE) on the lip and for this situation - large BUE - Oxford and Shaw had found no good agreement between their formula and the experimental data. Thus EN3 steel was discarded from the main drilling forces tests.

To specify a cutting speed was conditioned by the absence of coolant and by the heaviest feed to be tested. The author found the speed 260 rpm, within the range available, to be the more appropriate to the drilling forces tests.
7.3 Main Drilling Forces Tests

7.3.1 Testing procedure

The tests for drilling forces measurement were run dry to protect the dynamometer, to simplify the testing procedure and to avoid possible effects due to the variation in the cutting fluid and its action.

The number of drills tested was as for the wear tests (Section 6.3.1).

As for the wear tests, the drilling forces tests were first run for one drill point angle (Section 6.3.1). To eliminate any possible systematic error, the tests were run in a random sequence for the combination of the remaining factors. After completion of the tests with one point angle, the grinding machine was set for the other point angle and testing procedure was as for the first point angle.

For each set of drilling conditions and each drill type, tests were run four times in order to eliminate, by averaging, the effect of experimental random deviations. Drilling torques and thrusts were recorded by a UV recorder as specified in Section 7.2.2.1.

7.3.2 Drills features

Drills features were as for the wear tests (Section 6.3.2).

7.3.3 Material

The work material, EN8 steel, supplied in 3.05 m (10") lengths of 19.05 mm (¼") diameter bar was a nominal 0.40% carbon steel with the following limits to chemical composition:

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>0.35</td>
<td>0.05</td>
<td>0.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>max</td>
<td>0.45</td>
<td>0.35</td>
<td>1.00</td>
<td>0.060</td>
<td>0.060</td>
</tr>
</tbody>
</table>
A material sample was submitted for chemical analysis and the result proved it to be within the specified composition.

The bars were cut into pieces 30 mm long and the end pieces had been discarded.

The specimens were normalized and cleaned, and the tops were ground. The specimens were numbered and ten pieces were selected at random for hardness tests at each top.

A Rockwell hardness tester was used for testing the specimens hardness and the hardness numbers obtained after the readings fell in the interval 197 HB - 206 HB.

The pieces for drilling tests were selected in a random sequence and drilled with a 25 mm (= 2 d₀) deep hole.

7.4 Experimental Results

The results of the experiments are shown in Tables 7.2 (thrust) and 7.3 (torque). These results are presented graphically in Figure 7.3 (thrust for 118° point angle), Figure 7.4 (thrust for 134° point angle), Figure 7.5 (torque for 118° point angle) and Figure 7.6 (torque for 134° point angle).
### TABLE 7.2: Thrust (N)

<table>
<thead>
<tr>
<th>RPI (rev/in)</th>
<th>Feed (mm/rev)</th>
<th>Conventional Drill</th>
<th>New Design Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ground point angle</td>
<td>Ground point angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>118° 134°</td>
<td>118° 134°</td>
</tr>
<tr>
<td>240</td>
<td>0.106</td>
<td>1610 1943</td>
<td>1521 1668</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1697 1999</td>
<td>1603 1617</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1648 1952</td>
<td>1572 1626</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1627 1982</td>
<td>1553 1647</td>
</tr>
<tr>
<td>157</td>
<td>0.162</td>
<td>2456 2502</td>
<td>2262 2187</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2359 2540</td>
<td>2241 2179</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2406 2471</td>
<td>2311 2129</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2351 2556</td>
<td>2232 2213</td>
</tr>
<tr>
<td>103</td>
<td>0.247</td>
<td>3375 3447</td>
<td>3186 3015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3429 3437</td>
<td>3085 3017</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3329 3510</td>
<td>3153 2956</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3469 3369</td>
<td>3134 3042</td>
</tr>
<tr>
<td>70</td>
<td>0.363</td>
<td>4802 4694</td>
<td>4248 4155</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4824 4877</td>
<td>4294 4259</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4887 4727</td>
<td>4381 4127</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4709 4807</td>
<td>4208 4293</td>
</tr>
</tbody>
</table>
TABLE 7.3: Torque (N.cm)

<table>
<thead>
<tr>
<th>RPI (rev/in)</th>
<th>Feed (mm/rev)</th>
<th>Conventional Drill</th>
<th>New Design Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ground point angle</td>
<td>Ground point angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>118° 134°</td>
<td>118° 134°</td>
</tr>
<tr>
<td>240</td>
<td>0.106</td>
<td>642.0 751.6</td>
<td>622.8 711.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>671.4 743.7</td>
<td>694.0 784.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>645.4 738.1</td>
<td>636.3 738.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>653.3 757.3</td>
<td>648.8 732.4</td>
</tr>
<tr>
<td>157</td>
<td>0.162</td>
<td>1060 1135</td>
<td>1082 1267</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1017 1122</td>
<td>1076 1157</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1066 1099</td>
<td>1113 1191</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1041 1159</td>
<td>1053 1231</td>
</tr>
<tr>
<td>103</td>
<td>0.247</td>
<td>1485 1507</td>
<td>1631 1717</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1537 1637</td>
<td>1635 1683</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1499 1552</td>
<td>1568 1635</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1550 1573</td>
<td>1672 1755</td>
</tr>
<tr>
<td>70</td>
<td>0.363</td>
<td>2221 2254</td>
<td>2204 2502</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2140 2287</td>
<td>2316 2281</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2212 2224</td>
<td>2281 2400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2199 2320</td>
<td>2201 2355</td>
</tr>
</tbody>
</table>
FIGURE 7.3: Drilling thrust for 110° point angle
Four tests with each drilling feed.
Flute: Grinding-cylindrical

$R_0 = 6.35$
$D_0 = 31.00$
$W_0 = 1.95$
$V_g = 100.00$
$H_0 = 33.00$
$E_{xg} = 3.80$
$R_{kg} = 67.00$

FIGURE 7.4: Drilling thrust for 134° point angle
[Four tests with each drilling feed]
Figure 7.5: Drilling torque for 118° point angle

[Four tests with each drilling feed]
Flute - Grinding- 
cylindrical

R₀ = 6.35  D₀g = 31.00
Web = 1.95  Vg = 100.00
H₀ = 33.00  Exg = 3.30
Rkg = 67.00

FIGURE 7.6: Drilling torque for 134° point angle
(Four tests with each drilling feed)
7.5 Analysis of Results

The drilling forces were averaged for each set of cutting conditions and the results presented in Table 7.4 (thrust) and Table 7.5 (torque).

Graphics from Figures 7.3 to 7.6 and Tables 7.4 and 7.5 show that, for both drill types, drilling forces increase with feed, as expected. They also show some differences between the conventional drill and the new design drill.

For each feed, the thrust value relative to the $118^\circ$ point angle conventional drill has been given the value 100 and the thrust values for the other cases have been computed accordingly; the results are shown in Table 7.6. The same procedure has been adopted for the torque values and the results are shown in Table 7.7.

Table 7.6 shows that, for the $118^\circ$ point angle, the thrust is 5 to 10% (depends on the feed) lower for the new design drill than for the conventional one. For the $134^\circ$ point angle, the thrust for the new design drill is 10 to 20% lower than for the conventional one.

Table 7.7 shows that the reverse happens with the drilling torque: the new design drill yields a drilling torque approximately 0 to 10% bigger than the conventional one for either drill point.

An analysis of variance on the drilling forces results has been done in order to find if the effects of the tested drilling factors are statistically significant. Let drilling thrust be considered first and let all the drilling factors tested be analysed.

The following symbols are used:

- $d_1$ - conventional drill
- $d_2$ - new design drill
- $f_1$, $f_2$, $f_3$, $f_4$ - the feeds corresponding to 240, 157, 103 and 70 RPI respectively
### TABLE 7.4: Thrust (N) Averages (refer to Table 7.2)

<table>
<thead>
<tr>
<th>RPI (rev/in)</th>
<th>Feed (mm/rev)</th>
<th>Conventional Drill</th>
<th>New Design Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ground point angle</td>
<td>Ground point angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>118°</td>
<td>134°</td>
</tr>
<tr>
<td>240</td>
<td>0.106</td>
<td>1646</td>
<td>1969</td>
</tr>
<tr>
<td>157</td>
<td>0.162</td>
<td>2393</td>
<td>2517</td>
</tr>
<tr>
<td>103</td>
<td>0.247</td>
<td>3400</td>
<td>3441</td>
</tr>
<tr>
<td>70</td>
<td>0.363</td>
<td>4806</td>
<td>4776</td>
</tr>
</tbody>
</table>

### TABLE 7.5: Torque (N.cm) Averages (refer to Table 7.3)

<table>
<thead>
<tr>
<th>RPI (rev/in)</th>
<th>Feed (mm/rev)</th>
<th>Conventional Drill</th>
<th>New Design Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ground point angle</td>
<td>Ground point angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>118°</td>
<td>134°</td>
</tr>
<tr>
<td>240</td>
<td>0.106</td>
<td>653</td>
<td>748</td>
</tr>
<tr>
<td>157</td>
<td>0.162</td>
<td>1047</td>
<td>1129</td>
</tr>
<tr>
<td>103</td>
<td>0.247</td>
<td>1518</td>
<td>1568</td>
</tr>
<tr>
<td>70</td>
<td>0.363</td>
<td>2193</td>
<td>2272</td>
</tr>
</tbody>
</table>
### TABLE 7.6: Comparative Drilling Thrusts

<table>
<thead>
<tr>
<th>RPI (rev/min)</th>
<th>Feed (mm/rev)</th>
<th>Conventional Drill</th>
<th>New Design Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ground point angle</td>
<td>Ground point angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>118° 134°</td>
<td>118° 134°</td>
</tr>
<tr>
<td>240</td>
<td>0.106</td>
<td>1646N=100</td>
<td>120 95</td>
</tr>
<tr>
<td>157</td>
<td>0.162</td>
<td>2394N=100</td>
<td>105 94</td>
</tr>
<tr>
<td>103</td>
<td>0.247</td>
<td>3400N=100</td>
<td>101 92</td>
</tr>
<tr>
<td>70</td>
<td>0.363</td>
<td>4806=100</td>
<td>99 89</td>
</tr>
</tbody>
</table>

### TABLE 7.7: Comparative Drilling Torques

<table>
<thead>
<tr>
<th>RPI (rev/min)</th>
<th>Feed (mm/rev)</th>
<th>Conventional Drill</th>
<th>New Design Drill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ground point angle</td>
<td>Ground point angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>118° 134°</td>
<td>118° 134°</td>
</tr>
<tr>
<td>240</td>
<td>0.106</td>
<td>653 N.cm=100</td>
<td>115 100</td>
</tr>
<tr>
<td>157</td>
<td>0.162</td>
<td>1047 N.cm=100</td>
<td>108 103</td>
</tr>
<tr>
<td>103</td>
<td>0.247</td>
<td>1518 N.cm=100</td>
<td>103 107</td>
</tr>
<tr>
<td>70</td>
<td>0.363</td>
<td>2193 N.cm=100</td>
<td>104 103</td>
</tr>
</tbody>
</table>
\( \kappa_1, \kappa_2 \) - the point angles 118° and 134° respectively.

The drilling thrust averages (Table 7.4) for each set of drilling conditions are divided by 1000, for the sake of simplification of the calculations, and presented in Table 7.8.

**TABLE 7.8: Thrust-related Values (refer to Table 7.4)**

<table>
<thead>
<tr>
<th>Feed</th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \kappa_1 )</td>
<td>( \kappa_2 )</td>
<td>( \kappa_1 )</td>
</tr>
<tr>
<td>( f_1 )</td>
<td>1.646</td>
<td>1.969</td>
<td>1.562</td>
</tr>
<tr>
<td>( f_2 )</td>
<td>2.394</td>
<td>2.517</td>
<td>2.261</td>
</tr>
<tr>
<td>( f_3 )</td>
<td>3.400</td>
<td>3.441</td>
<td>3.139</td>
</tr>
<tr>
<td>( f_4 )</td>
<td>4.806</td>
<td>4.777</td>
<td>4.283</td>
</tr>
<tr>
<td>Totals</td>
<td>12.246</td>
<td>12.704</td>
<td>11.245</td>
</tr>
</tbody>
</table>

Grand total = 47.228

Sum of squares for feed effect, SSF (Table 7.8):

\[
SSF = \frac{1}{16} (6.817^2 + 9.349^2 + 12.987^2 + 18.075^2) - \frac{47.228^2}{64} = 4.47638
\]

Summing for the factor drill type (Table 7.8):

\[
\begin{array}{c|c|c}
\hline
& d_1 & d_2 \\
\hline
\text{TOTALS} & 24.950 & 22.278 \\
\hline
\end{array}
\]

Sum of squares for drill type effect, SSD:

\[
SSD = \frac{1}{32} (24.950^2 + 22.278^2) - \frac{47.228^2}{64} = 0.11156
\]
Summing for the factor drill point (Table 7.8):

\[
\begin{array}{c|c}
  \kappa_1 & \kappa_2 \\
  23.491 & 23.737 \\
\end{array}
\]

Sum of squares for point angle effect, SSP:

\[
SSP = \frac{1}{32} \left( (23.491^2 + 22.737^2) - \frac{47.228^2}{64} \right) = 0.00095
\]

Summing for the cross effect of drill type and feed (Table 7.8):

\[
\begin{array}{c|c|c}
  d_1 & d_2 \\
  \hline
  f_1 & 3.615 & 3.202 \\
  f_2 & 4.911 & 4.438 \\
  f_3 & 6.841 & 6.146 \\
  f_4 & 9.583 & 8.492 \\
\end{array}
\]

Sum of squares for cross effect drill type and feed, SSDF:

\[
SSDF = \frac{1}{8} \left( (3.615^2 + 3.202^2 + 4.911^2 + 4.438^2 + 6.841^2 + 6.146^2 + 9.583^2 + 8.492^2) - 0.111556 - 4.47638 - \frac{47.228^2}{64} \right) = 0.01767
\]

Sum of squares for drill type and point angle cross effect (Table 7.8), SSDP:

\[
SSDP = \frac{1}{16} \left( (12.246^2 + 12.704^2 + 11.245^2 + 11.033^2) - 0.11156 - 0.00095 - \frac{47.228^2}{64} \right) = 0.00700
\]
Summing for the cross-effect of point angle and feed (Table 7.8):

<table>
<thead>
<tr>
<th>( f_1 )</th>
<th>( f_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.208</td>
<td>3.609</td>
</tr>
<tr>
<td>4.655</td>
<td>4.694</td>
</tr>
<tr>
<td>6.539</td>
<td>6.448</td>
</tr>
<tr>
<td>9.089</td>
<td>8.986</td>
</tr>
</tbody>
</table>

Sum of squares for point angle and feed cross-effect, SSPF:

\[
SSPF = \frac{1}{8} \left( 3.208^2 + 3.609^2 + 4.655^2 + 4.694^2 + 6.539^2 + 6.448^2 + 9.089^2 + 8.986^2 \right) - 0.00095 - 4.47638 - \frac{47.228^2}{64} = 0.01038
\]

Sum of squares for the three factors cross-effect, (Table 7.8):

\[
\frac{1}{4} \left( 1.646^2 + 1.969^2 + \ldots + 4.209^2 \right) - 4.47638 - 0.11156 - 0.00095 - 0.01767 - 0.00700 - 0.01038 - \frac{47.228^2}{64} = 0.00143
\]

Total sum of squares (Table 7.2): 4.63013

The analysis of variance for drilling thrust is presented in Table 7.9.
TABLE 7.9: Analysis of Variance for Drilling Thrust

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill type</td>
<td>0.11156</td>
<td>1</td>
<td>0.11156</td>
<td>1115</td>
</tr>
<tr>
<td>Drill point</td>
<td>0.00095</td>
<td>1</td>
<td>0.00095</td>
<td>9.5</td>
</tr>
<tr>
<td>Feed</td>
<td>4.47638</td>
<td>3</td>
<td>1.49213</td>
<td>14,921</td>
</tr>
<tr>
<td>Type x point</td>
<td>0.00700</td>
<td>1</td>
<td>0.00700</td>
<td>70.0</td>
</tr>
<tr>
<td>Type x feed</td>
<td>0.01767</td>
<td>3</td>
<td>0.00589</td>
<td>58.9</td>
</tr>
<tr>
<td>Point x feed</td>
<td>0.01038</td>
<td>3</td>
<td>0.00346</td>
<td>34.6</td>
</tr>
<tr>
<td>Type x point x feed</td>
<td>0.00143</td>
<td>3</td>
<td>0.00048</td>
<td>4.8 **</td>
</tr>
<tr>
<td>Error</td>
<td>0.00476</td>
<td>48</td>
<td>0.00010</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>4.63013</td>
<td>63</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** Significant at 1% level

Observing Table 7.9, the interaction of the three tested drilling factors appears to be significant, (terminology as in Section 6.5). In such a case separate analyses on the original data should be done (105) to test statistically the effect of the drilling factors.

It is well established that feed has an important effect on the drilling forces (Section 7.1), thus let us first do a breakdown analysis by drilling feeds. Tables 7.10 to 7.13 present the analysis of variance for the data of Table 7.2 separated according to the feed value.
TABLE 7.10: Analysis of Variance for Drilling Thrust for 240 RPI

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point angle</td>
<td>3.4468</td>
<td>1</td>
<td>3.4468</td>
<td>64.03 ***</td>
</tr>
<tr>
<td>Drill type</td>
<td>0.0078</td>
<td>1</td>
<td>0.0078</td>
<td>0.15 n.s.</td>
</tr>
<tr>
<td>Interaction</td>
<td>0.0012</td>
<td>1</td>
<td>0.0012</td>
<td>0.02 n.s.</td>
</tr>
<tr>
<td>pointxtypetext</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>0.6460</td>
<td>12</td>
<td>0.0538</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>4.1018</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** Significant at 0.1% level
** Significant at 1% level
* Significant at 5% level
n.s. Not significant at 5% level

TABLE 7.11: Analysis of Variance for Drilling Thrust for 157 RPI

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point angle</td>
<td>4.5478</td>
<td>1</td>
<td>4.5478</td>
<td>45.39 ***</td>
</tr>
<tr>
<td>Drill type</td>
<td>1.3867</td>
<td>1</td>
<td>1.3867</td>
<td>13.84 **</td>
</tr>
<tr>
<td>Interaction</td>
<td>0.2278</td>
<td>1</td>
<td>0.2278</td>
<td>2.27 n.s.</td>
</tr>
<tr>
<td>pointxtypetext</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>1.2024</td>
<td>12</td>
<td>0.1002</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>7.3467</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 7.12: Analysis of Variance for Drilling Thrust for 103 RPI

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point angle</td>
<td>1.4522</td>
<td>1</td>
<td>1.4522</td>
<td>6.98</td>
</tr>
<tr>
<td>Drill type</td>
<td>5.7119</td>
<td>1</td>
<td>5.7119</td>
<td>27.44</td>
</tr>
<tr>
<td>Interaction pointxtype</td>
<td>0.0459</td>
<td>1</td>
<td>0.0459</td>
<td>0.22</td>
</tr>
<tr>
<td>Error</td>
<td>2.4980</td>
<td>12</td>
<td>0.2082</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>9.7080</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(See previous page for symbols)

TABLE 7.13: Analysis of Variance for Drilling Thrust for 70 RPI

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point angle</td>
<td>4.5078</td>
<td>1</td>
<td>4.5078</td>
<td>12.13</td>
</tr>
<tr>
<td>Drill type</td>
<td>2.9180</td>
<td>1</td>
<td>2.9180</td>
<td>7.85</td>
</tr>
<tr>
<td>Interaction pointxtype</td>
<td>0.3086</td>
<td>1</td>
<td>0.3086</td>
<td>0.83</td>
</tr>
<tr>
<td>Error</td>
<td>4.4590</td>
<td>12</td>
<td>0.3716</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>12.1934</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(See previous page for symbols)
Analysis of Tables 7.10 to 7.13 shows that the interaction between drill type and point angle is probably not significant for any feed. The effect of point angle is highly significant for the low to moderate feeds (240 RPI and 157 RPI, Tables 7.10 and 7.11), and significant (Table 7.13) or probably significant (Table 7.12) for the moderate to high feeds (70 RPI and 103 RPI). The analysis of the same tables also shows that the effect of drill type on drilling thrust is highly significant (Table 7.12), or significant (Table 7.11), for moderate feeds (103 RPI and 157 RPI, respectively) and probably not significant for low feeds (Table 7.10). For high feeds the effect of drill type on drilling thrust is probably significant (Table 7.13).

In Table 7.14 is presented a resumé of Tables 7.10 to 7.13.

TABLE 7.14: Resume of Analysis of Variance for Drilling Thrust, by Drilling Feeds (refer to Tables 7.10 to 7.13).  

<table>
<thead>
<tr>
<th>Effect</th>
<th>240 RPI</th>
<th>157 RPI</th>
<th>103 RPI</th>
<th>70 RPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point angle</td>
<td>64.03 ***</td>
<td>45.39 ***</td>
<td>6.98 *</td>
<td>12.13 **</td>
</tr>
<tr>
<td>Drill type</td>
<td>0.15 n.s.</td>
<td>13.84 **</td>
<td>27.44 ***</td>
<td>7.85 *</td>
</tr>
<tr>
<td>Interaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>point x type</td>
<td>0.02 n.s.</td>
<td>2.27 n.s.</td>
<td>0.22 n.s.</td>
<td>0.83 n.s.</td>
</tr>
</tbody>
</table>

(See Tables 7.10 and 7.11 for symbols)

Two further breakdown analyses for the effects on drilling thrust were done by drill point angles (Tables 7.15 and 7.16) and by drill types (Tables 7.17 to 7.18).
TABLE 7.15: Analysis of Variance for Drilling Thrust for 118° Point Angle

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>38.7422</td>
<td>3</td>
<td>12.9141</td>
<td>4562.46</td>
</tr>
<tr>
<td>Drill type</td>
<td>0.4987</td>
<td>1</td>
<td>0.4987</td>
<td>176.17</td>
</tr>
<tr>
<td>Interaction Feed x Type</td>
<td>0.2325</td>
<td>3</td>
<td>0.0775</td>
<td>27.39</td>
</tr>
<tr>
<td>Error</td>
<td>0.0680</td>
<td>24</td>
<td>0.0628</td>
<td></td>
</tr>
<tr>
<td>Table:</td>
<td>39.5414</td>
<td>31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(See Tables 7.10 and 7.11 for symbols)

TABLE 7.16: Analysis of Variance for Drilling Thrust for 134° Point Angle

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>33.0329</td>
<td>3</td>
<td>11.0110</td>
<td>4065.43</td>
</tr>
<tr>
<td>Drill type</td>
<td>1.3958</td>
<td>1</td>
<td>1.3958</td>
<td>515.34</td>
</tr>
<tr>
<td>Interaction Feed x Type</td>
<td>0.0731</td>
<td>3</td>
<td>0.0243</td>
<td>8.99</td>
</tr>
<tr>
<td>Error</td>
<td>0.0650</td>
<td>24</td>
<td>0.0027</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>34.5668</td>
<td>31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 7.17: Analysis of Variance for Drilling Thrust for Conventional Drill

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>40.3805</td>
<td>3</td>
<td>13.4602</td>
<td>4282.16</td>
</tr>
<tr>
<td>Point angle</td>
<td>0.1053</td>
<td>1</td>
<td>0.1053</td>
<td>33.50</td>
</tr>
<tr>
<td>Interaction Feed x Point</td>
<td>0.1398</td>
<td>3</td>
<td>0.0466</td>
<td>14.83</td>
</tr>
<tr>
<td>Error</td>
<td>0.0754</td>
<td>24</td>
<td>0.0031</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>40.7010</td>
<td>31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(See Tables 7.10 and 7.11 for symbols)

TABLE 7.18: Analysis of Variance for Drilling Thrust for New Design Drill

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>31.5111</td>
<td>3</td>
<td>10.5037</td>
<td>4375.24</td>
</tr>
<tr>
<td>Point angle</td>
<td>0.0229</td>
<td>1</td>
<td>0.0229</td>
<td>9.55</td>
</tr>
<tr>
<td>Interaction Feed x Point</td>
<td>0.0491</td>
<td>3</td>
<td>0.0164</td>
<td>6.82</td>
</tr>
<tr>
<td>Error</td>
<td>0.0576</td>
<td>24</td>
<td>0.0024</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>31.6407</td>
<td>31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(See tables 7.10 and 7.11 for symbols)
Analysis of Tables 7.15 and 7.16 reveals that the interaction of feed and drill type on drilling thrust is highly significant. Tables 7.17 and 7.18 show that the effect of the interaction between feed and point angle on drilling thrust is highly significant for the conventional drill (Table 7.17) and significant for the new design drill (Table 7.18).

Proceeding for the torque (Table 7.3) as for the thrust, the analysis of variance was also carried out and summarised in Table 7.19.

TABLE 7.19: Analysis of Variance for Drilling Torque

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance Estimate</th>
<th>Variance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill type</td>
<td>0.00416</td>
<td>1</td>
<td>0.00416</td>
<td>71</td>
</tr>
<tr>
<td>Point angle</td>
<td>0.00837</td>
<td>1</td>
<td>0.00837</td>
<td>142</td>
</tr>
<tr>
<td>Feed</td>
<td>1.37687</td>
<td>3</td>
<td>0.45896</td>
<td>7832</td>
</tr>
<tr>
<td>Type x Point</td>
<td>0.00023</td>
<td>1</td>
<td>0.00023</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>n.s.</td>
</tr>
<tr>
<td>Type x Feed</td>
<td>0.00205</td>
<td>3</td>
<td>0.00068</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>Point x Feed</td>
<td>0.00034</td>
<td>3</td>
<td>0.00011</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>n.s.</td>
</tr>
<tr>
<td>Type x Point x Feed</td>
<td>0.00014</td>
<td>3</td>
<td>0.000047</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>n.s.</td>
</tr>
<tr>
<td>Error</td>
<td>0.00281</td>
<td>48</td>
<td>0.000059</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>1.39497</td>
<td>63</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(See Tables 7.10 and 7.11 for symbols)
Table 7.19 shows that the effect of the interaction of the three factors, drill type x point angle x drilling feed, the effect of the interaction of drill type and point angle and the effect of the interaction of the point angle and drilling feed on the drilling torque are probably not significant. It also shows that the effect of the interaction of drill type and drilling feed on the drilling torque is significant while the effect of the point angle is highly significant.

To study the effect of the other factors, a breakdown analysis was done by feed and drill type. A résumé of the variance analysis by drilling feed is presented in Table 7.20

**TABLE 7.20**: Résumé of Analysis of Variance for Drilling Torque by Drilling Feed

<table>
<thead>
<tr>
<th>Effect</th>
<th>240 RPI</th>
<th>157 RPI</th>
<th>103 RPI</th>
<th>70 RPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point angle</td>
<td>64.03 ***</td>
<td>45.39 ***</td>
<td>6.98 *</td>
<td>12.13 **</td>
</tr>
<tr>
<td>Drill type</td>
<td>0.15 n.s.</td>
<td>13.84 **</td>
<td>27.94 ***</td>
<td>7.85 *</td>
</tr>
<tr>
<td>Interaction</td>
<td>0.02 n.s.</td>
<td>2.27 n.s.</td>
<td>0.22 n.s.</td>
<td>0.83 n.s.</td>
</tr>
<tr>
<td>point x type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(See tables 7.10 and 7.11 for symbols)

Analysis of Table 7.20 shows that the effect of the interaction of point angle and drill type on drilling torque is probably not significant as already seen in Table 7.19. The effect of the drill type is highly significant (103 RPI) or significant (157 RPI) for moderate drilling feeds and probably significant for high feeds (70 RPI); for low feeds (240 RPI) the effect of drill type on the drilling torque is probably not significant. The effect of point angle on the drilling
torque is highly significant for low to moderate feeds (240 RPI and 157 RPI) and probably significant to significant for moderate to high feeds (103 RPI to 70 RPI).

A resume of the variance analysis by drill type is presented in Table 7.21.

**TABLE 7.21: Resume of Analysis of Variance for Drilling Torque, by Drill Type**

<table>
<thead>
<tr>
<th>Variance Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effect</strong></td>
</tr>
<tr>
<td>Feed</td>
</tr>
<tr>
<td>Point angle</td>
</tr>
<tr>
<td>Interaction feed x point</td>
</tr>
</tbody>
</table>

(See Tables 7.10 and 7.11 for symbols)

Analysis of Table 7.21 shows that the interaction of drilling feed and point angle on the drilling torque is probably not significant, as already shown in Table 7.19. It also shows that feed and point angle are highly significant for drilling torque, as expected.
"...most of the information for the evaluation of cutting operations ... is closely related to the chip geometry".

Nakayama

8. ANALYSIS OF THE INFLUENCE OF FLUTE FORM ON CHIP FLOW
8.1 Introduction

The new design drill has shown higher wear rates and higher torque (especially for stronger feeds) in spite of presenting a better "heat sink" and approximately the same effective rake angle as the conventional drill.

In an attempt to investigate the reasons for such a difference in the performance of the two compared drill types, and further to develop a better criterion for drill design, the author took the view that the chip characteristics, being specific to each drill type, should be considered in analysing the drilling operation and the drill action.

8.2 Common Approach to Machining Chips

Frequently machining chips are looked at as a nuisance for the inconveniences such as chip disposal and interruption of the machining operation. Some chip classifications reflect this approach and they show the chips grouped into two major classes (71, 108): acceptable and unfavourable.

Many chip classifications can be found in literature (71, 73, 108, 109, 110, 111, 112, 113) and even in a recent edition of a British Standard (BS 5623). Many times, however, these classifications focus mainly on the conveyance and disposal features of the chips.

There are many reports in the literature on the devices and on the cutting conditions for chip control with single point cutting tools. For drilling chip control, literature is more scarce. However, some drills with special chip breaking features have been reported by Bhattacharyya (38), Oxford (21) and CETIM (17) (refer to Chapter 2, too).

The influence of drilling conditions on chip form and size have been referred to by Nakayama and co-workers (14), CETIM (17) and Galloway and co-workers (10).
Some workers, such as Spaans (100), Nakayama et al (14) and others (114, 115, 116) take the view that chip geometry is related to cutting efficiency. The author also believes that the machining chips are an important source of a great deal of information data about the cutting process.

8.3 Chips and Rigid Body Concept

In many works the chip is either explicitly or implicitly referred to as a rigid body [D.19].

Lee and Shaffer (47), in a paper on the orthogonal cutting, stated that the chip must leave the plastic region as a rigid body. For Dewhurst (117) the chip can be viewed as the continuous emergence of a rigid body. Spaans (73) assumes the chip to behave as a rigid body. Armarego and Cheng (72) make the assumption that the chip travels as a rigid body after shearing has occurred. Kronenberg (118) referred to the fact that it is customary to consider the chip as a stationary body in static equilibrium. Wallace (119) also assumed the chip to slide as a rigid body up the tool rake face.

The assumption that the chip is a rigid body is also implicit in works by Nakayama (120) and Henriksen (112), for instance.

8.4 Drilling Chips

Oxford (20) reported once on the chip formation mechanism along drill lips and found it to be similar to any other metal-cutting operation. He further measured the chip flow angle for several radial distances and for several drilling conditions.

Armarego and Cheng (121) measured the chip length ratio [D.5] for drilling chips.

Nakayama and co-workers (14), discussed, in qualitative terms, the factors which are supposed to influence the formation of drilling
chips and would determine their shape and size. They observed that "the basic form of the chip produced by twist drills is the conical helical chip with short pitch". (Figures 8.1 and 8.2).

Observations by the author of the drilling chips and the drilling operation were complemented by a visual study of a high speed cine film (1000 frames per second) showing a 19.52 mm diameter conventional drill producing 38.1 mm deep holes in EN8 steel at 640 rpm and 0.25 mm/rev. In this film the drill entry stage can be seen with great detail and the chips emerging from the hole, along the flute, can also be seen during drill penetration (Figures 8.1 and 8.2).

The author believes that the rigid body concept can be used with the drilling chips for analysis of their shape and kinematic properties.

Rigid bodies have properties of their own which are likely to enlighten some drilling aspects and to help with some predictions otherwise difficult.

The rigid body concept is used in this work as an analytical approach which is surprisingly successful, as it will be shown, mainly for the correlations between its predictions and experimental results reported in literature (Sections 8.6.2, 8.6.3 and 8.6.4).

8.5 Mathematical Model of an Helical Rigid Body Chip

The rigid body concept is a physical one and it is more general than most of the machining concepts.

To use the rigid body concept for chip analysis allows for the utilization of mathematical models and for implementation in computer programs.

This approach permits geometrical simulation and numerical investigation to be carried out which is expected:
FIGURE 8.1: Drilling chip inside hole and drill flute. (Frame from high speed cine film)

FIGURE 8.2: As in FIGURE 8.1 after drill rotated approximately 90 degrees
- to make possible to identify the parameters that govern the variation of chip flow along a drill lip
- to allow to identify the conditions and constraints the geometry of the flute drill imposes on the determination of chip form and size and chip flow
- to produce new information to be taken into account in the definition of a criterion for drill flute design.

8.5.1 Equations

The rigid body motion features are dealt with in many books on mechanics such as (80).

The motion of a rigid body can be regarded as a translation along a certain axis, \(a\), and simultaneous rotation about it.

Let (Figure 8.3i):

\[
\begin{align*}
\mathbf{a} & \quad - \quad \text{the rigid body axis} \\
\mathbf{O} & \quad - \quad \text{any point on the axis } \mathbf{a}, \\
\mathbf{P} & \quad - \quad \text{a current point on the rigid body}, \\
\mathbf{V}_t & \quad - \quad \text{the translation velocity of the rigid body along axis } \mathbf{a} \\
\mathbf{W}_c & \quad - \quad \text{the angular velocity of the rigid body about axis } \mathbf{a} \\
\mathbf{V}_c & \quad - \quad \text{Velocity of point } \mathbf{P}
\end{align*}
\]

Let a drilling chip (Figures 8.1, 8.2 and 8.3) be a rigid body.

From the mechanics of rigid bodies (80):

\[
\mathbf{V}_c = \mathbf{V}_t + \mathbf{W}_c \times \mathbf{OP}
\]

This can also be written:

\[
\mathbf{V}_c = \mathbf{V}_t + \mathbf{W}_c \times \mathbf{R}_c \tag{8.1}
\]
a - rigid body axis

\( \vec{V}_c \) - chip velocity at point \( P \)

\( \vec{R}_c \) - radial vector to point \( P \)

\( \vec{V}_t \) - translation velocity

\( \vec{W}_c \) - angular velocity

\( \eta \) - chip flow angle

\( S_f \) - rake face

\( S_a \) - flank face

FIGURE 8.3: Rigid body geometrical and kinematical variables (i) and rigid body chip (ii)
where $R_c$ is the radial vector of point $P$ referred to the chip axis.

The relevant geometrical features of an helical chip are shown in Figure 8.4 from where the following relationship can be written:

$$p_c = \pi d_{co} \cot \gamma_{co} \tag{8.2}$$

where 
- $p_c$ - chip lead
- $d_{co}$ - chip diameter
- $\gamma_{co}$ - chip helix angle at radius $d_{co}/2$

The number of revolutions per time unit of the chip about its axis is designated by $N_c$ and the following expressions can be written:

$$W_c = 2\pi N_c \tag{8.3}$$

$$V_t = p_c N_c \tag{8.4}$$

where
- $W_c = |\overrightarrow{W_c}|$ and
- $V_t = |\overrightarrow{V_t}|$

Let $\hat{a}$ be the unit vector on the chip instantaneous axis of rotation of the chip, then:

$$\overrightarrow{V_t} = p_c N_c \hat{a} \tag{8.5}$$

$$W_c = 2\pi N_c \hat{a} \tag{8.6}$$

Also let

- $\overrightarrow{V_c} = \overrightarrow{V} \hat{v}_c$ where $|\overrightarrow{V_c}| = 1$
- $\overrightarrow{R_c} = \overrightarrow{R} \hat{r}_c$ where $|\overrightarrow{R_c}| = 1$
As $v_t$ is normal to $w_c \times r_c$, from equation 8.1, it can be written

$$v_c = (v_t^2 + (|w_c \times r_c|)^2)^{\frac{1}{2}}$$

$$v_c = ((p_c n_c)^2 + (2\pi n_c r_c)^2)^{\frac{1}{2}}$$

8.7

If equations 8.5, 8.6 and 8.7 are substituted in equation 8.1 then

$$N_c \frac{(p_c^2 + (2\pi R_c)^2)^{\frac{1}{2}}}{v_c} = p_c n_c \hat{a} + 2\pi n_c \hat{a} \times (r_c \hat{r}_c)$$

$$v_c = \frac{p_c}{(p_c^2 + (2\pi R_c)^2)^{\frac{1}{2}}} \hat{a} + \frac{2\pi R_c}{(p_c^2 + (2\pi R_c)^2)^{\frac{1}{2}}} \hat{a} \times \hat{r}_c$$

8.1'

Equation 8.1' is the mathematical model, in the vectorial form, for a helical chip with lead $p_c$ where $p_c$ depends on the external diameter, $d_{co}$, of the chip and on the helix angle, $\gamma_{co}$, at the chip periphery (Equation 8.2).

The mathematical model represented by equation 8.1' can be written in algebraic form if the components of $v_c$, $\hat{a}$ and $\hat{r}_c$ in a referential system are known.

Let:

$$v_c = (v_1, v_2, v_3)$$

$$\hat{a} = (a_1, a_2, a_3)$$

$$\hat{r}_c = (r_{c1}, r_{c2}, r_{c3})$$
FIGURE 8.4: Geometrical features of an helical chip

FIGURE 8.5: Steel drilling chips diameter distribution for 12.7 mm diameter conventional drill. [Refer to next FIG for d_{CO}]
So:

\[ \hat{a} \times \hat{r}_c = \begin{vmatrix} i & j & k \\ a_1 & a_2 & a_3 \\ r_{c1} & r_{c2} & r_{c3} \end{vmatrix} = \]

\[ = (a_2 r_{c3} - a_3 r_{c2}, a_3 r_{c1} - a_1 r_{c3}, a_1 r_{c2} - a_2 r_{c1}) \]

where \( i, j, k \) are the unit vectors on the referential axes.

Then:

\[ v_{c1} = M \left[ p_c a_1 + 2\pi R_c (a_2 r_{c3} - a_3 r_{c2}) \right] \quad 8.1'a \]

\[ v_{c2} = M \left[ p_c a_2 + 2\pi R_c (a_3 r_{c1} - a_1 r_{c3}) \right] \quad 8.1'b \]

\[ v_{c3} = M \left[ p_c a_3 + 2\pi R_c (a_1 r_{c2} - a_2 r_{c1}) \right] \quad 8.1'c \]

where \[ M = \frac{1}{(p_c^2 + (2\pi R_c)^2)^{1/2}} \]

Equations 8.1'a to 8.1'c represent, in algebraic form, the mathematical model for a helical chip with parameter \( p_c \).

8.5.2 Analysis of parameter \( p_c \)

The rigid body chip lead, \( p_c \), is related to the chip helix angle through the chip diameter as can be seen in equation 8.2 and Figure 8.4.
8.5.2.1 Drilling chip diameter

From the earlier stages of this work many chips produced by different drill sizes, in different drilling conditions, for various steels, have been collected.

It was observed, and it has also been reported (17), that drilling chips produced by conventional drills tend to appear fragmented when feed increases and/or drill diameter decreases.

With 12.7 mm (1/2") conventional drills and for the feeds relative to 240 RPI and 157 RPI, many helical chips of full width (the length of the lip, from chisel corner to outer corner) could be collected. The diameters of these chips were measured and the respective distribution analysed (Figure 8.5).

The chips for the 240 RPI appeared to concentrate around the 5.9 mm diameter, and the ones for the 157 RPI around 5.6 mm diameter.

The author thought that these diameter values might be related to the space available inside the flute. This space was computed according to the biggest circle inside a section normal to the drill axis, as shown in Figure 8.6, and the computed value, $d'_{co}$, resulted to be 5.3 mm (refer to Figure 8.6).

The actual chip diameters appear to be somewhat over the computed value of $d'_{co}$ (refer to Figure 8.5): 5.9 mm and 5.6 mm against 5.3 mm for $d'_{co}$. This fact may be explained by the ability of the drilling chips to accommodate large elastic deformation as it can be checked by twisting, by hand, any drilling chip, by opening it (increases diameter) or closing it (decreases diameter). This is believed to be supported by the fact that different feeds (thus different chip thicknesses) yield chips of different average diameters (different compliance of the chips).

As a matter of chip diameter specification, for the computation with the chip model, a dimension of the space available inside the flute can be used as an approximation. Such a dimension can be, as a
FIGURE 8.6: Maximum circle inside the drill flute in a section normal to the drill axis
matter of simplification relatively to the method illustrated in Figure 8.6, the computed difference between the drill radius \( r_0 \) and the half web thickness \( W \): \( r_0 - W \) (Figure 8.6).

Nevertheless, the diameter of the chip decreases from the outer corner to the chisel corner mainly as a consequence of the decreasing cutting speed along the lip, from the periphery to the drill axis.

8.5.2.2 Drilling chip helix angle

The chip helix angle, \( \gamma_{\text{co}} \) (Figure 8.4), can be related to the chip flow angle, \( \alpha_0 \) (Figure 8.3), at the point \( O_c \) (outer corner) as it will be shown.

If, as generally recognized in the field of oblique cutting, the inclination angle has an important influence on the determination of the chip flow angle, the chip helix angle will be equally determined by the inclination angle too.

By definition, the chip flow angle, \( \alpha \), is given by (Figure 8.3):

\[
\cos (90 - \alpha) = \frac{\mathbf{e} \cdot \mathbf{V}_c}{|\mathbf{V}_c||\mathbf{e}|} = \frac{\mathbf{V}_c \cdot \mathbf{e}}{\mathbf{V}_c}
\]

where \( \mathbf{e} \) is assumed to be the unit vector on the tangent to the cutting edge at the selected point.

From equations 8.1 and 8.8:

\[
\sin \alpha = \frac{(\mathbf{V}_t + \mathbf{w}_c \times \mathbf{R}_c) \cdot \mathbf{e}}{\mathbf{V}_c}
\]

\[
\sin \alpha = \frac{\mathbf{V}_t \cdot \mathbf{e} + (\mathbf{w}_c \times \mathbf{R}_c) \cdot \mathbf{e}}{\mathbf{V}_c}
\]

8.9
Using equations 8.5 and 8.6 in equation 8.9 it results:

\[
\sin \eta = \frac{N_c p_c \hat{a} \cdot \hat{e} + (2\pi N_c \hat{a} \times \hat{R}_c) \cdot \hat{e}}{V_c} \quad 8.9'
\]

\[
\sin \eta = \frac{p_c \cos \kappa_c + 2\pi R_c (\hat{a} \times \hat{R}_c) \cdot \hat{e}}{V_c} \quad 8.9''
\]

where \( \kappa_c \) (Figure 8.7) is the angle between the cutting edge at the selected point and the instantaneous axis of rotation of the chip, and \( \hat{R}_c \) is the unit vector in the direction of \( R_c \), and \( R_c \) the length of \( \hat{R}_c \).

From vectorial analysis (78), the product \((\hat{a} \times \hat{R}_c) \cdot \hat{e}\) represents the volume of a parallelepiped having \( \hat{a} \), \( \hat{R}_c \) and \( \hat{e} \) as edges.

\( \hat{a} \) and \( \hat{R}_c \) are unit vectors and normal to each other. From Figure 8.7:

\[
\begin{align*}
\frac{HJ}{AH} &= \frac{GI}{AG}; \quad AH = 1; \quad HJ = \frac{GI}{AG} \\
\frac{AB}{AG} &= \cos \kappa_c; \quad AB = 1; \quad AG = \frac{1}{\cos \kappa_c}; \quad HJ = GI \cos \kappa_c \\
GI &= MN \\
\frac{MN}{AN} &= \frac{g_c}{R_c} \\
MN &= \frac{g_c}{R_c} AN; \quad AN = BG = \tan \kappa_c; \quad MN = \frac{g_c}{R_c} \tan \kappa_c = GI \\
HJ &= GI \cos \kappa_c \frac{g_c}{R_c} \tan \kappa_c \cos \kappa_c = \frac{g_c}{R_c} \sin \kappa_c
\end{align*}
\]

\[
\therefore (\hat{a} \times \hat{R}_c) \cdot \hat{e} = 1.1. HJ = HJ = \frac{g_c}{R_c} \sin \kappa_c
\]
\[ \sin \theta = \frac{g_c}{R_c} \]

**FIGURE B.7:** Position of the chip axis relative to the cutting edge

\[ \begin{align*}
AP &= R_c' \\
AB &= r_1 = 1 \\
AD &= l_c = 1 \\
\overrightarrow{a} \cdot \overrightarrow{e} &= \\
AB \cdot AD \cdot HJ &= \\
1 \cdot \overrightarrow{HJ} &= \overrightarrow{HJ}
\end{align*} \]

**FIGURE 8.8:** Maximum theoretical possible chip flow angle at the drill outer corner.
Equation 8.9 can now be written in the following way:

\[
\sin \theta = \frac{P_C \cos \kappa_C + 2\pi R_C R_C \sin \kappa_C}{V_C} \tag{8.9iii}
\]

As \( V_C \) is given by equation 8.7, then equation 8.9 becomes:

\[
\sin \theta = \frac{P_C \cos \kappa_C + 2\pi g_C \sin \kappa_C}{1/M} \tag{8.9iv}
\]

or

\[
\sin \theta = P_C M \cos \kappa_C + 2\pi R_M R_C \frac{g_C}{R_C} \sin \kappa_C \tag{8.9v}
\]

From Figure 8.3 it can be seen that:

\[
\cos \gamma_C = P_C M \tag{8.10}
\]

\[
\sin \gamma_C = 2\pi R_C M \tag{8.11}
\]

where

\[
M = \frac{1}{(P_C^2 + (2\pi R_C)^2)^\frac{1}{2}}
\]

Then

\[
\sin \theta = \cos \gamma_C \cos \kappa_C + \sin \gamma_C \frac{g_C}{R_C} \sin \kappa_C \tag{8.9vi}
\]

where (Figure 8.7):

- \( \gamma_C \) - chip helix angle at the selected point
- \( R_C \) - chip radial distance from the selected point to the chip axis
- \( g_C \) - distance from the chip instantaneous axis of rotation to the tangent to the lip at the selected point
\( \kappa_c \) - angle between the chip instantaneous axis of rotation and the tangent to the lip at the selected point.

At the outer corner, equation 8.9vi is written:

\[
\sin \eta_0 = \cos \gamma_{co} \cos \kappa_{co} + \sin \gamma_{co} \frac{g_{co}}{R_{co}} \sin \kappa_{co} \quad 8.9\text{vii}
\]

The maximum theoretically possible value of \( \eta_0 \) at the drill periphery is illustrated in Figure 8.8.

For one conventional drill with the features \( 2W' = 2 \text{ mm}; \gamma_f = 30^\circ; \kappa = 59^\circ \) and \( d_0 = 12.7 \text{ mm} \left( \frac{1}{2}'' \right) \) the angle \( \eta_0 \) was computed and found to be \( 30.9^\circ \).

Making \( g_{co} = 0.1 \) and \( \kappa_{co} = 180^\circ \), which have been obtained from one example, and for one chip 5.3 mm diameter, the above equation 8.9vi gives \( \gamma_{co} = 60^\circ \) for \( \eta_0 = 30.9^\circ \). This corresponds to a chip lead of nearly 10 mm.

The chips referred to in the last section were also measured for chip lead. The results have shown a dispersed distribution with the majority of the values falling in the interval 3-5 mm. These values correspond to chip helix angles comprehended between approximately \( 80^\circ \) and \( 73^\circ \).

8.6 Computing Approach to Drilling Chips

For computing approach purposes the following conditions are supposed to apply to drilling chips:

i) the chip is formed at the drill lip and it is born a rigid body;

ii) the chip is generated all along the lip, from the chisel corner up to the outer corner, and any lateral deformation is neglected;
iii) any action (by the hole wall or the flute heel, for example) on the chip formed at the lip is responded by the chip, for its permanent form and size, at its root, i.e. at the surface of separation chip/workpiece;

iv) the rigid body chip tends to be tangent to the rake face at the drill lip and the chip contact length \[D.10\] is neglected;

v) the chip diameter is governed by the space available in the drill flute and in the hole;

vi) chip radius decreases from the outer corner towards the chisel corner.

One condition is also assumed for the lip and for the flute face: the lip and the flute face are not altered either by wear or by built-up-edge \[D.3\] during drilling.

At this stage the instantaneous axis of rotation of the chip is not yet known. However, some conditions controlling the size and the flow of drilling chips have already been referred to.

It is possible to compute a chip rigid body motion, for a given chip lead, with the drill lip as a generator line, for an instantaneous axis selected to a guess. Then it is possible to compute the deviation of the computed rigid body to the pre-specified conditions: chip diameter and tangency to the rake face.

If the instantaneous axis is defined by two points, B and M, Figure 8.9, it is possible, starting from the points determined to a guess, to determine a set of pairs of points in the neighbourhood of the starting one and to define a set of instantaneous axes with each pair of points. The above referred to deviations can be computed for each new instantaneous axis and compared between each other in order to find the one which is nearer to the desired solution.

From the new instantaneous axis the process can proceed as indicated until the best axis is found as an exact solution may not be possible.
A computer program (Appendix 8) was designed and built up, according to the described strategy, in order that the best rigid body chip complying to the specifications could be found.

A rigid body chip axis is presented in Figure 8.10 for one chip 4 mm lead, 6.4 mm diameter. For this example, the axis is 0.09 mm distant from the cutting edge and inclined 27.01° to the same edge as referred to the outer corner.

8.6.1 Drilling chip geometrical simulation

The above referred to computer program was developed in order to geometrically simulate the chip. Figure 8.11 shows the geometrically simulated rigid body chip for the same conditions as for Figure 8.10.
Figure B.10: Computer generated drilling chip axis for one chip 4 mm lead and 6.1 mm diameter.
FIGURE 8.11: Computer geometrically simulated rigid body chip

For axis and conditions as in FIGURE 8.10

Flute - Grinding-
conventional cylindrical

R0 = 6.35 D0g = 26.00
Web = 1.95 Vg = 80.00
H0 = 33.00 Exg = 2.80
Rk = 59.00 Rkg = 59.00
FIGURE 8.12: Views of drilling chip emerging from the drill lip

[Refer to FIGURE 8.11 - computer simulated chip]
Figure 8.12 shows an actual chip produced by a conventional drill with the features as for Figures 8.10 and 8.11, and for the following cutting conditions: 820 rpm, 240 RPI, EN43 steel, soluble oil as coolant.

Figure 8.13 shows the computed chip axis for the new design drill. A similar simulation to that in Figure 8.12 is shown in Figure 8.14 for this drill.

The main apparent difference between the simulated chip shown in Figure 8.11 and the one shown in Figure 8.14 refers to the geometric shape which is cone-like for the conventional flute and bell-like for the new design flute. Other major and more significant differences will be referred to in the sections ahead.

8.6.2 Chip flow angle: prediction by the present model compared to measurements by Oxford

Some workers, in studying the conventional drill lip action with the cutting mechanics approach, have made several assumptions for the chip flow angle.

Bhattacharyya (25) once assumed the empirical Stabler's rule:

\[ \eta = \lambda \]  

4.17

to be valid in the drilling operation.

Armarego and Cheng (72) made a study of conventional drills to which the rake face was made flat at the drill lip, by grinding, and attempted three different chip flow angle laws:

i) \( \eta = \lambda \)

ii) \( \eta = \tan^{-1} (\tan \lambda \cos \gamma_n) \)  

4.19

iii) \( \eta = (0.9 - 0.2 \gamma_n) \lambda \)  

8.12

where the two last ones are arbitrary laws.
FIGURE 8.13: Computer generated drilling chip axis for one chip 1 mm lead and 6.4 mm diameter
Flute - new

Grinding- cylindrical

$R_0 = 6.35$
$\text{Web} = 1.95$
$H_0 = 33.00$

$D_{0g} = 26.00$
$V_g = 80.00$
$E_{xg} = 2.80$
$R_{kg} = 59.00$

FIGURE 8.11: Computer geometrically simulated rigid body chip

For axis and conditions as in FIGURE 8.13
Laws (i) and (ii) have already been dealt with by the author in Chapter 4.

The law (iii) has shown to better serve the theoretical purposes of Armarego and Cheng who found it to yield smaller angles than those with the rule by Stabler.

For conventional drills, the same workers - Armarego and Cheng - assumed the chip velocity at each point to be on a plane parallel to the drill axis and normal to the radius at the selected point (72).

They further developed a formula for the calculation of this angle, which is, according to the assumption, the angle between the lip and the tangent to the helix, measured on the plane tangent to the rake face, at the selected point, and found

\[ \eta = \sin^{-1} \left( \cos \gamma \cos \kappa + \frac{W'}{r} \sin \gamma \cos \kappa \right) \]  

where

- \( \eta \) - chip flow angle at the selected point
- \( \gamma \) - helix angle at the selected point
- \( \kappa \) - \( \frac{1}{2} \) point angle
- \( 2W' \) - lip spacing
- \( r \) - radial distance.

The author computed this angle by the model presented in Chapter 4 and by means of vectorial analysis and found the values to coincide, as expected, with those by the above formula. Incidentally the author notes that the formula by Armarego and Cheng is unusable with curved lips.

Equation 4.17 (Stabler) and equation 8.13 (Armarego and Cheng) are presented in Figure 8.15 compared to drilling chip measurements by Oxford (20), (refer to Figure 8.16 ii).
FIGURE 8.15: Drilling chip flow angle versus inclination angle from three sources: i (20) (refer to FIG 8.16ii); ii (45); iii (72)
FIGURE 8.16: Chip flow lines:

- Computer simulated (author's approach)
- Recorded by OXFORD (1,20)
Flute - conventional  Grinding - cylindrical

$R_0 = 9.52$  $D_0g = 10.00$
$W_{eb} = 2.79$  $V_g = 90.00$
$H_0 = 32.00$  $E_{xg} = 3.50$
$R_k = 59.00$  $R_{kg} = 59.00$

FIGURE B.17: Drilling chip flow angle versus inclination angle as predicted by the author. [Compare with FIGURE B.15]
The drill features to which Figure 8.15 refers to are (Oxford (20)): \( r_0 = 9.52 \text{ mm}, \ 2W = 2.79 \text{ mm}, \ \gamma_f = 32^\circ, \ 2\kappa = 118^\circ. \)

The author used his rigid body approach for computing the chip flow angle (Figure 8.16) and for \( d_{co} = 8 \text{ mm} \) and \( p_c = 5.5 \text{ mm} \) (values that tests with 19.52 mm diameter conventional drills from the shelf confirmed to be representative) found the result shown in Figure 8.17.

The agreement between the experimental values and the prediction by the present model is not only qualitative but also quantitative.

The deviations of the predicted chip flow angle from the measured ones, for the higher values of the inclination angle (occurring close to the chisel corner) may be explained by the effect of the chisel edge chips, which has not been considered in the present approach, and may increase the chip flow angle of the lip produced chips by locally forcing them out (Figure 8.18). However, the chip flow near the chisel corner is likely to be so strongly complex and disturbed (there are two distinct processes of cut at the chisel corner neighbourhood - one by the lip and the other by the chisel edge) that a theoretical approach for this point could hardly succeed.

FIGURE 8.18
Drilling chip embedded in press moulded resin, cut along its axis, showing larger concentrations of material at the area closer to the chip axis (a)
To compare the conventional drill with the new design one, the rigid body approach was considered for both 12.7 mm diameter drill types.

Figure 8.19 shows the chip flow angle together with the inclination angle versus the distance along the lip for the conventional drill. The chip flow angle was also plotted against the inclination angle in Figure 8.20.

Figures 8.21 and 8.22 show similar representation to Figures 8.19 and 8.20 respectively, for the new design drill.

Figure 8.21 shows that the inclination angle is such that it has a minimum near the point at 3 mm from the chisel corner, and increases to either side of this point.

Figure 8.22 shows that for the conditions considered in the computation (chip diameter to be accommodated inside the flute) a rigid body chip would have two parts with two distinct performances: for one part the chip flow angle would increase together with the inclination angle, for the other the chip flow angle would decrease with increasing inclination angle.

If the inclination angle is the major variable controlling the chip flow angle for oblique cutting (14, 45, 73) (see equation 4.17, for example) the situation depicted in Figure 8.22 would be quite unusual as it shows two different tendencies for two distinct parts of the same chip. In fact, it is observed in Figure 8.26 (compare to Figure 8.24) and Figure 8.27i that, for the case analysed, the chip splits in two as if two chips were produced.

Apparently it could be asked if a rigid body that yields a chip flow angle as the one shown in Figures 8.28 and 8.29 - chip flow angle increases when the inclination angle increases and decreases with decreasing inclination angle - would be possible with the new design drill.
FIGURE 8.19: Drilling chip flow angle, from rigid body approach (5.4 mm chip diameter and 4 mm chip lead), and drill lip inclination angle.
**FIGURE 8.20:** Drilling chip flow angle from rigid body approach (i) [refer to FIGURE 8.19] and STABLER’s rule versus drill lip inclination angle.

<table>
<thead>
<tr>
<th>Flute - conventional</th>
<th>Grinding - cylindrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_0 = 6.35 )</td>
<td>( D_{0g} = 28.00 )</td>
</tr>
<tr>
<td>( \text{Web} = 1.95 )</td>
<td>( V_g = 90.00 )</td>
</tr>
<tr>
<td>( H_0 = 33.00 )</td>
<td>( E_{xg} = 3.00 )</td>
</tr>
<tr>
<td>( R_k = 59.00 )</td>
<td>( R_{kg} = 59.00 )</td>
</tr>
</tbody>
</table>
FIGURE 8.21: Drilling chip flow angle, from rigid body approach (5.4 mm chip diameter and 4 mm chip lead), and drill lip inclination angle.
Flute - new
Grinding- cylindrical

R₀ = 6.35  D₀g = 28.00
Web = 1.95  Vg = 90.00
H₀ = 33.00  Exg = 3.00
Rkg = 59.00

a - chip's internal part
b - chip's external part

FIGURE B.22: Drilling chip flow angle from rigid body approach (i) [refer to FIGURE B.21] and STABLER's rule versus drill lip inclination angle
FIGURE 8.23: Cone-like chips produced on drill entry
[1/2" and 118° conventional drill; 820 rpm
and 157 rpi; EN43 steel]

FIGURE 8.24: Conical helical drilling chips generated
inside hole and flute - drill and condi-
tions as for FIG 8.23 (Refer to FIG 8.1)
FIGURE 8.25: Bell-like chips produced on drill entry
[1/2" and 118° new design drill; 820 rpm
and 157 rpi; EN43 steel]

FIGURE 8.26: Split drilling chips generated inside
hole and flute - drill and conditions
as for FIG 8.25]
FIGURE 8.27: Frozen drilling chips:

i) by non-conventional drill (split chip)

ii) by conventional drill

Such a chip flow angle was computed for a rigid body chip with parameters $d_{co} = 9$ mm (chip diameter) and $p_c = 4$ mm (chip lead) (Figure 8.30).

This rigid body would be possibly produced if enough space was provided for the chip to flow as it would require a "cylinder" at least approximately 9 mm diameter (the flute and hole "produce" a "cylinder" about only 5.4 mm).

Such a space is actually available at the entry of the drill where the chip is not constrained by the hole walls, Figure 8.25 (compare to Figure 8.23), and can proceed without splitting as a rigid body.
FIGURE 8.28: Drilling chip Flow angle, from rigid body approach (9.0 mm chip diameter and 4 mm chip lead), and drill lip inclination angle.
FIGURE 8.29: Drilling chip flow angle from rigid body approach (i) [refer to FIGURE 8.28] and STABLER’s rule versus drill lip inclination angle
Flute - new

Grinding - cylindrical

R0 = 6.35  D0g = 28.00
Web = 1.95  Vg = 90.00
H0 = 33.00  Exg = 3.00
Rkg = 59.00

FIGURE 8.30: Computer geometrically simulated rigid body chip

[drill entry] for the new design drill
8.6.3 Variation of the chip length ratio along drill lip. Prediction by the present model versus experimental data reported in literature

The cutting ratio is the ratio of the uncut chip thickness, \( t_1 \), to the chip thickness, \( t_2 \): \( t_1/t_2 \). Sometimes the reciprocal, \( t_2/t_1 \) - chip thickness ratio - is used instead.

In the cases where chip thickness is difficult to measure, another ratio is used: the chip length ratio, which is the chip length divided by the corresponding uncut length.

The cutting ratio has been analysed, measured and discussed by many workers in the area of machining (4, 12, 25, 43, 45, 47, 73, 119, 122). It depends on many factors, and reports in literature frequently refer to empirical correlations between the cutting ratio and the cutting factors. However, only one reference dealing with one sort of cutting ratio (chip length ratio) of the drilling chips was found in literature (121).

The chip length ratio (and the cutting ratio too) is difficult to predict, in general. Nevertheless it appears that it would be possible to predict its relative variation along a cutting edge such as a drill lip as regards to the lip cutting geometry variation, chip flow variation and material approaching speed variation.

From Figure 4.34 and admitting that there is no loss of material, neither material density variation across the lip, nor chip lateral deformation, it can be written:

\[ \varepsilon_1 t_1 b_1 = \varepsilon_2 t_2 b_2 \]  

where \( \varepsilon_1 \) - length of uncut chip
\( t_1 \) - uncut chip thickness
\( b_1 \) - uncut chip width
\( \varepsilon_2 \) - length of chip
If cutting time is equal to 1, equation 8.14 can be written:

$$v \ t_1 \ b_1 = V_c \ t_2 \ b_2$$

when:

- $V$ - cutting speed
- $V_c$ - chip speed

The chip length ratio is defined by:

$$r_x = \frac{t_2}{t_1} = \frac{V_c}{V}$$

$V_c$ is proportional to the chip radial distance at the selected point on the lip, and $V$ is proportional to the drill radial distance at the same point.

Making $r_x = 1$ at the outer corner, the variation of $r_x$ along the lip can be referred to this value.

Armarego (121) once reported on the experimental determination of the chip length ratio of drilling chips by cutting and measuring annuli chips of different sizes. He used one drill with the following features: $r_o = 12.7 \ mm$, $2W = 3.2 \ mm$, $\gamma_f = 32^\circ$ and $\kappa_g = 122^\circ \ 50'$. His results are shown in Figure 8.31 by the points fitted by curve i.

The features of the drill utilized by Armarego were used with the rigid chip model and the relative chip length ratio was computed and computer plotted in Figure 8.31 (curve ii).

The model, in accordance with the experimental results which Armarego obtained by special methods, predicts a decrease in the chip length ratio along the lip, from the outer corner towards the chisel corner.
FIGURE 8.31: Variation of the relative chip length ratio along the drill lip. (Refer to text for drill features)
The author would like to consider the subject a little further, considering the cutting ratio too.

From Figure 4.34 it results:

\[
\frac{b_1}{\cos \lambda} = \frac{b_2}{\cos \eta} \quad 8.16
\]

where: \( \lambda \) – inclination angle  
\( \eta \) – chip flow angle

Then, from equation 8.15:

\[
V \cdot t_1 \cdot b_1 = V_c \cdot t_2 \cdot \frac{\cos \eta}{\cos \lambda} \cdot b_1
\]

\[
\therefore \quad \frac{t_1}{t_2} = \frac{V_c \cdot \cos \eta}{V \cdot \cos \lambda} \quad 8.17
\]

The variation of the cutting ratio along the lip is determined by the chip radial distance, drill radial distance, inclination angle and chip flow angle at each point selected on the lip (equation 8.17).

As for the chip length ratio, making arbitrarily \( t_1/t_2 = 1 \) at the outer corner, the variation of \( t_1/t_2 \) along the lip can be referred to this value.

For the same drill and conditions used for Figure 8.31, the variation of \( t_1/t_2 \) was computer plotted in Figure 8.32 where it is represented by curve i together with the variation of the chip length ratio, curve ii.

Curve i in Figure 8.32 predicts a sudden increase of the chip thickness close to the chisel corner.

Some full width chips, as in Figure 8.18, show a sudden increase of thickness close to the chisel corner. However, no systematic experiment (with and without pilot holes, for example) has been made
FIGURE 8.32: Variation of the relative cutting ratio and length ratio of drilling chip, along the lip. (Drill features and drilling chip parameters as for FIGURE 8.31)
at this stage to prove that the increase of thickness agrees quantitatively with the predictions.

If the chip yielded by the new design drill could be described for all drill lip points as a full width rigid body (from the outer corner to the chisel corner), the relative cutting ratio to be expected would appear like the one shown in Figure 8.33. In other words, such a chip would show a greater thickness at the middle than at the inner and outer parts.

Few bits of chips produced by the new design drill (Figure 8.26) keep full width. Some of these bits were embedded in resin and press moulded and prepared as shown in Figure 8.18 to be observed and to be measured by the microscope.

The tendency was for the chips to show a higher thickness, thus a lower cutting ratio, at their middle zones. At this stage, however, no systematic experiment has been undertaken in order to provide that the prediction for the new design drill is correct.

8.6.4 Fitness of the rigid body drilling chip to the flute face at the drill lip and correlation with experimental data of lip stress and lip temperature reported in the literature for conventional drills

The drill flute is an helical rigid body with an axis which is the drill axis.

The drilling chip is approached in this work as a rigid body with an helical motion with a proper axis, in general not coincident with the drill one, with a maximum diameter determined by the flute/hole space and conically shaped.

The rigid body chip was computed in the previous sections according to the conditions and restrictions imposed on it by the flute geometry.
FIGURE 8.33: Variation of the relative chip cutting ratio along the new design drill lip computed from the rigid body chip approach. [Drilling chip parameters as for FIGURE 8.21]
For simplicity of analysis the chip contact length [0.10] is not considered, and one condition to be imposed on the computed rigid body chip should be that it would be tangent to the flute face at the drill lip. However, numerical and graphical investigation revealed that this condition is in conflict with the limits on chip size (flute size). Thus the condition that the rigid body chip should be as tangent as possible to the flute face at the lip was imposed instead.

After a rigid body chip solution is found, the final deviation of the rigid body chip from the tangent to the flute face can be known at each point.

Fitness of the computed drill chip to the flute face is assessed at each lip point by computing the deviation of the chip velocity from the tangent to the flute face (Figure 8.34).

The patterns of contact (Figure 8.34) between the computed chip and the flute face was found to be similar to each other in a very extensive numerical investigation carried out by the author with conventional drills. A perfect tangency between computed chip and the flute face appear at some distance from the outer corner (point A, Figure 8.34), and no tangency between this point and the outer corner as the computed chip velocity points up the flute face. For the points from point A to near the chisel corner, the computed chip velocity points down the flute face as if it was penetrating it.

The referred to pattern of contact between the computed chip and the conventional flute face at the lip is shown in Figure 8.34 by the line (i).

This pattern of contact means that the chip would tend to leave the flute face, behind the lip, near the outer corner, and would tend to penetrate the flute face behind the lip, along the area in the middle of the lip.

This can be shown by using a plan that contains the chip axis and rotates about it producing successive sections of the chip and
FIGURE 8.31: Pattern of contact between the computed chip and the flute (rake) face at the lip.  
[Refer to FIGURES 8.19 and 8.21 for drill features and drilling chip parameters]
of the flute behind the lip.

This technique was also implemented in the computer program shown in Appendix 8 and some sections were computer plotted. Figure 8.35 shows the sections yielded by the above referred to plan passing at the outer corner, after rotating 5° from the previous position and after rotating 10° from the first position.

This pattern of contact of the chip model at the drill lip suggests that, for some stress components on the drill lip resultant from the action of the chip on the flute face, the outer corner and its vicinity should appear alleviated relative to other points further located from the outer corner. This hypothesis seems to be supported and validated by experimental results already reported in literature (41, 57).

Law and co-workers (41) have found by photoelastic methods that the maximum shear stress along the lip presents a pattern shown by line (ii) in Figure 8.36.

These workers specified the drill they used just by its diameter: 78.2 mm (3"). In order to use his model and computing approach to find the pattern of contact between the chip and the flute face at the lip shown by line (i), Figure 8.36, the author assumed the following additional features: \(2W = 8\) mm (the minimum web for a 76.2 mm diameter drill, according to catalogue C.1; \(\gamma_f = 30^\circ\) (a common drill helix angle) and \(2\alpha = 118^\circ\) (standard drill point angle).

Also Saxena and co-workers (57, 123) have measured the temperature at the drill lip and found it to have the pattern represented by line (iii) in Figure 8.36. This was known to Law and co-workers who wrote in their paper (41): "It is interesting to note that the maximum shear distribution along the cutting edge is similar to an experimental temperature distribution (57)".
FIGURE 8.35

Computer plotted sections of chip and flute face, near the lip, yielded by a plan rotating about the chip axis, and at three positions: i, ii, iii. [Refer to FIG 8.19 for chip and drill features]
FIGURE 8.36: Computed pattern of contact between chip and flute face at lip (i) - refer to Figure 8.31; maximum shear stress at the lip (ii) (11); temperature near the lip (iii) (123)
8.7 **Chapter Closure**

Chip splitting seems to correlate with torque increase, thrust decrease and wear rate increase.

Approaches to drilling forces prediction can be found which consist of dividing the main cutting edge in a number of elementary cutting edges, and computing the total force as a summation of the forces on each one of these smaller cutting edges. One of such approaches (12) - claimed to give good predictions with the conventional drill - has been tested by the author (included in computer program shown in Appendix 1) with the new design drill and failed: it predicts higher torques and higher thrusts (experiments show lower thrusts, compared to the conventional drill) (Chapter 7).

Based on the belief (and on the successes reported in this thesis) that the rigid body concept would be a better approach to drilling forces computation, the author could predict a torque increase and a thrust decrease with the new design drill. However, a deeper analysis of the assumptions and method for drilling forces prediction by the author has to be done before a definitive statement can be made.

The author believes that rigid body chips can be formed and flow with different degrees of efficiency within a range of drill lip and drill flute geometries. To base flute design on a rigid body chip criterion seems to the author a direction strongly worthwhile to take.
CONCLUSIONS AND SUGGESTIONS

FOR FURTHER WORK
The work reported in this thesis can be divided into the following parts:

i) Analysis of drill geometry (Chapters 2, 3 and 4).
ii) Design of a new drill flute (Chapter 5).
iii) Comparative performance tests between a conventional drill and the new flute drill (Chapters 6 and 7).
iv) Analysis of the drilling chips in relation to the drill lip and drill flute geometry (Chapter 8).

In the present work, twist drills are analysed according to the geometry and cutting angles along the lips rather than according to the traditional drill features such as those referred to in Chapter 1. The main purpose of this approach is to deal with non-straight drill lips either with conventional or non-conventional flute faces.

To deal with twist drills by referring to the cutting angles is more complex than by the traditional drill features as the surfaces determining the drill have to be defined and mathematically modelled and the cutting angles have to be computed by vectorial analysis.

Mathematical models are better dealt with by computing techniques. The advantages of these techniques are multi-fold and some of them have been experienced by the author throughout this work as they:

i) provide for numerical solutions when the analytical ones could hardly be achieved;
ii) allow for numerical investigation;
iii) allow for geometric simulation;
iv) allow for mathematical model testing;
v) allow for reformulation of problems and hypotheses;
vi) enlarge the field of research for the amount of information data that can be dealt with and for the complex relationships that can be analysed.
Conclusions

1. When the drill lips are straight lines the flute face related cutting angles can be calculated by formula available in literature. For non-straight drill lips the cutting angles either flute face related, or flank surface related, or flute face and flank surface related depend on the lip shape and cannot be computed before defining the surfaces determining the lip.

2. Twist drill surfaces are generally machine generated and can be mathematically modelled.

3. Seven distinct mathematical models (corresponding to the same number of surfaces) can be used to determine and to simulate completely the drill point:
   i) two flute faces
   ii) two flute heels
   iii) two flank surfaces
   iv) one cylindrical surface.

   The complete determination and simulation of the drill point by these mathematical models can be demonstrated by computer aided design techniques.

4. Traditionally a flute face is defined as a ruled surface whose shape depends on four parameters: \( r_0, 2W', \gamma_f \) and \( \kappa \). For complete definition of the flute profile the flute heel can be mathematically modelled. This model can be defined by one parameter determining the heel profile corner relatively to the face profile corner and by the condition of a common tangent with the face profile at the point on the same helical line as the chisel corner.

5. For convenience the cylindrical grinding was used. The cylindrical grinding surface can be mathematically modelled with four parameters: \( d_{og}, \nu_g, \epsilon_x g \) and \( \kappa_g \) which allow for free
specification of the drill point features: point angle, chisel edge angle, nominal relief angle and elevation of the heel corner relatively to the outer corner. The freedom to specify the referred to features is achieved at the cost of the lip straightness.

6. The flute face mathematical model and the flank surface mathematical model determine the drill lip and the cutting angles which can be computed by vectorial analysis. The shape and the length of the lip and the chisel edge can be computed from the simulated intersections of the referred to mathematical models. The flank contour on the drill cylindrical surface and the heel point contour can also be computed from these mathematical models and the others referred to in conclusion 3.

7. The configuration of a geometrically simulated drill point depends on the parameters of the mathematical models relative to the surfaces determining the drill point. The cutting angles such as the normal rake angle, the normal clearance angle and the inclination angle along the drill lip also depend on these parameters.

8. The flute face form can be determined on the basis of other conditions rather than to be a ruled surface. To use non-ruled surfaces for the flute face form makes the lip to be curved and makes the cutting angles to be flank surface dependent.

9. The flute form can be determined from the inclination angle law along the lip once the flank surface is known. Iterative numerical methods implemented in a computer program allow for the flute specification to be given in terms of other cutting angles rather than the inclination angle. Such a flute can be determined by successive controlled alterations to an inclination angle law given to a guess.
10. A flute form to yield a uniform wedge angle along the lip produces a normal rake angle law and an inclination angle law different to those of the conventional drill. For some values of the wedge angle, used as a design parameter, little modification is introduced to the effective rake angle as compared to the conventional drill.

11. To modify the flute form, the lip shape and the cutting angles along the lip affects drill performance as far as lip wear, drilling forces and chip form and size are concerned.

12. Lip wear at five equally spaced points on the lip, from the outer corner, for both the conventional drill and the new design drill show similar wear patterns but different intensities as far as drill type, point position and drilling conditions are concerned. Lip wear is smaller for the new design drill at the initial drilling stage, especially for the points closest to the outer corner. For this drill type, the average wear rate during the longer and slower part of the global wear process is in general higher than for the conventional drill.

13. Analysis of variance of the wear rate results shows that: the points equally spaced on the drill lips, near the outer corner, do not respond in the same way to wear performance; the points at the same radial distance on the two tested drill types do not respond in the same way either. The very outer corner of the drill is not so representative of lip wear as referred to drilling factors as other points in its neighbourhood.

14. Analysis of variance of the wear rate results at five points on the drill lips, at the neighbourhood of the outer corner, has shown that the difference between drill types is significant at two intermediate points (points 2 and 3), probably significant at one extreme point (point 1) and at the nearest point to the outer corner (point 4), and non-significant at the outer corner.
15. Analysis of variance has also shown that, for both drill types, the effect of cutting speed is highly significant for the points tested except for the outer corner where it appears to be probably significant. The effect of the drilling feed is highly significant for two intermediate points (points 2 and 3), is significant for points 1 and 4 and non-significant for the outer corner. The effect of the point angle and the effect of the interaction of the drilling factors analysed are non-significant too. Variability of the wear rate at the very outer corner suggests that other inner points on the lip near the outer corner should be selected when drill lip wear rate measurement is intended.

16. Drilling torque in general is higher and drilling thrust is lower for the new design drill than for the conventional one. The experimental results show that with the new design drill the torque increases between 0 to 10% as the thrust decreases between 5 to 20%.

17. Analysis of variance on the drilling forces results has shown that, for the drilling thrust, the effect of the interaction of drilling feed and drill point angle and drill type is significant. Analysis of variance by drill point angles, for the drilling thrust, has shown that the effect of the interaction of drilling feed and drill type is highly significant, and the analysis of variance by drill types has shown the effect of the interaction of drilling feed and drill point to be also highly significant.

18. Analysis of variance on the drilling thrust results, by drilling feeds, has shown the effect of the interaction of the drill point angle and drill type to be non-significant, and the effect of the drill point angle to be highly significant for low to moderate feeds (240 to 157 RPI) and significant or probably significant for high (70 RPI) and moderate feeds (103 RPI), respectively. The effect of the drill type has shown to be highly significant
to significant for moderate feeds (103 and 157 RPI) and probably significant or non-significant for the extreme feeds (70 and 240 RPI, respectively).

19. Analysis of variance on the drilling torque results has shown the effect of the interaction of the three factors tested, drill type, drill point angle and drilling feed, to be non-significant. Also, the effect of the interaction of the drilling feed and drill point angle, and the interaction of drill type and drill point angle have shown to be non-significant.

20. Analysis of variance on the drilling torque results, by drill types, has shown that the effect of the drilling feed and the effect of the drill point angle are highly significant. Analysis of variance by drilling feeds has shown the effect of the point angle to be highly significant for low to moderate feeds (240 and 157 RPI), and significant to probably significant for high to moderate feeds (70 to 103 RPI). The effect of the drill type has revealed it to be highly significant (103 RPI) to non-significant (240 RPI).

21. To increase the wedge angle - "heat sink" - at the outer corner and thereabouts, and designing for the same effective rake angle as for the conventional drill, according to the hypothesis put forward, did not improve drill lip wear rate performance. The departure from the conventional flute reported in this work appears to correlate with wear rate increase, drilling torque increase, thrust decrease and chip splitting.

22. Chips can be analysed from the rigid body concept. Rigid body chips can be mathematically modelled and dealt with by computing techniques.
23. Drilling chip mathematically modelling allow for chip flow simulation and for prediction of variables such as: drilling chip flow angle, relative chip speed, relative chip length ratio and relative cutting ratio. It also allows for the analysis of fitness of a modelled drilling chip to the flute face.

24. Predictions for the chip flow angle by the approach by the author agree with experimental data reported in literature (by Oxford). Predictions for relative chip length ratio by the same approach correlate with experimental data reported in literature (by Armarego).

Prediction, by the novel approach to drilling chip flow, of the fitness of the modelled chip to the flute face at the drill lip correlates with experimental data relative to shear stress and to temperature near the lip reported in literature (by Law and co-workers and Saxena and co-workers, respectively).

Suggestions for Further Work

The new flute design - based on the condition of an increased wedge angle at the outer corner when compared to the conventional drill design while leaving the effective rake angle almost unaltered - did not prove to be an improvement in drilling steel relative to the conventional drill.

Drill flute is traditionally designed to yield a straight lip. It seems fortunate that such a purely geometric and empirical criterion has in general succeeded for the many different drilling conditions (feeds, speeds, materials, for instance).

Such a success, in the author's opinion, is due to the fact that the traditional flute design can cope with full width (outer corner to chisel corner) rigid body chips. However, rigid body chips may possibly be produced within a certain range of flute designs though with different chip flow efficiency and different drill performance.
An approach to general flute design and also drill point simulation has been given in the present work. Chip rigid body mathematical modelling and computer aided chip simulation has been given in this work too.

The avenues ahead suggested by the author are:

1. To investigate and establish the range of drill flute (and drill point) designs that can cope with rigid body chips.

2. To introduce in the analysis and simulation the chip contact length and investigate its influence on the range of flute designs established in the previous point.

3. To extend the rigid body chip mathematical model to provide for consideration of drilling feed or rather "drilling feed"/"drill diameter" ratio.

4. To build up an approach to drilling forces prediction based on chip flow (which should predict for torque increase and thrust decrease with flutes similar to the one the author designed and tested).

5. To investigate the possibilities of lip wear prediction (or relative wear along the lip) by a chip flow approach.

6. To base drill design on specifications established according to rigid body drilling chip production.
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BS 5533: Geometry of the active part of cutting tools,  

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iv) **Films**

1. Drill action and drilling chip flow.  
Loughborough University of Technology, 16 mm Black and white print.
2. Plastic flow of material during machining.
The College of Aeronautics Cranfield, England.
16 mm Black and white print.
Computer program for drill point geometric simulation and cutting angles computation for any set of cylindrical grinding conditions and any flute shape (refer to Chapters 2, 3 and 4).

This FORTRAN program uses subroutines from GINO and NAG libraries which are not listed here.
DRILL POINT SIMULATION AND CUTTING ANGLES COMPUTATION FOR ANY SET OF CYLINDRICAL GRINDING CONDITIONS AND ANY FLUTE SHAPE

DESIGNED, DEVELOPED AND IMPLEMENTED BY MANUEL OSS SANTOS PAIS

SUBROUTINES FROM NAG LIBRARY AND GINO LIBRARY ARE USED

IMPLICIT DOUBLE PRECISION(A-H, O-Z)
REAL XWEARG(200), RWARG(200), ZWEARG(200), DWEARG(200)
REAL R3H, WEBH, H0H, ROH, EXGH, VGH, RKGH, ROGH
REAL YELICB, ZELICB, YLIM8, RAA, YFLOH', YFIGH
REAL RAGE(200), X00POS, Y00POS, X0POS, Y0POS
REAL XAXIS, YAXIS, X0POS, Y0POS
REAL RAKFS(200), RAKFL(200), RAKFA(200), RAKFB(200)
REAL RAKFK(200)
REAL XPACG(200), YPACG(200), ZPACG(200)
REAL DFTR(200), DFNR(200), DFTE(200), DFNSU(200)
REAL X1(200), Y1(200), YIN(200), YIA(200), XIA(200)
REAL TIMEU(200), TIIWI(200), TIIWA(200)
REAL XFLU(200), YFLU(200), XCHIG(200), YCHIG(200), ZCHIG(200)
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REAL ETAARM(200), ETALEE(200), ETABRO(200), ETAKRO(200)
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REAL XCLTD(200), YCLTD(200), ZCLTD(200), XSTG(200), YSTG(200), ZSTG(200)
REAL XSTARG(300), YSTARG(300), ZSTARG(300), XSECG(300), YSECG(300), ZSECG(300)
REAL DFPR(200), DFQR(200), DFRI(200), DVSNI(200), ADVSNI(200)
REAL XHEEL(200), YHEEL(200), ZHEEL(200), XHEELG(200), YHEELG(200)

COMMON/BLO1/R0, WEB, H0, EXG, VG, RKG, ROG
COMMON/BLO2/CONS, PI
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, SNSKO
COMMON/BLO4/2, 2H
COMMON/BLO5/S, NPOINT, DLAP, ISEC, IHE
COMMON/BLO6/COEF, NCOEF, I
COMMON/BLO7/XCLE, YCLE, IPL, IHLST, PHIL2
COMMON/BLO8/XFLUEE, YFLUEE, DMAR, XSTEEL, YSTEEL, ANGLEC, YEEL
COMMON/BLO10/CUTRAT, DINC, RAK, FRIC
COMMON/BLO11/COFL, NSTFL
COMMON/BLO12/RE, PMSE, DMSE, SCE1, SCE2, SCE3
COMMON/BLO13/XSEC, YSEC, ZSEC, HSEC
COMMON/BLO14/RSPACE, PSPACE, SPACE
COMMON/BLO15/XLAP, YLAP
COMMON/BLO16/COEA, COEB
COMMON/BLO17/XEELA, YEELA, ZWEB
COMMON/BLO18/XCHID, YCHID, ZCHID
COMMON/BLO19/XHEELD, YEELD, ZHEELD
COMMON/BLO20/XCLEAD, YCLEAD, SCLEAD
COMMON/BLO21/XHEEL, YHEEL, ZHEEL
COMMON/BLO22/RFKE, RKAPL, RAKFI, RKAPB
COMMON/BLO23/XSTG, YSTG, ZSTG, RAD1, INEAR, RPI, DIWKE
COMMON/BLO24/WHEAR, WEAH, WEAH
EXTERNAL PAN, FEEL, PIIL, FIN, FLANK, FON, FOUTCR, FSPACE, FSCFL
EXTERNAL FUN, FUNSEC, FWEB, GRIN, GPALE, MONIT, MONUT, RESID
EXTERNAL RESUD, ROTAC, VIJK

C
C DATA READING
WRITE(1, 6808)
6808 FORMAT('READ PARAMETERS TO CONV FLUTE: R, W, WEB, H0, RO')
READ(1, *) R, W, WEB, H0, RO
WRITE(1, 795)
795 FORMAT('GRINDING PARAMETERS')
READ(1, *) EXG, VG, RKG, ROG
WRITE(1, 8668)
8668 FORMAT('READ SPEED AND FEED')
READ(1, *) RPM, RPI
WRITE(1, 8861)
READ(l,*)NSTAB
WRITE(l,10)
FORMAT('READ S=1. FOR SPECIAL DRILL/
READ ALSO NPOINT')
READ(I,NPOINT)
IF(S.NE.1.)GO TO 12
WRITE(l,11)
FORMAT('READ NCOEF')
READ(I,*)NCOEF
12 WRITE(I,13)
FORMAT('READ RADIAL LIMITS TO FLUTE')
READ(I,*),RSTAN1,RSTAN2
WRITE(1,8004)
8004 FORMAT('DATA FOR CHISEL CORNER COMPUTATION')
WRITE(1,8008)
8008 FORMAT('PRINT/(-1)-NO CALL/(1)-EACH ITERATION'
$('0'-FINAL ITER.')
READ(l,*)IPRINT
C STARTING POINT FOR CHISEL CORNER COMPUTATION
CORN(1)=WEB/2.
CORN(2)=-WEB/2.
CORN(3)::=WEB/2.
WRITE(1,8002)
8002 FORMAT('READ STEP FOR CHISEL CORNER CALCULATION')
READ(l,*)STEP
C MAXCAL IS THE NUMBER OF ITERATIONS
MAXCAL=1000
WRITE(1,8005)
8005 FORMAT('READ STEP FOR PRINTING TABLES')
READ(I,INSAITO)
WRITE(1,8006)
8006 FORMAT('DRILLING FORCES ?')
READ(l,INFORCA)
WRITE(1,7001)
7001 FORMAT('READ HEEL PARAMETER')
READ(l,ANGCLE)
ANGCLE=ANGCLE*CONS
WRITE(1,7015)
7015 FORMAT('OPEN HEEL ?')
READ(l,INILIST)
C FTOL=1.E-7
XTOL=1.E-6
EPS=1.E-7
EPS1=EPS
EPV=EPS
IFAIL=0
ZCLE1=1.
ZCLE2=1.5*R0
DMAR=0.35
PI=3.14159265
CONSP=PI/180.
R0=R0*CONS
C CVSG=DCOS(VG*CONS)
SNVG=DSIN(VG*CONS)
CSKOU=DCOS(RO*CONS)
SNKOU=DSIN(RO*CONS)
Z=DSQRT(RO**2-(EXG-1/2.)**2)/SNKOU
C COMPUTING THE OUTER CORNER
PX=WEB/2.
PY=-0*X*CSKOU/SNKOU
ZOUT1=0*X+0*Y2.
ZOUT2=-0*X+2.
CALL CS5ACF(ZOUT1,ZOUT2,EPS,EPV,FOUTCR,ZOUT,IFAIL)
WRITE(1,2780)
2780 FORMAT('OUTER CORNER COMPUTED')
C ==-==-================================-==-=-=-=-=-
IF(S.NE.1.)GO TO 15
C READING FROM FILE
READ(5,*)NP
DO 204 I=1,NP
READ(S,*)XL(I),YL(I)
204 CONTINUE
WRITE(1,206)(XL(I),YL(I),I=1,NP)
206 FORMAT(2F10.4)
CALL ER2ACF(XL,YL,NP,COEF,NCOEF,REF)
XL1=1/2.
XL2=1/2.
CALL CS5ACF(XL1,XL2,EPS,EPV,RO,ROTAC,SLK,IFAIL)
PHLO=DATAN(YL0/XL0)
PHLL=DATAN(-WEB/2./R3)/DSQRT(1.-(WEB/2./R3)**2)
PHLB=PHL0*DSIN(R0)/DCOS(MSANG)
SISANG=PHLO-PHLL+PHLB
DO 610 I=1,NP
XL(I)=XL(I)*DCOS(SISANG)+YL(I)*DSIN(SISANG)
YL(I)::=-XL(I)*DSIN(SISANG)+YL(I)*DCOS(SISANG)
XLG(I)=XL(I)
YLG(I)=YL(I)
610 CONTINUE
SISANG=SIANG/CONS
WRITE(1,208)(XL(I),YL(I),I=1,NP)
208 FORMAT(2F10.4)
E=EPS
600 CONTINUE
C NON-CONV. FLUTE SECTION
CALL ER2ACF(XL,YL,NP,COEF,NCOEF,REF)
C WEB=-2.*COEF(1) IF WEB WAS MEASURED ALONG Y AXIS
N=3
LV=3
C CHISEL CORNER DETERMINATION
CALL E44FCF(M,N,RESID,MONIT,IPRINT,MAXCAL,ETA,XTOL.
$STEP,CORN,FE,RE,FJAC,LI,SMON,V.LV,NITER,NF,IF,LIW,WE,
$LW,IFAIL)
C
GO TO 8014
8011 CALL E04FCF(M,N,RESID,MONIT,IPRINT,MAXCAL,ETA,XTOL.
$STEP,CORN,FE,RE,FJAC,LV,SMON,V.LV,NITER,NF,IF,LIW,WE,
$LW,IFAIL)
8014 CONTINUE
WRITE(1,2779)
2779 FORMAT(/'CHISEL CORNER COMPUTED')
XCORN=CORN(1)
YCORN=CORN(2)
ZCORN=CORN(3)
ZWEB1=ZCORN+1.
CALL C05ACF(ZWEB1,ZWEB2,EPS,EPV,FWEB,ZWEB,IFAIL)
WRITE(1,9999)ZWEB
9999 FORMAT('ZWEB=',F10.3)
C
======c===================================================
C COMPUTING ANGLES, POINT BY POINT
C
DO 5 I=1,NPOINT
111=I
NLIP=I
I=I+1
Z=ZOUT-FLOAT(I-1)*(ZOUT-ZCORN)/FLOAT(NPOINT-1)
38 ALPHA=Z/R0·DSIN(H0)/DCOS(H0)
ZSTG(I)=Z
ZSTGD(I)=Z
IF(S .EO. 1.)GO TO 33
C FLUTE AND FLANK INTERSECTION
CALL C05ACF(RSTAN1,RSTAN2,EPS,EPV,FAN,XST,IFAIL)
GO TO 32
39 CALL C05ACF(RSTAN1,RSTAN2,EPS,EPV,FAN,XST,IFAIL)
YST=Z/R0
DO 75 J=1,NCOEF
YST=YST+COEF(J)*XST
75 CONTINUE
C
GO TO 34
32 U2R=W2R/2./RSTAN
PHST=(DATAN(W2R/DSQRT(1.-W2R**2))+DSQRT(RSTAN**2
S-W2R**2)***2)*DSIN(H0)/DCOS(H0)/R0*CSK01/SK01)
XFLU(I)=RSTAN*DCOS(PHST)
YFLU(I)=RSTAN*DSIN(PHST)
YFLUD(I)=RSTAN*DSIN(PHST)
XFLUD(I)=RSTAN*DCOS(PHST)
XFLUD(I)=RSTAN*DCOS(PHST)
YFLUD(I)=RSTAN*DSIN(PHST)
YFLUD(I)=RSTAN*DSIN(PHST)
IF(I .EQ. 1)XFLU=0.*RSTAN*DCOS(PHST)
IF(I .EQ. 1)YFLU=0.*RSTAN*DSIN(PHST)
XST=RSTAN*DCOS(PHST)
YST=RSTAN*DSIN(PHST)
RSTAN=DSQRT(XST**2+YST**2)
34 RSTAN=DSQRT(XST**2+YST**2)
XFLU(I)=XST
YFLU(I)=YST
XFLUD(I)=XST
YFLUD(I)=YST
IF(I .EQ. 1)XFLU=0.*RSTAN*DCOS(PHST)
IF(I .EQ. 1)YFLU=0.*RSTAN*DSIN(PHST)
RAD1=0.*RSTAN
RAD1=0.*RSTAN
GO TO 36
36 CONTINUE
C
CALL GRIN(ZZA,AXX,BYY,CXY,DDX,EY,FE)
C VECTOR NORMAL TO FUNK
C POINTING OUTWARDS
DFDX=2.*XST*AXX+YST*CXY+DDX
DFDY=2.*YST*BYY+CXY·XST+EY
DFDZ=XST·(-2.*SK01*CSK01·SNVG)+YST{-2.*SK01
$*CSK01*CSVG)+SK01-2.*Z-Z0)
DF=DSQRT(DFDX**2+DFDY**2+DFDZ**2)
DFDX=DFDX/DF
DFDY=DFDY/DF
DFDZ=DFDZ/DF
IF(IFDDA .GT. 0.8)GO TO 40
DFDX=-DFDX
DFDY=-DFDY
DFDZ=-DFDZ
C VECTOR NORMAL TO RADIUS AND ON THE FLANK
C POINTING IN THE VELOCITY DIRECTION
XFLNR=UR*DCOS(PHST)
UR1=UR+RSTAN*DCOS(PHST)
UR1=UR+RSTAN*DCOS(PHST)
XFLNR=UR*UR2*XFLNR
XFLNR=UR*UR2*XFLNR
XFLNR=UR*UR2*XFLNR
YFLNR=UR1*UR2*YFLNR
YFLNR=UR1*UR2*YFLNR
YFLNR=UR1*UR2*YFLNR
\[ ZFLNR = \sqrt{XFLNR^2 + YFLNR^2 + ZFLNR^2} \]

\[ XFLNR = XFLNR / ZFLNR \]

\[ YFLNR = YFLNR / ZFLNR \]

\[ ZFLNR = ZFLNR / ZFLNR \]

\[ \text{IF}(YFLNR \lt 0.0) \text{GO TO} 160 \]

\[ XFLNR = -XFLNR \]

\[ YFLNR = -YFLNR \]

\[ ZFLNR = -ZFLNR \]

160 CONTINUE

C VECTOR TANGENT TO FLUTE AT Z

C POINTING OUTWARDS

NDER = 1

HBASE = 1E-5

IF(NDER .EQ. 1) GO TO 130

C DERIVATIVES

CALL D04AAF(RSTAN,UDER,HBASE,NDER,EREST,FON,IFAIL)

DYDX = DSIN(PHST) / COS(PHST) + RSTAN * OER(1)

DYDX = DYDX / DYDX

GO TO 140.

130 XST = XFLR(I)

YST = YFLR(I)

CALL D04AAF(XST,NDER,HBASE,NDER,EREST,FON,IFAIL)

DYDX = DER(1)

140 DYDX = DATAN(DYDX)

XTG = COS(DYDX)

YTG = SIN(DYDX)

ZTG = 0.0

DERIV(1) = DYDX / CONS

IF(XTG .GT. 0.0) GO TO 120

XTG = -XTG

YTG = -YTG

C VECTOR TANGENT TO HEELIX AND POINTING TO SHANK

C HELIX ANGLE TOO

120 XTGH = DSIN(PHST)

YTGH = DCOS(PHST)

COTH = RSTAN / RSTAN * DCOS(0) / DSIN(0)

XC = DSQR(XTGH**2 + YTGH**2 + COTH**2)

XTGH = XTGH / XC

YTGH = YTGH / XC

ZTGH = COTH / XC

ZTGH = DSQR(1.0 - ZTGH**2)

STGHI = Datan(XTGH / ZTGH) / CONS

C VECTOR NORMAL TO RAKE FACE POINTING TO SHANK

XNRA = YTG * ZTGH

YNRA = XTG * ZTGH

ZNRA = XTG * YTGH - XTGH * YTG

XYZN = DSQR(XNRA**2 + YNRA**2 + ZNRA**2)

XNRA = XNRA / XYZN

YNRA = YNRA / XYZN

ZNRA = ZNRA / XYZN

IF(ZNRA .LT. 0.0) WRITE(1,45)

45 FORMAT('ZNRA IS NEGATIVE')

C VECTOR TANGENT TO CUTTING EDGE

C POINTING OUTWARDS

CE1 = YNRA * DFX - ZNRA * DFY

CE2 = ZNRA * DFX - YNRA * DFY

CE3 = DFX * CE1**2 + CE2**2 + CE3**2

CE1 = CE1 / CE2

CE2 = CE2 / CE3

CE3 = CE3 / CE3

C

CE1(I) = CE1

CE2(I) = CE2

CE3(I) = CE3

CE3A = DSQR(1.0 - CE3**2)

CE3P(I) = DATAN(CE3A / CE3) / CONS

IF(CE1 .LT. 0.0) WRITE(1,50)

50 FORMAT('CE1 IS NEGATIVE')

C VECTOR NORMAL TO CUTTING EDGE AND ON THE RAKE FACE

C POINTING TO DRILL AXIS

XTRA = 1.0

CTRAX = (ZNRA * CE2 - YNRA * CE3) / (ZNRA * CE2)

CTRAX = (YNRA * XTRA * CE1 - XNRA * XTRA * CE2) / (CE2 * ZNRA)

YTRA = (-ZTRA*CE3-XTRA*CE1)/CE2

ZTRA = ZTRA / YTRA

IF(YTRA .GT. 0.0) GO TO 55

XTGRA = -XTGRA

YTRA = -YTRA

ZTRA = -ZTRA

C ANGLE BET. TANGENT TO HELIX AND NORMAL TO C CUTTING EDGE ON THE RAKE FACE

55 AFL01 = XTGH*XTRA + YTGH*YTRA + ZTGH*ZTRA

AFL02 = DSQR(1.0 - AFL01**2)

ETAARM = DATAN(AFL02 / AFL01) / CONS

C VECTOR NORMAL TO CUTTING EDGE AND ON THE C RAKE FACE, POINTING IN VELOCITY DIRECTION

XTFIA = 1.0

CZFIA = (DFDZ*CE2-DFDY*CE1) / (DFDZ*CE2)

CZFIA = (DFDY*XTFIA*CE1-DFDX*XTFIA*CE2) / (DFDZ*CE2)

ZTFIA = CSTFIA / CTFIA

YTFIA = (-ZTFIA*CE3-XTFIA*CE1)/CE2

ZTFIA = ZTFIA / YTFIA

IF(YTFIA .GT. 0.0) GO TO 60

XTFIA = -XTFIA

YTFIA = -YTFIA

ZTFIA = -ZTFIA

C NORMAL WEDGE ANGLE
COSAN = X*XTFLA + Y*YTFLA + Z*ZTFLA
SINAN = DSQRT(1. - COSAN**2)
ANGC = DATAN(SINAN/COSAN)

IF(ANGC .GT. 0.0) GO TO 100

ANGC = PI + ANGC

100

WEDGE(I) = ANGC/CONS

VECTOR NORMAL TO MACHINED SURFACE

C POINTING TO THE SHANK

VV1 = -2.*PI*RPM/60.*RSTAN*DSIN(PHST)
VV2 = +2.*PI*RPM/60.*RSTAN*DCOS(PHST)
VV3 = 25.4/RPI*RPM/60.
VV = DSQRT(VV1**2+VV2**2+VV3**2)
VV1 = VV1/VV
VV2 = VV2/VV
VV3 = VV3/VV
XNMSU = -VW2*CE3+VW3*CE2
YNMSU = -VW3*CE1+VW1*CE3
ZNMSU = -VW1*CE2+VW2*CE1
SU = DSQRT(XNMSU**2+YNMSU**2+ZNMSU**2)
XNMSU = XNMSU/SU
YNMSU = YNMSU/SU
ZNMSU = ZNMSU/SU

C VECTOR NORMAL TO CUTTING EDGE, ON THE MACHINED SURFACE

C AND POINTING IN THE VELOCITY DIRECTION

XTMSU1 = (ZMSU*CE2-YMSU*CE1)/(ZMSU*CE2)
XTMSU2 = (YMSU*CE1-XMSU*CE1)/(CE2*ZMSU)
XTMSU3 = (ZMSU*CE3-XMSU*CE1)/(CE2*ZMSU)
XTMSU = DSQRT(XTMSU1**2+XTMSU2**2+XTMSU3**2)
XTMSU = XTMSU/XTMSU

IF(YTSU .GT. 0.0) GO TO 20

XTSU = 1./CTU1
CTU1 = XTMSU*XNMSU1*UU2-XTSU*UUl*YNMSU1
CTU2 = YNMSU1*UU3-XTSU*ZNMSU1
CTU3 = DSQRT(XTMSU**2+YTSU**2+ZTSU**2)
XTSU = XTMSU/CTU3
YTSU = YNMSU1/CTU3
ZTSU = ZNMSU1/CTU3

IF(ZTSU .GT. 0.0) GO TO 111

XTSU = -XTSU
YTSU = -YTSU
ZTSU = -ZTSU

C INCLINATION ANGLE

COSI = UU1*CE1+UU2*CE2
SINI = DSQRT(1.-COSI**2)
AIN = DATAN(SINI/COSI)
AIN = PI/2. - AIN
AINC(I) = AIN/CONS

C NORMAL RAKE ANGLE

COSRA = X*YTFLA+Y*YTFLA+Z*ZTFLA
SINRA = DSQRT(1. - COSRA**2)
AINS = DATAN(SINRA/COSRA)
SIGN1 = XMSU*YTMSU+YNMSU*YTMSU+ZNMSU*YTMSU
SIGN = DSQRT(XYMSU**2+YNMSU**2+ZNMSU**2)
RALK = RAK(SIGN)
RAK = RAK(SIGN)
RAKE(I) = RAK/CONS

C PARALLEL RAKE ANGLE (AS DEFINED BY GALLOWAY)

CEN1 = XOUT-XCORN
CEN2 = YOUT-YCORN
CEN3 = ZOUT-ZCORN
CEN = DSQRT(CEN1**2+CEN2**2+CEN3**2)
CEM1 = CEM1/CEMM
CEM2 = CEM2/CEMM
CEM3 = CEM3/CEMM

XNEG = 1.
YNEG = XNEG*CEM2/CEM1
ZNEG = -(XNEG*CEM1 + YNEG*CEM2)/CEM3
XYZ = DSQRT(XNEG**2 + YNEG**2 + ZNEG**2)

xNEG = XNEG/XYZ
YNEG = YNEG/XYZ
ZNEG = ZNEG/XYZ

COSRA = XNEG*XTRA + YNEG*YTRA + ZNEG*ZTRA
SINRA = DSQRT(1.-COSRA**2)
SIGN1 = XNEG*XNRA + YNEG*YNRA + ZNEG*ZNRA
SIGN2 = DSQRT(SIGN1)
SIGN = SIGN1/SIGN2
RAG = DATAN(SINRA/COSRA)*SIGN/CONS

C NOMINAL RELIEF ANGLE
(C AS DEFINED BY GALLOWAY)

COREL2 = U1*XFLNR + U2*YFLNR
SIREL = DSQRT(1.-COREL**2)
REL = DATAN(SIREL/COREL)
RELIEF(I) = REL/CONS

C CHIP FLOW ANGLE ACCORDING TO BROWN AND ARNAEGO
ETAB = DATAN(DSIN(AIN)/OCOS(AIN)*DCOS(RAK))
ETABRO(I) = ETAB/CONS

C APPROACH OF USUI TYPE
IF(NSTAB .EQ. 2) GO TO 8067
ETA = AIN
GO TO 8069

8067 ETA = DATAN(1./DCOS(RAK)+DSIN(RAK))/DSIN(AIN)/DCOS(AIN)*DCOS(RAK)
ETALE = DABS(ETA)/CONS
ETALEE(I) = ETALE
8069 ETALP(I) = ETA/CONS
ETAK = DSIN(AIN)/DCOS(AIN)*DSIN(RAK)
ETARK = DATAN(ETAK)/CONS
ETAKRO(I) = ETAKR
RSN = ETARK*DSIN(AIN)
RSNI(I) = RSN
IF (I .EQ. 1) GO TO 498
DL(I) = -9.
DL(I) = DSQRT(XSTGD(I)-XSTGD(I-1)+YSTGD(I)+2-2*YSTGD(I))*2
S = YSTGD(I-1)+2*YSTGD(I-1)+2*YSTGD(I-1)+2
SS = SS+DL(I)
SS(I) = SS
IF(NFORCA .EQ. 0) GO TO 1009

C WIRIYACOSOL PREDICTOR FOR DRILLING FORCES
C
C VECTOR NORMAL TO PLANE PARALLEL TO CUTTING EDGE AND TO DRILL AXIS, POINTING OUTWARDS
XNZETA = CE2
YNZETA = CE1

2NZETA = 0.
CNZETA = DSQRT(XNZETA**2 + YNZETA**2 + ZNZETA**2)
XNZETA = XNZETA/CNZETA
YNZETA = YNZETA/CNZETA
ZNZETA = ZNZETA/CNZETA
C VECTOR NORMAL TO THE CUTTING EDGE AND ON THE PLANE PARALLEL TO DRILL AXIS AND TO CUTTING EDGE
C POINTING TO THE DRILL SHANK
XZETA = 1.
YZETA = XZETA/YZETA*XZETA
ZTETA = CTZETA*DSQRT(XZETA**2 + YZETA**2 + ZZETA**2)
XZETA = XZETA/CTZETA
YZETA = YZETA/CTZETA
ZTETA = ZTETA/CTZETA
C ZETA ANGLE (WIRIYACOSOL)
COZETA = XVCE*XZETA+YVCE*YZETA+ZVCE*ZTETA
IF(COZETA .LT. 0) COZETA = -COZETA
SIZETA = DSQRT(1.-COZETA**2)
ZETAT = DATAN(SIZETA/COZETA)

C FORCES ON THE MAIN LIP
BM2 = DSIN(EITA)/DCOS(EITA)
DINC = DCOS(AIN)
SINC = DSIN(AIN)
RAK = RAK
IF(NDESLI .EQ. 0) RAK = 0.
TMA = (74390.-191.*RAK/CONS)*.45359/(25.4)**2
T1 = 1./RI/2.*CE2A*DCOS(ZETA)**2
T1W(I) = T1
DB = DL(I)*DINC
DA = T1*DB
FRIC = 16.84+3.589*RAK/CONS
FRICN = DATAN(DSIN(FRIC*COS)*DCOS(FRIC*COS)*DCOS(ETA))
RACK = RAK
IF(NCORT .EQ. 0) RAK = 0.
CUTRA = .3427+.0292*RAKC/CONS+.0292*VV/25.4/12.*60.
VCHIP(I) = VCD(I)*CUTRA
PHIN = 1.-CUTRA*(DCOS(ETA)/DCOS(RAK))/DCOS(RAK)
PHIN = DATAN(PHIN/PHIN2)
BWIY = (DCOS(PHIN+FRICN-RAK))**2
BWIY1 = (BWIY**2+FRICN)**2
BWIRY2 = BWS*DSIN(BWIY1)+DSIN(BWIY1)**2
BWIRY1 = BWS*DSIN(BWIY1)**2
BWIR = DSQRT(BWIRY2)
BWIR = DSQRT(BWIRY1)
BW1 = FRICN-RAK
BW2 = SW
BW3 = DSIN(FRIC)
BW4 = DSIN(PHIN)
BW5 = TMA*DA

DFP = DSW*(DCOS(BW1)*DINC+BW2*SINC*BW3)/BWIY/BW4/DINC
DFPR(I) = DFP
C
DFQ = DSW*DSIN(BW1)/BWIY/BW4/DINC
DFQR(I) = DFQ
C
DFR = BWS \times (DCOS(BW1) - \text{SINC}(BW2 + \text{DINC} \times BW3)) / SWIRIY / BW4 / DINC

DFR(I) = DFR

RTOQR = (RSTAN + RESO) / 2.

DK1P = (48.25 - 7.957 \times RAK / CONS) \times 45359 / 25.4

DK1Q = (360.31 - 4.086 \times RAK / CONS) \times 45359 / 25.4

C

DFRR(I) = DFR

RTORQ = (RSTAN + RESO) / 2.

DKIP = (481.25 - 7.9 \times RAK / CONS) \times 45359 / 25.4

DKIQ = (36e.31 - 4.3 \times RAK / CONS) \times 45359 / 25.4

C

CFl = UU1 \times XTRA + UU2 \times YTRA + UU3 \times ZTRA

CF2 = XVCE \times XTRA + YVCE \times YTRA + ZVCE \times ZTRA

CF3 = XTSTU \times XTRA + YTSTU \times YTRA + ZTSTU \times ZTRA

CF4 = UU1 \times XNRA + UU2 \times YNRA + UU3 \times ZNRA

CF5 = XVCE \times XNRA + YVCE \times YNRA + ZVCE \times ZNRA

C

DFTRA = DFP \times CF1 + DFO \times CF2 - DFR \times CF3

DFR(I) = DFR

DFNRA = -DFP \times CF4 - DFO \times CF5 + DFR \times CF6 + 1.e-0 \times \text{RPI}^{-3}

DFNRA = -DFNRA

DFTE = -DFP \times CF7 - DFO \times CF8 + DFR \times CF9

DFTE = -DFTE

DFTRA = DFP \times CF1 + DFO \times CF2 - DFR \times CF3

CHISEL POINT - DEAD CENTER

CHISEL = -DATAN\left(\frac{1 - OFDZ^2}{-DFDZ}\right) / CONS

CHISEL = -CHISEL

C

CHISEL EDGE

CHISEL = -CHISEL

C

C = \text{CHISEL POINT - CHISEL EDGE}

C

C

FORMAT(\"/LIP, ANGLES AND FORCES ON THE LIP COMPUTED\"")
500  CONTINUE
WRITE(1, 2782)
505  CONTINUE
WRITE(1, 2783)
2782  FORMAT(/'CHISEL  EDGE  COMPUTED'/)
2783  FORMAT(/'FLANK  CONTOUR  ON  CYLINDRICAL  SURFACE  COMPUTED'/)
500  CONTINUE
WRITE(1, 2782)
505  CONTINUE
WRITE(1, 2783)
WRITE(I,8022)XSTG(I),YSTG(I),ZSTG(I)
WRITE(I,8020)(CORN(I),I=1,3)
WRITE(I,8026)CHILN
WRITE(I,8032)(ZVALUE AT X=Y=CJ.,F6.3)
WRITE(I,8032)ZOUCH=ZSTG(I)-ZCORN
WRITE(I,8032)DIFFERENCE ZOUTE-ZCORN •
WRITE(I,8032)ARESTA=DSORT«XSTG(1)-XCORN)**2+(YSTG(I)-YCORN)**2+
S(ZSTG(I)-ZCORN)**2)
ANPTMA=(ZSTG(I)-ZCORN)/ARESTA
ANPTME=DSORT(1.-ANPTMA**2)
ANPTM=DATAN(ANPTME/ANPTMA)/CONS*2.
WRITE(I,8033)ANPTM
WRITE(I,8034)CHISEL ANGLE AT CORNER',F12.2)
DOCHCO=XCORN* (XSTG(I )-XCORN) +YCORN* (YSTG(I)-YCORN)
FICHCO=DSORT(XCORN**2+YCORN·*2)
FECHCO=DSORTC(XSTG(I)-XCORN)**2+(YSTG(I)-YCORN)**2)
DOCHCO=DOCHCO/FICHCO/FECHCO
EOCHCO=DSORT(1.-DOCHCO**2)
BICHCO::-DATAN (EOCHCO/DOCHCO) /COI.JS+180.
WRITE(I,8036) BICHCO
FORMAT('CHISEL ANGLE CHISEL-C/OUTER-C . ', F12. 2)
FOCHCO=FOCHCO/FICHCO
GOCHCO=DSORT(I.-FOCHCO**2)
FOCHCO=180.-DATAN(GOCUCO/FOCHCO)/CONS
WRITE(I,8038)FOCHCO
WRITE(1,8836)BICHC
FORMAT('CHISEL ANGLE CHISEL-C/OUTER-C . ',F12.2)
FOCHCO=FOCHCO/FICHCO
GOCUCO=DSORT(I.-FOCHCO**2)
GOCUCO=180.-DATAN(GOCUCO/FOCHCO)/CONS
WRITE(1,8838)FOCHCO
FORMAT('ANGLE BET. CHISEL EDGE AND XX AXIS',F12.2)
WRITE(1,8824)CHILEN
FORMAT('CHISEL EDGE LENGTH ',F6.3)
WRITE(1,8830)SS
FORMAT('LIP LENGTH ',F12.3)
CONTINUE
C IF(IHILST .EQ. 1) GO TO 7014
IF(S .EQ. 1.) GO TO 7012
NSTFLU=40
DO 7013 J=1,NSTFLU
RSTFL(I)WEB/2.+FLOAT(J-1)/FLOAT(NSTFLU-1)*WEB
WEB=WEB/2./RSTFL(I)
IF(RSTFL(I) .LE. WEB/2.) GO TO 7020
PHSTFL(I)=DATA(W2R/DSQRT(1.-W2R*2)))+DSQRT(RSTFL(I)
*W2R-(WEB/2.)*2)*DSIN(H0)/DCOS(H0)/RS*CSKOU/SKOU
GO TO 7021
7020 PHSTFL(I)=PI/2.
7021 XHSTFL(I)=RSTFL(I)*DCOS(PI/2)
YSTFL(I)=RSTFL(I)*DSIN(PI/2)
7013 CONTINUE
READ(1,)* RSTFL
call CS9ACF(XHSTFL,YHSTFL,NSTFLU,COFL,NSTFLU,REFL)
DO 7000 I=1,NPOINT
Z=ZCLEE-FLOAT(I-1)*(ZCLEE-ZCORN)/FLOAT(NPOINT-1)
ALPHA=Z/R*DSIN(H0)/DCOS(H0)
IF(I .NE. 1) GO TO 7017
RHEEL1=.8*R0
RHEEL2=1.1*R0
7017 CALL CA5ACF(RHEEL1,RHEEL2,EPS1,EPV1,FEEL1,IEL1,IFAIL)
RHEEL1=.8*RHEEL
RHEEL2=1.2*RHEEL
IF(RHEEL1 .LT. WEB/2.) RHEEL1=WEB/2.
XHH(I)=XSTG(I)
YHH(I)=YSTG(I)
ZHH(I)=ZSTG(I)
XHEL(I)=XSTG(I)
YHEL(I)=YSTG(I)
ZHEL(I)=ZSTG(I)
7000 CONTINUE
GO TO 7022
7014 DO 7001 I=1,NPOINT
Z=ZCLEE-FLOAT(I-1)*(ZCLEE-ZCORN)/FLOAT(NPOINT-1)
ALPHA=Z/R*DSIN(H0)/DCOS(H0)
IF(I .NE. 1) GO TO 7017
RHEL1=.8*R0
RHEL2=1.1*R0
7017 CALL CS9ACF(RHEL1,RHEL2,EPS1,EPV1,FEEL1,IEL1,IFAIL)
RHEL1=.8*RHEL
RHEL2=1.2*RHEL
IF(RHEL1 .LT. WEB/2.) RHEL1=WEB/2.
XHEE(I)=XSTG(I)
YHEE(I)=YSTG(I)
ZHEE(I)=ZSTG(I)
XHEL(I)=XSTG(I)
YHEL(I)=YSTG(I)
ZHEL(I)=ZSTG(I)
7001 CONTINUE
GO TO 7022
$YEELD(I) = YEELGA$

CONTINUE

WRITE(1, 6001)

FORMAT('HEEL DRILL POINT CONTOUR COMPUTED')

WRITE(1, 90002)

FORMAT('PLOTS ( 2) OR TABLES ( 1) ?')

READ(1, *) IJK1

IF(IJK1 .EQ. 0) GO TO 90005

WRITE(1, 1985)

FORMAT('ANGLES ACROSS LIP ?')

READ(1, ) IJKL

IF(IJKL .EQ. 3) GO TO 1996

WRITE(1, 90)

FORMAT(3X, 6F7.2)

WRITE(I, 1987)

FORMAT('LIP AND FLUTE ?')

READ(1, *) IJK2

IF(IJK2 .EQ. 0) GO TO 2987

WRITE(1, 1988)

FORMAT('ARC AND MACHINED SURFACE ?')

READ(1, *) IJK3

IF(IJK3 .EQ. 0) GO TO 2989

WRITE(1, 1990)

FORMAT('CHISEL EDGE ?')

READ(1, *) IJK4

IF(IJK4 .EQ. 0) GO TO 2990

$CHIRAK(I), CHIAX(I), TORCH(I), TRCH(I), I=1, NPOINT, NSALTO$

WRITE(1, 90001)

FORMAT('DERIVATIVES AND FORCES ?')

READ(1, *) IJK5

IF(IJK5 .EQ. 0) GO TO 1993

WRITE(1, 96)

FORMAT('SECONDARY CLEARANCE ?')

READ(1, *) IJK6

IF(IJK6 .EQ. 0) GO TO 9085

WRITE(1, 1997)

FORMAT('THICKNESS ?')

READ(1, *) IJK7

IF(IJK7 .EQ. 0) GO TO 9085

WRITE(1, 1998)

FORMAT('FORCES PLOTTING')

READ(1, *) IJK8

IF(IJK8 .EQ. 0) GO TO 2628

DEVICE - TEK(1), C10(2)

READ(1, *) IJR

IF(IJR .EQ. 0) GO TO 2628

WRITE(1, 2628)

2628 CALL T4010

XAXIS = 160.

YPOSX = YPOSX + YAXIS

GO TO 2629, 2630, IDEV

2629 CALL T4010

XAXIS = 160.

YPOSX = YPOSX + YAXIS

GO TO 2631

2630 CALL C10S1N

W
XAXIS=180.
X0POS=50.
Y0POS=46.
Y0POSX=Y0POS*YFLOW*YAXIS/FLOAT(NFY)
CALL DEVVAP(297.,210.,0)
2631 CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0,X0POS,Y0POSX,XAXIS,1)
CALL AXIPOS(0,X0POS,Y0POSY,AXIS,2)
CALL AXISCA(2,IR0,0.,R00,1)
CALL AXISCA(2,IR0,0.,R00,2)
CALL AXIDRA(2,1,1)
CALL AXIDRA(-2,-1,2)
C NLOO=NPOINT
CALL CHASIZ(2,2,2)
CALL GRASYM(RADI,DFTR,NLOO,4,0)
CALL GRASYM(RADI,DFTR,NLOO,5,0)
CALL GRASYM(RADI,DFTR,NLOO,7,0)
CALL CHAMOD
C READ(1.*)SEPARA
9033 WRITE(1,9033)
9031 FORMAT('PLOTTING FORCES DFTR,DFNR,DFTE?')
READ(1,*)IPORC
IF(IPORC.EQ.0) GO TO 932
WRITE(1,2623)
2623 FORMAT(/'DEVICE - TEK(l)
CALL SE281
CALL PICCIE
CALL WINDOW(2)
IF(IANG1.EQ.4) GO TO 2505
CALL AXIPOS(0,20.,50.,183.,1)
CALL AXIPOS(2,23.,50.,120.,2)
GO TO 2506
CALL AXIPOS(2,20.,20.,180.,1)
CALL AXIPOS(2,20.,20.,120.,2)
GO TO 2504
2503 CALL AXIPOS(1,5,30.,80.,2)
2504 CALL AXIDRA(-2,-1,2)
1997 CALL GRACUR(RADI,RACK,NPOINT)
CALL CHAMOD
GO TO 2501
1998 CALL GRACUR(RADI,RACK,NPOINT)
CALL CHAMOD
GO TO 2501
1999 CALL GRACUR(RADI,RELIEF,NPOINT)
CALL CHAMOD
GO TO 2501
2000 CALL GRACUR(RADI,WEDGE,NPOINT)
CALL CHAMOD
GO TO 2501
2500 CALL GRACUR(RADI,AINC,NPOINT)
CALL CHAMOD
C CALL AXISCA(2,IR0,0.,R00,1)
CALL AXISCA(2,IR0,0.,R00,2)
CALL AXIDRA(2,1,1)
CALL AXIDRA(-2,-1,2)
GO TO 2501
2502 CALL GRACUR(RADI, RAKE, NPOINT)
CALL CHAMOD
GO TO 2501
2503 CALL GRACUR(RADI, RAKE, NPOINT)
CALL CHAMOD
GO TO 2501
2504 CALL GRACUR(RADI, RELIEF, NPOINT)
CALL CHAMOD
2501 CONTINUE
C
READ(1,*) SEPARA
GO TO 2501

C
2561 FORMAT(/'EFFECTIVE RAKE PLOTTING?')
READ(1, 2561)
IF(IRK .EQ. 0) GO TO 1979
WRITE(1, 2563)
GO TO 2571

C
DO 2564 I = 1, NPOINT
SRAK1 = DSIN(AINC(I)*CONS)**2 + DCOS(AINC(I)*CONS)**2
SRAK2 = DSIN(AINC(I)*CONS) * DSIN(ETALEE(I)*CONS) * DSIN(RAKE(I)*CONS)
SRAK3 = DSIN(AINC(I)*CONS) * DSIN(ETAARM(I)*CONS) * DSIN(RAKE(I)*CONS)
SRAK4 = DSIN(AINC(I)*CONS) * DSIN(ETABRO(I)*CONS) * DSIN(RAKE(I)*CONS)
SRAK5 = DSIN(AINC(I)*CONS) * DSIN(ETAKRO(I)*CONS) * DSIN(RAKE(I)*CONS)
CONTINUE
GO TO (2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574)

C
2566 CALL CHAMOD
GO TO 2570
2567 CALL GRACUR(RADI, RAKFL, NPOINT)
CALL CHAMOD
GO TO 2570
2568 CALL GRACUR(RADI, RAKFB, NPOINT)
CALL CHAMOD
GO TO 2570
2569 CALL GRACUR(RADI, RAKFK, NPOINT)
CALL CHAMOD
GO TO 2570
2570 CALL CHAMOD
GO TO 2570
2571 FORMAT(/'MORE EF. RAKE PLOTS?')
READ(1, 2571)
IF(IGR .NE. 0) GO TO 2562
WRITE(1, 2572)
FORMAT(/'CHIP FLOW ANGLE AGAINST INCLINATION ANGLE?')
READ(1, 2572)
IF(ICHFL .NE. 0) GO TO 2524
WRITE(1, 2525)
CALL T40HJ
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0, 20., 50., 90., 1)
CALL AXISCA(2.8, 90., 0., 2)
CALL AXIDRA(2, 1, 1)
CALL AXIDRA(-2., -1, 2)
GO TO (2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534)

C
2572 GO TO (2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534)

C
DO 2564 I = 1, NPOINT
SRAK1 = DSIN(AINC(I)*CONS)**2 + DCOS(AINC(I)*CONS)**2
SRAK2 = DSIN(AINC(I)*CONS) * DSIN(ETALEE(I)*CONS) * DSIN(RAKE(I)*CONS)
SRAK3 = DSIN(AINC(I)*CONS) * DSIN(ETAARM(I)*CONS) * DSIN(RAKE(I)*CONS)
SRAK4 = DSIN(AINC(I)*CONS) * DSIN(ETABRO(I)*CONS) * DSIN(RAKE(I)*CONS)
SRAK5 = DSIN(AINC(I)*CONS) * DSIN(ETAKRO(I)*CONS) * DSIN(RAKE(I)*CONS)
CONTINUE
GO TO (2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574)

C
2573 GO TO (2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534)

C
DO 2564 I = 1, NPOINT
SRAK1 = DSIN(AINC(I)*CONS)**2 + DCOS(AINC(I)*CONS)**2
SRAK2 = DSIN(AINC(I)*CONS) * DSIN(ETALEE(I)*CONS) * DSIN(RAKE(I)*CONS)
SRAK3 = DSIN(AINC(I)*CONS) * DSIN(ETAARM(I)*CONS) * DSIN(RAKE(I)*CONS)
SRAK4 = DSIN(AINC(I)*CONS) * DSIN(ETABRO(I)*CONS) * DSIN(RAKE(I)*CONS)
SRAK5 = DSIN(AINC(I)*CONS) * DSIN(ETAKRO(I)*CONS) * DSIN(RAKE(I)*CONS)
CONTINUE
GO TO (2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574)
2572 CALL GRACUR(AINC, ETALEE, NPOINT)
CALL GRACUR(AINC, ETAARM, NPOINT)
CALL GRACUR(AINC, ETAKRO, NPOINT)
CALL GRACUR(AINC, ETAKRO, NPOINT)
2531 CONTINUE
CALL GRAMOV(8., 8.)
CALL BROKEN(1)
CALL GRALIN(AINC(NPOINT), AINC(NPOINT))
CALL CHAMOD
C READ(1,*)ISEPARA
WRITE(1,2532)
2532 FORMAT('MORE CHIP FLOW PLOTS?')
READ(1,*)IGFL
WRITE(1,933)
933 IF (IGFL .GT. 0) GO TO 1979
WRITE(1,1959)
1959 FORMAT('/READ FACTOR TO COORDINATE AXES')
XAXIS=FACT*157.89
YAXIS=FACT*127.53
WRITE(1,1970)
1970 FORMAT('/T4010 (1) OR C1051N (2)?/')
READ(1,*)IDEV
WRITE(1,2507)
2507 FORMAT('DRAWING AXES?')
READ(1,*)IAAX
WRITE(1,1971)
1971 CALL T4010
1976 CALL PICICLE
CALL WINDOW(2)
CALL AXIPOS(0,80., XAXIS, 1)
CALL AXIPOS(0,80., YAXIS, 2)
CALL AXISCA(2.26, 10., 10., 1)
CALL AXISCA(2.15, -8., 7., 2)
IF (IAAX .EQ. 0) GO TO 2508
CALL AXIDRA(2.1, 1)
CALL AXIDRA(-2., 1, 2)
2508 CONTINUE
C
DO 937 I=1, NPOINT
XMAX=R8
YMAX=R8
XI(I)=-(R8-1.)+FLOAT(I)/FLOAT(NPOINT)*2.*XMAX-1.
YI(I)=DSQRT(R8**2-XI(I)**2)
YIN(I)=-YI(I)
YIA(I)=-(R8-1.)*FLOAT(I)/FLOAT(NPOINT)*2.*YMAX-1.
937 CONTINUE
DO 1937 I=1, NPOINT
XSTG(I)=XSTG(I)
YSTG(I)=YSTG(I)
XCHIG(I)=XCHIG(I)
YCHIG(I)=YCHIG(I)
XHEELG(I)=XHEELG(I)
YHEELG(I)=YHEELG(I)
XSTG(I)=XSTG(I)
YSTG(I)=YSTG(I)
XHEELG(I)=XHEELG(I)
1937 CONTINUE
DO 1938 J=1, NPOINT
XCHIG(J)=XCHIG(J)
1938 CONTINUE
IF (INFILE .EQ. 0) GO TO 2657
C WRITE IN FILE
WRITE(6,2655)R8, WEB, H0, RO, EXG, VG, RKG, ROG
2655 FORMAT(8F12.6)
WRITE(6,2656)XI(I), YI(I), YIN(I), YIA(I), XIA(I), XIAN(I)
$..XSTG(I), I=1, NPOINT)
WRITE(6,2620)YSTG(I), YCHIG(I), YCHIG(I), XHEELG(I)
$..XHEELG(I), I=1, NPOINT)
2651 FORMAT(14)
2652 FORMAT(7R12.6)
2650 FORMAT(5F12.6)
2657 CONTINUE
DO 2559 I=1, NPOINT
DO 1935 J=1, NPOINT
XSTG(I)=XSTG(I)
YSTG(J)=YSTG(J)
XSTG(I)=XSTG(I)
YSTG(J)=YSTG(J)
1935 CONTINUE
DO 1936 J=1, NPOINT
XCHIG(J)=XCHIG(J)
YCHIG(J)=YCHIG(J)
1936 CONTINUE
IF (INFILE .EQ. 0) GO TO 2656
WRITE(6,2653)XCHIG(I), YCHIG(I), XSTG(I), YSTG(I),
$..XSTG(I), I=1, NPOINT)
2658 CONTINUE
C
CALL GRACUR(XSTG, YSTG, NPOINT)
CALL GRACUR(XHEELG, YHEELG, NPOINT)
CALL CHAMOD
DO 7862 I=1, NPOINT
XHEELG(I)=XHEELG(I)
YHEELG(I)=YHEELG(I)
7802 CONTINUE
IF (IWFILE .EQ. 0) GO TO 2659
WRITE(6,2654)(XHEELG(I),YHEELG(I),I=1,NPOINT)

2653 FORMAT(4F12.6)
2654 FORMAT(2F12.6)
2659 CONTINUE
C
CALL GRACUR(XHEELG,YHEEL,NPOINT)
CALL GRACUR(X1,Y1,NPOINT)
CALL GRACUR(X1A,Y1A,NPOINT)
CALL GRACUR(X1AN,Y1A,NPOINT)
CALL CHAMOD

CONTINUE
C
READ(1,*)ISEPARA
WRITE(1,2518)
2518 FORMAT(‘MORE VIEWS ?’)
READ(1,*,IVIEW)
IF (IVIEW .NE. 0) GO TO 2524
C
1942 WRITE(1,1941)
1941 FORMAT(‘SIDE VIEW OF THE SIMULATED DRILL POINT’)
READ(1,*)IPLADO
WRITE(1,2509)

2509 FORMAT(‘DRAWING AXES ’)
READ(1,*)IAX
WRITE(1,2543)

2543 FORMAT(‘4010 (1) OR C1051N (2) ’)
READ(1,*,IDEV)
WRITE(1,2515)

2515 FORMAT(‘READ FACTOR TO COORDINATE AXES’) 
READ(1,*)FACT
GO TO(2541,2542),IDEV

2541 XAXIS=FACT*157.69
YAXIS=FACT*157.53
CALL T4010
GO TO 2544

2542 XAXIS=FACT*160.
YAXIS=FACT*120.
CALL C1051N

2544 CALL PICCLE
CALL WINDOW(2)
CALL AXIPX(-90.0,-20.,XAXIS,1)
CALL AXIPX(-90.0,-20.,YAXIS,2)
CALL AXISCA(2.20.,-10.,10.,1)
CALL AXISCA(2.15,-3.,12.,2)
IF (AX .EQ. 0) GO TO 2510
CALL AXIDRA(2.1,1)
CALL AXIDRA(-2.1,2)

2510 CONTINUE
C
ZLIM2=ZCLEA(1)+.5*R0
DO 23413 I=1,NPOINT

23413 XSTG(I)=XSTCD(I)
YSTG(I)=YSTG1(I)
XHEELG(I)=XHEELD(I)
YHEELG(I)=YHEELD(I)
XCLEA(I)=XCLEAD(I)
XCHIG(I)=XCHID(I)
ZELIC=ZSTG(1)+FLOAT(I-1)/FLOAT(NPOINT-1)*(ZLIM2-ZSTG(1))
ZELIC1=ZELIC
ZELI=ZELIC-ZSTG(1)
PFL1=DATAH(YSTG(I)/XSTG(I))
PFL1=-PFL1+2*ZELI*DSIN(H0)/DCOS(H0)/R0
XELIC1(I)=R0*DSIN(PFL1)
YELIC1(I)=R0*DSIN(PFL1)

2040 CONTINUE
C
DO 2041 I=1,NPOINT
ZELIC=ZHEELG(I)+FLOAT(I-1)/FLOAT(NPOINT-1)*(ZLIM2-
S-ZHEELG(1))
ZELIC2(I)=ZELIC
ZELI=ZELIC-ZHEELG(I)
PFL1=DATAH(YHEELG(I)/XHEELG(I))
IF (PFL1 .GE. 0) PFL11=(PFL1-PI-PFL1)
IF (PFL1 .LT. 0) PFL11=-PFL1
XELIC2(I)=R0*DSIN(PFL1)
YELIC2(I)=R0*DSIN(PFL1)

2041 CONTINUE
C
CALL GRACUR(XSTG,YSTG,NPOINT)
CALL GRACUR(XCHIG,ZCHIG,NPOINT)
CALL GRACUR(XELIC1,ZELIC1,NPOINT)
CALL CHAMOD
DO 1945 I=1,NPOINT
XSTG(I)=-XSTG(I)
XELIC1(I)=-XELIC1(I)

1945 CONTINUE
DO 1946 J=1,NPOINT
XCHIG(J)=-XCHIG(J)

1946 CONTINUE
CALL GRACUR(XSTG,YSTG,NPOINT)
CALL GRACUR(XCHIG,ZCHIG,NPOINT)
CALL GRACUR(XCLEA,ZCLEA,NPOINT)
CALL GRACUR(XHEELG,ZHEELG,NPOINT)
CALL GRACUR(XELIC2,ZELIC2,NPOINT)
CALL CHAMOD

C
READ(1,*)ISEPARA
WRITE(1,2519)

2519 FORMAT(‘MORE VIEWS ?’)
READ(1,*,IVIEW)
IF (IVIEW .NE. 0) GO TO 2524
1942 WRITE(1,1947)

WRITE(1,2518)
FORMAT('SIDE VIEW AFTER 90 DEGREES ROTATION ? ')
READ(1,*)IPLADe
IF(IPLADe.EQ.0) GO TO 934
WRITE(1,2511)
2511 FORMAT('DRAWING AXES ? ')
READ(1,*)IAX
WRITE(1,2545)
2545 FORMAT('T4010 (1) OR C1051N (2) ? ')
READ(1,*)IDEV
WRITE(1,2516)
2516 FORMAT('READ FACTOR TO COORDINATE AXES ')
READ(1,*),FACT
GO TO(2546,2547),IDEV
2546 XAXIS=FACT*157.89
YAXIS=FACT*127.53
CALL T4010
GO TO 2548
2547 XAXIS=FACT*160.
YAXIS=FACT*120.
CALL C1051N
2548 CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0,90.,180.,XAXIS,1)
CALL AXISCA(2,10.,180.,1,1)
CALL AXISCA(2,15.,-3.,12.,1)
IF(IAX.EQ.9) GO TO 2512
CALL AXIDRA(2,1,1)
CALL AXIDRA(-2,-1,2)
2512 CONTINUE

C
DO 1977 I=1,NPOINT
YSTG(I)=YSTGD(I)
YCHIG(I)=YCHID(I)
YHEELG(I)=YHEELD(I)
1977 CONTINUE
CALL GRACUR(YCHIG,ZCHIG,50)
CALL CHAMOD
DO 1950 I=1,NPOINT
YCHIG(I)=YCHIF(I)
YHEELG(I)=YHEELD(I)
1950 CONTINUE
CALL GRACUR(YCHIG,ZCHIG,NPOINT)
CALL CHAMOD
IF(YSTG(NPOINT).LT.0.) GO TO 1953
DO 1954 I=1,NPOINT
YSTG(I)=YSTGD(I)
1954 CONTINUE
1953 CONTINUE
CALL GRACUR(YSTG,ZSTG,NPOINT)
CALL GRACUR(YHEELG,ZHEELG,NPOINT)
CALL GRACUR(YELIC1,ZELIC1,NPOINT)
CALL GRACUR(YELIC2,ZELIC2,NPOINT)
YELIC8=YELIC2(1)
ZLIMS=ZLIM2
CALL GRAMOV(YELIC8,ZELIC8)
CALL GRALIN(YELIC8,ZLIM8)
CALL CHAMOD
DO 1951 I=1,NPOINT
YHEELG(I)=YHEELG(I)
YELIC2(I)=YELIC2(I)
1951 CONTINUE
CALL GRACUR(YHEELG,ZHEELG,NPOINT)
CALL GRACUR(YCLEA,ZCLEA,NPOINT)
YELIC8=YELIC2(1)
CALL GRAMOV(YELIC8,ZELIC8)
CALL GRALIN(YELIC8,ZLIM8)
CALL CHAMOD
C
READ(1,*)SEPARA
WRITE(1,2520)
2520 FORMAT('MORE VIEWS ? ')
READ(1,*)VIEW
IF(VIEW.EQ.0) GO TO 1948
934 WRITE(1,2575)
2575 FORMAT('THREE SIMULTANEOUS VIEWS ? ')
READ(1,*)IPONTA
IF(IPONTA.EQ.0) GO TO 2574
WRITE(1,2576)
2576 FORMAT('READ FACTOR TO COORDINATE AXES ')
READ(1,*),FACT
XAXIS=FACT*157.89
YAXIS=FACT*127.53
CALL T4010
GO TO 2578
2578 FORMAT('DRAWING AXES ? ')
READ(1,*)IAX
IF(IAX.EQ.1) GO TO 2579
XAXIS=FACT*160.
YAXIS=FACT*120.
CALL C1051N
GO TO 2580
2579 CALL T4010
2580 CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0,90.,180.,XAXIS,1)
CALL AXISCA(2,10.,180.,1,1)
CALL AXISCA(2,15.,-3.,12.,1)
IF(IAX.EQ.9) GO TO 2581
CALL AXIDRA(2,1,1)
CALL AXIDRA(-2,-1,2)
2581 CONTINUE
DO 2582 I=1,NPOINT
XMAX=0
YMAX=R0
X(I)=-(R0-1.)*FLOAT(I)/FLOAT(NPOINT)*2.*(XMAX-1.)
Y(I)=DSQRTR(R0**2-X(I)**2)
YIN(I)=-Y(I)
YIA(I)=-(R0-1.)*FLOAT(I)/FLOAT(NPOINT)*2.*(YMAX-1.)
XIA(I)=DSQRTR(R0**2-YIA(I)**2)
XIAN(I)=-XIA(I)

CONTINUE

DO 2582 I=1,NPOINT
XSTG(I)=XSTG(I)
YSTG(I)=YSTG(I)
XCHIG(I)=XCHIG(I)
YCHIG(I)=YCHIG(I)
XHEELG(I)=XHEELG(I)
YHEELG(I)=YHEELG(I)
XSTG(I)=-XSTG(I)
XHEELG(I)=-XHEELG(I)

CONTINUE

CALL GRACUR(XSTG,YSTG,NPOINT)
CALL GRACUR(XCHIG,YCHIG,NPOINT)
CALL CHAMOD
DO 2587 I=1,NPOINT
XSTG(I)=XSTG(I)
YSTG(I)=YSTG(I)
XCHIG(I)=XCHIG(I)
YCHIG(I)=YCHIG(I)

CONTINUE

CALL GRACUR(XSTG,YSTG,NPOINT)
CALL GRACUR(XHEELG,YHEELG,NPOINT)
CALL CHAMOD
DO 2589 I=1,NPOINT
XHEELG(I)=-XHEELG(I)
YHEELG(I)=-YHEELG(I)

CONTINUE

CALL GRACUR(XHEELG,YHEELG,NPOINT)
CALL CHAMOD
DO 2591 I=1,NPOINT
XSTG(I)=XSTG(I)
YSTG(I)=YSTG(I)
XHEELG(I)=XHEELG(I)
YHEELG(I)=YHEELG(I)
XCLEA(I)=XCLEA(I)
XCHIG(I)=XCHIG(I)
YHEELG(I)=YHEELG(I)
YHEELG(I)=-YHEELG(I)

CONTINUE

CALL GRACUR(XSTG,YSTG,NPOINT)
CALL GRACUR(XCHIG,YCHIG,NPOINT)
CALL GRACUR(XHEELG,YHEELG,NPOINT)
CALL CHAMOD
DO 2593 I=1,NPOINT
XSTG(I)=-XSTG(I)
XHEELG(I)=-XHEELG(I)
YHEELG(I)=-YHEELG(I)

CONTINUE

CALL AXISCA(2.28,-10.,10.,1.)
CALL AXISCA(2.15,-3.,12.,2.)
IF(IAX .EQ. 0) GO TO 2598
CALL AXIDRA(2.,1.,1.)
CALL AXIDRA(-2.,-1.,2.)

CONTINUE

ZLIM2=ZCLEA(I)+.5*R0
DO 2595 I=1,NPOINT
ZSTG(I)=ZSTG(I)
YSTG(I)=YSTG(I)
ZHEELG(I)=ZHEELG(I)
ZHEELG(I)=ZHEELG(I)

CONTINUE

CALL GRACUR(XSTG,ZSTG,NPOINT)
CALL GRACUR(XCHIG,ZCHIG,NPOINT)
CALL GRACUR(XHEELG,ZHEELG,NPOINT)
CALL GRACUR(XHEELG, ZHEELG, NPOINT)
CALL GRACUR(XELIC1, ZELIC1, NPOINT)
CALL GRACUR(XELIC2, ZELIC2, NPOINT)
CALL CHAMOD

C
DO 2604 I = 1, NPOINT
XSTG(I) = -XSTG(I)
XCLEA(I) = -XCLEA(I)
XHEELG(I) = -XHEELG(I)
XELIC1(I) = -XELIC1(I)
XELIC2(I) = -XELIC2(I)
2604 CONTINUE

C
CALL AXIPOS(0, 130., 90., XAXIS, 1)
CALL AXIPOS(40., 130., 90., YAXIS, 2)
CALL AXISCA(2, 20., -10., 19., 1)
CALL AXISCA(2, 15., -3., 12., 2)
IF (IAX.EQ. 0) GO TO 2595
CALL AXIDRA(2, 1.1)
CALL AXIDRA(-2, 1.2)
2595 CONTINUE

C
DO 2596 I = 1, NPOINT
YSTG(I) = YSTGD(I)
YCHIG(I) = YCHID(I)
YHEELG(I) = YHEELD(I)
2596 CONTINUE
CALL GRACUR(YCHIG, ZCHIG, NPOINT)
CALL CHAMOD

C
DO 2597 I = 1, NPOINT
YCHIG(I) = -YCHIG(I)
2597 CONTINUE
CALL GRACUR(YCHIG, ZCHIG, NPOINT)
CALL CHAMOD

C
IF (YSTG(NPOINT) .LT. 0.) GO TO 2598
DO 2599 I = 1, NPOINT
YSTG(I) = -YSTG(I)
2599 CONTINUE

C
CALL GRACUR(YSTG, I5TG, NPOINT)
CALL GRACUR(YHEELG, ZHEELG, NPOINT)
CALL GRACUR(YELIC1, ZELIC1, NPOINT)
CALL GRACUR(YELIC2, ZELIC2, NPOINT)
YELIC3 = YELIC2(1)
ZELIC8 = ZELIC2(1)
ZLIM8 = ZLIM2
CALL GRALIN(YELIC, ZELIC8)
CALL GRAMOV(YELIC, ZLIM8)
CALL CHAMOD

C
DO 2600 I = 1, NPOINT
YHEELG(I) = -YHEELG(I)
YELIC2(I) = -YELIC2(I)
2600 CONTINUE

2601 FORMAT('MORE VIEWS?')
READ(1, *) VIEW
IF (VIEW .NE. 0) GO TO 934

934 FORMAT('SECTION NORMAL TO DRILL AXIS?')
READ(1, *) IAX
WRITE(1, 2560)
930 FORMAT('DRAWING AXES?')
READ(1, *) IAX
WRITE(1, 2517)
2517 FORMAT('READ FACTOR TO COORDINATE AXES')
READ(1, *) FACT
RECI = FACT
WEBH = WEB
HHE = HHE/CONS
READ(1, *) XPOS, XCAP
XAXIS = FACT*157.53
WRITE(1, 2550) XAXIS, XCAP
GO TO(2551, 2554), IDEV
2550 XAXIS = FACT*157.89
YAXIS = FACT*127.53
CALL T41P
GO TO 2552
2551 XAXIS = FACT*160.
YAXIS = FACT*128.
CALL T41P
2552 CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0. XPOS, 80., XAXIS, 1)
CALL AXIPOS(0. XPOS, 80., YAXIS, 2)
CALL AXISCA(2, 20., -10., 11., 1)
CALL AXISCA(2, 15., -8., 7., 2)
IF (IAX .EQ. 0) GO TO 2514
CALL AXIDRA(2, 1.1)
CALL AXIDRA(-2, 1.2)
2514 CONTINUE
DO 7006 I = 1, NPOINT
XFLU(I) = XFLUD(I)
7006 CONTINUE
YEELGO(I)=YEELGO(I)
XFLU(I)=-XFLU(I)
YEELG(I)=-YEELG(I)

C
DO 7007 I=1,NPOINT
XFLU(I)=-XFLU(I)
YFLU(I)=-YFLU(I)
XEELG(I)=-XEELG(I)
YEELG(I)=-YEELG(I)
IF(NORSEC .EQ. 0) GO TO 7007
C WRITE IN FILE
WRITE(6,2638)XFLU(I),YFLU(I),XEELG(I),YEELG(I)

C
CALL GRACUR(XFLU,YFLU,NPOINT)
CALL BROKEN(IBRO)
CALL GRACUR(XEELG,YEELG,NPOINT)
CALL CHAMOD

C
WRITE IN FILE
WRITE(6,2638)XFLU(I),YFLU(I),XEELG(I),YEELG(I)

C
READ(*,I1)SEPARA
WRITE(1,7042)
FORMAT(/'MORE VIEW'S)
READ(I,*)VIEW
IF(VIEW .NE. 0) GO TO 934

C
READ(1,*),FLUT
WRITE(1,940)
FORMAT('CIRCLE INSIDE THE FLUTE ?')
READ(1,*),FLUT
IF(FLUT .EQ. 0) GO TO 940
DO 7041 I=1,NPOINT
XFLU(I)=XFLUD(I)
YFLU(I)=YFLUD(I)

2638 FORMAT(4F10.4)
CALL CHAMOD
CALL BROKEN(0)
CALL GRACUR(XFLU,YFLU,NPOINT)
CALL BROKEN(IBRO)
CALL GRACUR(XEELG,YEELG,NPOINT)
CALL CHAMOD

C
WRITE(1,2521)
FORMAT(/'MORE VIEWS ?')
READ(1,*),VIEW
IF(VIEW .NE. 0) GO TO 934

C
READ(1,*),FLUT
WRITE(1,940)
FORMAT('CIRCLE INSIDE THE FLUTE ?')
READ(1,*),FLUT
IF(FLUT .EQ. 0) GO TO 940
DO 7041 I=1,NPOINT
XFLU(I)=XFLUD(I)
YFLU(I)=YFLUD(I)
DO 7830 I=1,NPOINT
X(I)=2.*XC0-X(I)
Y(I)=2.*YC0-Y(I)
703A CONTINUE
CALL GRACUR(X,Y,NPOINT)
CALL CHAMOD
READ(1.*) SEPARA
IF (.IFLUT.EQ.0) GO TO 2536
WRITE(1,7e24)
7e24 FORMAT(/'CIRCLE AGAIN 1'/)
READ(1,*) IFLUT
IF (.IFLUT.EQ.0) GO TO 2536
ALPHA=ZOUT/RA*DSIN(HA)/DCOS(H0)
PHCA=DATAN(YC0/XC0)
PHC=PHCA+ALPHA
RXYC0=DSQRT(XC0**2+YC0**2)
550 COORDINATES OF THE CENTER OF THE CIRCLE
ZEM=ZOUT
7045 WRITE(1,7042) XEM, YEM, ZEM
7042 FORMAT(/'XEM=', F8.4, 3X, 'YEM=', F8.4, 3X, 'ZEM=', F8.4/) WRITE(1,2535)
2535 FORMAT(/'SECTION NORMAL TO ACTUAL CUTTING EDGE 1')
READ(1,*) IFLAL
IF (.IFLAL.EQ.0) GO TO 2536
SC2E = C2E1 (NSEC)
SC2C = C2C1 (NSEC)
SC2S = C2S1 (NSEC)
G0 TO 2536
WRITE(1,2557)
2557 FORMAT(/'SECTION NORMAL TO THE TANGENT TO HELIX ?')
READ(1,*) IHE
IF (.IHE.EQ.0) GO TO 2558
PHH1=DATAN(YSTGD(1)/XSTGD(1))
PHH2=PHH1-(PI-ANGCLE)/2.
XHH=RA*DCOS(PHH2)
YHH=RA*DSIN(PHH2)
XSE1=XHH2
YSE1=YHH2
ZSE1=XSTGD(1)
RRXY=DSQRT(XH**2+YH**2)
XH=RRXY/COS(PHH2)
YH=RRXY/SIN(PHH2)
SC1E=SC1E1 (NSEC)
SC2E=SC2E1 (NSEC)
SC3E=SC3E1 (NSEC)
GO TO 2536
2558 WRITE(1,2537)
2537 FORMAT(/'FOR OTHER SECTION READ COORDINATES/'
5'TO 2 POINTS')
READ(1,*) XPO1, YPO1, ZPO1, XP02, YP02, ZP02
SC1E=SC1E1 (NSEC)
SC2E=SC2E1 (NSEC)
SC3E=SC3E1 (NSEC)
SCD=DSQRT(SC1**2+SC2**2+SC3**2)
SC1E=SC1E1 (NSEC)
SC2E=SC2E1 (NSEC)
SC3E=SC3E1 (NSEC)
GO TO 2536
2534 FORMAT(/'READ DEBT:')
READ(1,*) IDELTA
NLOSC=E*YPO1
NLEEP=NSEC+MLEEP
ISEC=E
NLAAP=NSEC
DO 1966 I=NSEC,NLOOSC
   IF(1 .GT. NPOINT) GO TO 1957
   XSE=XFLUD(I)
   YSE=YFLUD(I)
   GO TO 1972
   CONTINUE
   IF(XSE .NE. 0.) GO TO 1949
   CALL EXIT
   PHSE=DATAN(YSE/XSE)
   IF(PHSE .GT. 0.) PHSE-PHSE-PIN
   RSE=DSQRT(XSE**2+YSE**2)
   DSEC=-(SCE1*XSE1+SCE2*YSE1+SCE3*ZSE1)
   CALL C05ACF(PHSE1, PHSEC2, EPS, EPV, FUNSEC, PHSEC, IFAIL)
   PHSE1=PHSEC-10.*CONS
   PHSEC2=PHSEC+10.*CONS
   XSEC1=XSEC
   YSEC1=YSEC
   ZSEC1=ZSEC
   XMSEC=XSEC
   ZMSEC=ZSEC
   CALL GRIN(ZSEC,ZE,AXX,BYY,CXY,DDX,EY,FF)
   F2=AXX*XSEC+BYY*YSEC+CXY*XSEC+DXX*XSEC
   5-EY*YSEC+FF
   IF(1 .GT. NPOINT) AND. F2 .GT. 0.0) GO TO 1981
   XSTAR=(XSEC-XSE1)*V11+(YSEC-YSE1)*V12+(ZSEC-ZSE1)*V13
   YSTAR=(XSEC-XSE1)*VJ1+(YSEC-YSE1)*VJ2+(ZSEC-ZSE1)*VJ3
   C FOR VERIFICATION XSTAR COULD BE PRINTED
   XSTARG(1)=XSTAR
   YSTARG(1)=YSTAR
   ZSTARG(1)=ZSTAR
   IF(1 .GT. NLEEP) GO TO 2005
   CALL C05ACF(YSCFL1,YSCFL2,EPS,EPV,FSCFL,YSCFL,IFAIL)
   YSCFL1=YSCFL-DELTAY
   YSCFL2=YSCFL+DELTAY
   YSCFLA=(XSEC-XSE1)*VJ1+(YSCFL-YSE1)*VJ2+(ZSEC-ZSE1)*VJ3
   YSCFLG(1)=YSCFLA
   XSCFLG(I)=XSTARG(I)
   CONTINUE
   WRITE(1,2539)
   FORMAT(/'DRAWING AXES 7')
   READ(1,*)IAX
   WRITE(1,2553)
   FORMAT(/'T4eJ10(1) , C1051N (2) OR SE281(3) 7')
   READ(1,*)IDEV
   GO TO(2554,2555,2556),IDEV
   XAXIS=FACT*157.89
   YAXIS=FACT*127.53
   CALL T4010
   GO TO 2556
   XAXIS=FACT*16E.
   YAXIS=FACT*120.
   CALL C13S1N
   GO TO 2556
   XAXIS=FACT*160.
   YAXIS=FACT*12.
   CALL E281
   CALL PICCLE
   CALL WINDOW(2)
   CALL AXIDRA( 2 I1)
   CALL AXIDRA(-2,-1,2)
   CONTINUE
   NLAAP=I
   NLOOSC=NLAAP
   WRITE(1,1994)
   CONTINUE
   NLOOP=NLAAP
   WRITE(1,1995)
   CONTINUE
   NLOOP=NLAAP
   WRITE(1,1995)
   CONTINUE
   NLOOP=NLAAP
   WRITE(1,1995)
   CONTINUE
   NLOOP=NLAAP
   WRITE(1,1995)
   CONTINUE
   NLOOP=NLAAP
   WRITE(1,1995)
WRITE(1,1967)
FORMAT('MORE SECTIONS 7')
READ(1,*)MSEC
IF(MSEC .NE. 0) GO TO 1962
2011 WRITE(1,2010)
FORMAT('MORE SECTIONS 7')
READ(1,*)ISEPAR
IF(ISEPAR .EQ. 0) GO TO 2031
2012 WRITE(1,2012)
FORMAT('READ Y AT WHICH IS THE PLANE PAR. TO CUT. EDG.')
READ(1,*)YPACE1
PHPCAC1=.0
PHPCAC2=89.9*CONS
DO 2013 I=1,NPOINT
RPACE=DSQRT(XFLUD(I)**2+YFLUD(I)**2)
PHPA=DATAN(YFLUD(I)/XFLUD(I))
CALL COSACF(PHPAC1, PHPAC2, EPS, EPV, FPACE, PHPACE, IFAIL)
XPAC=RPACE*DCOS(PHPACE+PHPA)
YPAC=RPACE*DSIN(PHPACE+PHPA)
ZPAC=PHPACE*RO*OCOS(H0)/OSIN(H0)
XPACG(I)=XPAC
YPACG(I)=YPAC
ZPACG(I)=ZPAC
2013 CONTINUE
C 2017 CALL SE281
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0.90.,80.,157.99,1)
CALL AXIDRA(-2,-1,2)
CALL GRACUR(XPACG,ZPACG,NPOINT)
CALL CHAMOD
C READ(1,*)ISEPAR
WRITE(1,2036)
FORMAT('MORE SECTIONS 7')
READ(1,*)MORE
IF(MORE .NE. 0) GO TO 2031
C 2034 CONTINUE
CALL SE281
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0.90.,80.,157.99,1)
CALL AXIDRA(-2,-1,2)
CALL GRACUR(XPACG,ZPACG,NPOINT)
CALL CHAMOD
C READ(1,*)ISEPAR
WRITE(1,2036)
FORMAT('MORE SECTIONS 7')
READ(1,*)MORE
IF(MORE .NE. 0) GO TO 2031
C 2034 CONTINUE
CALL SE281
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0.90.,80.,157.99,1)
CALL AXIDRA(-2,-1,2)
CALL GRACUR(XPACG,ZPACG,NPOINT)
CALL CHAMOD
C READ(1,*)ISEPAR
WRITE(1,2036)
FORMAT('MORE SECTIONS 7')
READ(1,*)MORE
IF(MORE .NE. 0) GO TO 2031
C 2034 CONTINUE
CALL SE281
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0.90.,80.,157.99,1)
CALL AXIDRA(-2,-1,2)
CALL GRACUR(XPACG,ZPACG,NPOINT)
CALL CHAMOD
C READ(1,*)ISEPAR
WRITE(1,2036)
FORMAT('MORE SECTIONS 7')
READ(1,*)MORE
IF(MORE .NE. 0) GO TO 2031
C 2034 CONTINUE
CALL SE281
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0.90.,80.,157.99,1)
CALL AXIDRA(-2,-1,2)
CALL GRACUR(XPACG,ZPACG,NPOINT)
CALL CHAMOD
FUNCTION FEEL(XEEL)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20),COEEL(3),COFL(40)
COMMON/BLO1/R0,WEB,H0,EXG,VG,RKG,ROG
COMMON/BLO2/CONS,PI
COMMON/BLO3/ALPHA,CSVG,SNVG,CSKOI,SNKOI,CSKOU,SNKOU
COMMON/BLO4/2,28,ZHI
COMMON/BLO5/5,NPOINT,NLAAP,ISEC,INE
COMMON/BLO6/COEF,NCOEF,III
COMMON/BLO8/XFLUEE,YFLUEE,DMAR,XSTEEL,YSTEEL,ANGCLE,YEEL
COMMON/BLO11/COFL,NSTFLI
COMMON/BLO13/XEELA,YEELA,ZWEB
CALL GRIN(Z,Z0,AXX,SYY,CXY,DDX,EY,FF)
YEELDV=COEF(2)
IF(S .NE. 1.) YEELDV=4.
XEEL=-WEB/2.
YEEL=-WEB/2.
DO 6 J=1,NSTFLI
YEEL=YEEL+COFL(J)*XEEL*(J-1)
6 CONTINUE
YEEL=YEEL
DO 5 J=1,NSTFLI
YEEL=YEEL+COFL(J)*XEEL**(J-1)
5 CONTINUE
YEEL=YEEL
RETURN
END

FUNCTION FILL(XEEL)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20),COEEL(3),COFL(40)
COMMON/BLO1/R0,WEB,H0,EXG,VG,RKG,ROG
COMMON/BLO2/CONS,PI
COMMON/BLO3/ALPHA,CSVG,SNVG,CSKOI,SNKOI,CSKOU,SNKOU
COMMON/BLO4/2,28,ZHI
COMMON/BLO5/5,NPOINT,NLAAP,ISEC,INE
COMMON/BLO6/COEF,NCOEF,III
COMMON/BLO8/XFLUEE,YFLUEE,DMAR,XSTEEL,YSTEEL,ANGCLE,YEEL
COMMON/BLO11/COFL,NSTFLI
COMMON/BLO13/XEELA,YEELA,ZWEB
CALL GRIN(Z,Z0,AXX,SYY,CXY,DDX,EY,FF)
W=WEB/2./XEEL
IF(XEEL .LE. WEB/2.) GO TO 1
ANG=DATAN(W/DSQRT(1.-W**2))/DSIN(H0)/DCOS(H0)
COEL(1)=YEEL
COEL(2)=YEELDV
COEL(3)=(YEEL+XEEL+COEL(2)-COEL(1))/XEEL**2
WEED=DATAN(YEEL/XEEL)+3.14159265
YEEL=YEEL
GO TO 2
1 YEEL=COEL(1)+COEL(2)*XEEL+COEL(3)*XEEL**2
2 XST1=DSQRT(XEEL**2+YEEL**2)
PST=PHST+XST1
YEEL=YEEL+XST1*YST1+DDX*XST1+DY*YST1
RETURN
END
FUNCTION FIN(XST)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20)
COMMON/BL03/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
COMMON/BLO6/COEF, NCOEF, III
YST = XST
DO 150 J = 1, NCOEF
  YST = YST + COEF(J) * XST**(J-1)
CONTINUE

PHST = OATAN(YST/XST)
RSTAN = OSQRT(XST**2 + YST**2)
PHST = PHST + ALPHA
XST = RSTAN * OCOS(PHST)
YST = RSTAN * DSIN(PHST)
FIN = YST
RETURN
END

FUNCTION FLANK(ZCLE)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20)
COMMON/BLO1/R0, WEB, H0, EXG, VG, RKG, ROG
COMMON/BLO2/CONS, PI
COMMON/BLO4/Z, Z0, ZHH
COMMON/BLO6/COEF, NCOEF, III
COMMON/BLO7/XCLE, YCLE, IFIL, IHILST, PHIIL2
COMMON/BLO8/XFLUEE, YFLUEE, DRM, XSTEEL, YSTEEL, AUGCLE, YEEL

IF (IFIL .NE. 1) GO TO 1
PHIL = DATA(N[YFLUEE/XFLUEE])
PHIL = PHIL + AUGCLE
IF (IHILST .NE. 1) GO TO 2
W2R = WEB/2. /RO
PHIL = DATA(N[W2R/DSQRT(1.-W2R**2)] + DSQRT(R0**2 - (WEB/2.)***2) - DSIN(H0)/DCOS(H0)/R0*CSKOU/SNKOU

PHST = PHIL + ALPHA
XCLE = RO*DCOS(PHST)
YCLE = RO*DSIN(PHST)
PHIL2 = DATA(N[YCLE/XCLE])
FIN = YCLE
RETURN
END

FUNCTION FON(RSTAN)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/BLO1/R0, WEB, H0, EXG, VG, RKG, ROG
COMMON/BLO2/CONS, PI
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
COMMON/BLO4/Z, Z0, ZHH
COMMON/BLO5/S, NP0INT, NLAP, ISEC, HUE
COMMON/BLO7/XOUT, YOUT

ALPHA = ZOUT/R0*DSIN(H)/DCOS(H0)
W2R = DATA(N[W2R/DSQRT(1.-W2R**2)] + DSQRT(R0**2 - (WEB/2.)***2) - DSIN(H0)/DCOS(H0)/R0*CSKOU/SNKOU

PHST = PHIL + ALPHA
XST = RSTAN * OCOS(PHST)
YST = RSTAN * DSIN(PHST)
FIN = YST
RETURN
END

FUNCTION FOUTCR(ZOUT)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/BLO1/R0, WEB, H0, EXG, VG, RKG, ROG
COMMON/BLO2/CONS, PI
COMMON/BLO4/Z, Z0, ZHH
COMMON/BLO5/S, INPOINT, NLAP, ISEC, HUE
COMMON/BLO7/XOUT, YOUT

ALPHA = ZOUT/R0*DSIN(H)/DCOS(H0)
W2R = DATA(N[W2R/DSQRT(1.-W2R**2)] + DSQRT(R0**2 - (WEB/2.)***2) - DSIN(H0)/DCOS(H0)/R0*CSKOU/SNKOU

PHST = PHIL + ALPHA
XST = RSTAN * OCOS(PHST)
YST = RSTAN * DSIN(PHST)
FIN = YST
RETURN
END

FUNCTION FPACE(PHPACE)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/BLO1/R0, WEB, H0, EXG, VG, RKG, ROG
COMMON/BLO2/CONS, PI
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
COMMON/BLO6/COEF, NCOEF, III
YPACE = RPACE*DSIN(PHPACE + PHPACE)
PSPACE = YPACE - YPACE1
RETURN
END

FUNCTION FSCFL(YSCFL)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/BLO1/R0, WEB, H0, EXG, VG, RKG, ROG
COMMON/BLO2/CONS, PI
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
COMMON/BLO6/COEF, NCOEF, III
YPACE = RPACE*DSIN(PHPACE + PHPACE)
PSPACE = YPACE - YPACE1
RETURN
END
COMMON/BLO3/CONS, PI
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
COMMON/BLO4/2, 20, 2NH
COMMON/BLO5/5, NPOINT, NLAAP, ISEC, IHE
COMMON/BLO12/RSE, PHSE, DSEC, SCE1, SCE2, SCE3
COMMON/BLO13/XSEC, YSEC, ZSEC, 2MSCE

C IF(ISEC .GT. NLAAP)ZSEC=-(-SCE1*XSEC-SCE2*YSCFL-DSEC)/SCE3
CALL GRIN(Z, ZOH, AXX, BYY, CXY, DDX, EY, FF)
IF(ISEC .LT. NLAAP) GO TO 2
FSCFL=R**2-XSEC**2-YSCFL**2 GO TO 1
FSCFL=AXX*XSEC**2+BYY*YSCFL**2+CXY*XSEC*YSCFL-DDX*XSEC
EY*YSCFL+FF
IF(IHE .NE. 1) GO TO 4
FSCFL=R**2-XSEC**2-SCE3*2
CONTINUE RETURN

FUNCTION FUN(RSTAN)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
INTEGER NPOINT
COMMON/BLO1/R, WEB, H0, EXG, VG, RKG, ROG
COMMON/BLO2/CONS, PI
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
COMMON/BLO4/Z, ZOH, ZHH
COMMON/BLO5/S, NPOINT, NLAAP, ISEC, IHE
COMMON/BLO6/COEF.NCOEF.III
COMMON/BLO8/XFLUEE, YFLUEE, DMAR, XSTEEL, YSTEEL, ANGCLE, YEEL
COMMON/BLO11/COSPHA
W2R=WEB/2./RSTAN
PHST=(DA7AN(W2R/2.**2)+DSQR(W2R/2.**2))*PSHT+ALPHA
XST=RSTAN*CSKOU/SNKOU
RETURN
END
SUBROUTINE GRIN(Z, ZOH, AXX, BYY, CXY, DDX, EY, FF)
IMPLICIT DOUBLE PRECISION(A-H,0-2)
COMMON/BLO1/R, WEB, H0, EXG, VG, RKG, ROG
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
AXX=CSVG**2+(CSKOI**2)*(SNVG**2)
BYY=SNVG**2+(CSKOI**2)*(CSVG**2)
CXY=2.*SNVG*CSVG-2.*(CSKOI**2)*SNVG*CSVG
DDX=2.*EXG*CSKOI**2-(Z-Z0)*CSKOU*SNKOI
EY=2.*EXG*SNKOI**2-(Z-Z0)*CSKOI*CSVG
FF=EXG**2-ROG**2+(Z-Z0)**2)*SNKOI**2
RETURN END
FUNCTION GRSPACE(PHSPACE)
IMPLICIT DOUBLE PRECISION(A-H,0-2)
COMMON/BLO14/RSPACE, PHPA, YPACE1
COMMON/BLO16/COEA, COEB

YPACE=RPACE*DSIN(PHSPACE+PHPHA)
XPACE=RPACE*DCOS(PHSPACE+PHPHA)
YPACE1=COEA*XPACE+COEB

RETURN

END

SUBROUTINE MONIT(M,N,CORN,RE,FJAC,LJC,SMON,IGR,NITER,NF,IW,LIW,WE,F,LW)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION CORN(3), REO), E'JAC(3,3),

FE=RE(1)**2+RE(2)**2+RE(3)**2

WRITE(I,20)NITER,FE

20 FORMAT('AFTER',I4,' ITERATIONS',2X,'THE SUM OF SQ. IS' ,S,F9.3)

WRITE(I,22) (CORN(I),1=1,N)

22 FORMAT ('AT THE POINT',F10.4)

RETURN

END

SUBROUTINE RESID(IFLAG, M, N, CORN, RE, HI, LIW, WE, LW)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION RE(3),CORN(3),IW(1),WE(120)

COMMON/BLO1/R0. WEB, H0, EXG, VG, RKG, ROG
COMMON/BL02/CONS, PI
COMMON/BL03/ALPHA, CSVG, SNVG, CSK0I, SNK0I, CSKOU, SNKOU
COMMON/BL04/Z.Z0, ZHH

XCORN=CORN(I)
YCORN=CORN(2)
ZCORN=CORN(3)

CALL GRIN(Z,ZO,AXX,BVY,CXY,DDX,EY,FF)

RSTAN=DSQRT(XCORN**2+YCORN**2)

PHSTXY=-DATAN(YCORN/XCORN)

ALPHA=ZCORN/R0*DSIN(HO)/DCOS(HO)

PHST=-PHSTXY-ALPHA

XST1=RSTAN*DCOS(PHST)
YST1=RSTAN*DSIN(PHST)

YST=YST+DFST1

DO 70 J=1, NCOEF

YST=YST+COEF(J)·XST1·CJ-1)

70 CONTINUE

RU(1)=AXX·XCORN·*2+BVY·YCORN·*2+CXY·XCORN·YCORN+DDX
RU(2)=AXX·XCORN·*2+BVY·YCORN·*2+CXY·XCORN·YCORN-DDX
RU(3)=YST-YST1

RETURN

END

FUNCTION ROTAC(XLK)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(NCOEF)

COMMON/BLO1/R0. WEB, H0, EXG, VG, RKG, ROG

W2R=WES/2./RSTAN

PHSTXY=-DATAN(YCORN/XCORN)

ALPHA=ZCORN/R0*DSIN(HO)/DCOS(HO)

PHST=-PHSTXY-ALPHA

XST1=RSTAN·DCOS(PHST)
YST1=RSTAN·DSIN(PHST)

YST=YST+COEF(J)·XST1·CJ-1)

RETURN

END
COMMON/BLO6/COEF,NCOEF,III
COMMON/BLO15/XL0,YL0

YLK=0.
DO 75 J=1,NCOEF
    YLK=YLK+COEF(J)*XLK**(J-1)
CONTINUE
75
R=DSQRT(XLK**2+YLK**2)
ROTAC=R-R0
XLK=XLK
YLK=YLK

RETURN
END

SUBROUTINE VIJK(SCE1,SCE2,SCE3,VJ1,VJ2,VJ3,VI1,VI2,VI3)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)

VK1=SCE1
VK2=SCE2
VK3=SCE3

VJ1=1.
VJ2=-(VJ2*VK2)/VK1
VJ3=0.
VJ=DSQRT((VJ1**2+VJ2**2+VJ3**2)
VJ1=VJ1/VJ
VJ2=VJ2/VJ
VJ3=VJ3/VJ

VI1=1.
VI2=-(VI1*VJ1)/VJ2
VI3=-(VI1*VK1+VI2*VK2)/VK3
VI=DSQRT((VI1**2+VI2**2+VI3**2)
VI1=VI1/VI
VI2=VI2/VI
VI3=VI3/VI

RETURN
END

END
APPENDIX 2

Computer geometric simulation of drill point showing the effect of flute design and cylindrical grinding parameters on drill point design (refer to Chapter 4).
Flute - conventional

Grinding - cylindrical

\[ R_0 = 5.00 \]
\[ \text{Web} = 1.80 \]
\[ H_0 = 27.50 \]
\[ R_k = 59.00 \]

\[ D_{0g} = 26.00 \]
\[ U_g = 90.00 \]
\[ E_xg = 2.50 \]
\[ R_{kg} = 59.00 \]

Computer geometric simulation of drill point
Flute - Grinding convectional cylindrical

\[ \begin{align*}
R_0 &= 7.00 & D_0g &= 26.00 \\
Web &= 1.80 & U_g &= 90.00 \\
H_0 &= 27.50 & E_xg &= 2.50 \\
R_k &= 59.00 & R_kg &= 59.00
\end{align*} \]

[Refer to previous page: varying RO]

Computer geometric simulation of drill point
Flute -
conventional

Grinding-
cylindrical

R0 = 6.00
Web = 0.50
HO = 27.50
Rk = 59.00

D0g = 26.00
Vg = 90.00
Exg = 2.50
Rkg = 59.00

Computer geometric simulation of drill point
Flute - Grinding -
conventional cylindrical

\begin{align*}
R0 &= 6.00 \\
Web &= 2.50 \\
H0 &= 27.50 \\
Rk &= 59.00
\end{align*}

\begin{align*}
D0g &= 26.00 \\
Vg &= 90.00 \\
Exg &= 2.50 \\
Rkg &= 59.00
\end{align*}

[Refer to previous page: varying Web]

Computer geometric simulation of drill point
Flute - Grinding -
conventional cylindrical

R0 = 6.00  D0g = 26.00
Web = 1.80  Vg = 90.00
HO = 10.00  Exg = 2.50
Rk = 59.00  Rkg = 59.00

Computer geometric simulation of drill point
Computer geometric simulation of drill point

Flute - conventional
Grinding - cylindrical

RO = 6.00  D0g = 25.00
Web = 1.80  Ug = 90.00
HO = 40.00  Exg = 2.50
Rk = 59.00  Rkg = 59.00

[Refer to previous page: varying HO]
Computer geometric simulation of drill point
Flute - conventional

Grinding - cylindrical

$R_0 = 6.00$  $D_0g = 26.00$

$\text{Web} = 1.80$  $Ug = 90.00$

$H_0 = 27.50$  $Exg = 2.50$

$R_k = 68.00$  $R_kg = 68.00$

[Refer to previous page: varying $R_k$ and $R_kg$]

Computer geometric simulation of drill point
Flute - conventional  Grinding - cylindrical

R0 = 6.00  D0g = 20.00
Web = 1.80  Ug = 90.00
H0 = 27.50  Exg = 2.50
Rk = 59.00  Rkg = 59.00

Computer geometric simulation of drill point
Flute - Grinding -
conventional cylindrical

R0 = 6.00    D0g = 32.00
Web = 1.80    Vg = 90.00
H0 = 27.50    Exg = 2.50
Rk = 59.00    Rkg = 59.00

[Refer to previous page: varying D0g]

Computer geometric simulation of drill point
Flute - Grinding-
conventional cylindrical

R0 = 6.00  D0g = 26.00
Web = 1.80  Ug = 60.00
H0 = 27.50  Exg = 2.50
Rk = 59.00  Rkg = 59.00

Computer geometric simulation of drill point
Computer geometric simulation of drill point

Flute - Conventional cylindrical

Grinding-

R0 = 6.00  D0g = 26.00
Web = 1.80  Vg = 95.00
HO = 27.50  Exg = 2.50
Rk = 59.00  Rkg = 59.00

[Refer to previous page: varying Vg]
Flute - conventional
Grinding - cylindrical

RO = 6.00  
Web = 1.80  
H0 = 27.50  
Rk = 59.00  

D0g = 26.00  
Vg = 90.00  
Exg = 2.00  
Rkg = 59.00

Computer geometric simulation of drill point
Computer geometric simulation of drill point

Flute - conventional cylindrical
Grinding - cylindrical

R0 = 6.00  D0g = 26.00
Web = 1.80  Vg = 90.00
H0 = 27.50  Exg = 3.50
Rk = 59.00  Rkg = 59.00

[Refer to previous page: varying Exg]
Computer plots of normal rake angle against radial distance showing the effect of flute design and cylindrical grinding parameters on the rake angle variation (refer to Chapter 4).
Flute - conventional
Grinding- cylindrical

R0 = 7.0 (i)  
Web = 1.80
H0 = 27.50
Rk = 59.00

R0 = 5.0 (ii)  
D0g = 26.00
Vg = 90.00
Exg = 2.50
Rkg = 59.00

[Refer to Appendix 2: varying R0]
Flute - conventional
Grinding - cylindrical

$R_0 = 6.00$  $D_0g = 26.00$
$\text{Web} $  $Vg = 90.00$
$H_0 = 27.50$  $Exg = 2.50$
$R_k = 59.00$  $R_{kg} = 59.00$

Web
$0.5 \ (i)$
$2.5 \ (ii)$

[Refer to Appendix 2: varying Web]
Refer to Appendix 2: varying HUD

Flute: conventional

Grinding: cylindrical

Rake:

H0 = 10.0
Rk = 59.00
Rd = 6.00
Vg = 1.80
Exg = 2.50

Radial distance, mm

354
Flute - conventional
Grinding- cylindrical

R0 = 6.00
Web = 1.80
H0 = 27.50
Rk = 59.00

D0g | 20.0 (i)
Vg = 90.00
Exg = 2.50
Rkg = 59.00

D0g | 32.0 (ii)

[Refer to Appendix 2: varying D0g]
Flute - conventional
W0 = 6.00
Web = 1.80
H0 = 27.50
Rk = 59.00

Grinding - cylindrical
D0g = 26.00
Vg = 2.50
Exg = 2.50
Rkg = 59.00

Vg | 60.0 (i) | 95.0 (ii)

[Refer to Appendix 2: varying Vg]
Flute - conventional
Grinding - cylindrical

R0 = 6.00  D0g = 26.00
Web = 1.80  Vg = 30.00
H0 = 27.50  Exg
Rk = 59.00  Rkg = 59.00

Exg | 2.0 (i)  3.5 (ii)

[Refer to Appendix 2: varying Exg]
APPENDIX 4

Computer plots of normal clearance angle against radial distance showing the effect of flute design and cylindrical grinding parameters on clearance angle variation (refer to Chapter 4).
Flute - Grinding-
conventional cylindrical

<table>
<thead>
<tr>
<th>R0</th>
<th>D0g = 26.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web</td>
<td>Vg = 30.00</td>
</tr>
<tr>
<td>H0</td>
<td>Exg = 2.50</td>
</tr>
<tr>
<td>Rk</td>
<td>Rkg = 59.00</td>
</tr>
</tbody>
</table>

R0 | 5.0 (i) |
R0 | 7.0 (ii) |

[Refer to Appendix 2; varying R0]
Flute - conventional
Grinding - cylindrical

$R_0 = 6.00$  $D_0g = 26.00$
$V_g = 90.00$
$H_0 = 27.50$  $E_{xg} = 2.50$
$R_k = 59.00$  $R_{kg} = 59.00$

[Refer to Appendix 2: varying Web]
Flute - conventional
Grinding - cylindrical

R0 = 6.00  D0g= 26.00
Web=  1.00  Vg = 90.00
H0     Exg=  2.50
Rk = 59.00  Rkg= 59.00

H0 | 10.0 (i)
   | 40.0 (ii)

Refer to Appendix 2: varying H0
Flute - conventional  Grinding - cylindrical

R₀ = 6.00  D₀g = 26.00
Web = 1.80  Vg = 90.00
H₀ = 27.50  Exg = 2.50
Rk  Rkg

Rk = Rkg

48.0 (i)  68.0 (ii)

[Refer to Appendix 2: varying Rk and Rkg]
Flute - Grinding-
conventional cylindrical

R0 = 6.00  D0g
Web = 1.00  Vg = 90.00
H0 = 27.50  Exg = 2.50
Rk = 59.00  Rkg = 59.00

D0g | 20.0 (i)
    | 32.0 (ii)

[Refer to Appendix 2: varying D0g]
Flute - conventional
Grinding - cylindrical

R0 = 6.00  D0g = 26.00
Web = 1.80  Vg
H0 = 27.50  Exg = 2.50
Rk = 59.00  Rkg = 59.00

Vg | 60.0 (i)
   | 95.0 (ii)

[Refer to Appendix 2: varying Vg]
Computer plots of inclination angle against radial distance showing the effect of flute design and cylindrical grinding parameters on inclination angle variation (refer to Chapter 4).
Flute - conventional
Grinding - cylindrical

R₀  |  D₀g = 26.00
Web  |  V₉ = 90.00
H₀  |  Eₓg = 2.50
Rₖ  |  Rₖg = 59.00

R₀  |  5.0 (i)
    |  7.0 (ii)

radial distance, mm

Inclination angle, deg

[Refer to Appendix 2: varying R₀]
Flute - Grinding-
conventional cylindrical

$R_0 = 6.00$ $D_0g = 26.00$

Web $V_g = 90.00$

$H_0 = 27.50$ $E_{xg} = 2.50$

$R_k = 59.00$ $R_{kg} = 59.00$

Web $0.5 \,(i)$

$2.5 \,(ii)$
Flute - conventional
Grinding - cylindrical

R0 = 6.00
Web = 1.80
H0 = 59.00

D0g = 26.00
Vg = 90.00
Exg = 2.50
Rkg = 59.00

H0 10.0 (i)
H0 40.0 (ii)

(Refer to Appendix 2: varying H0)
Flute - conventional
Grinding - cylindrical

$R_0 = 6.00 \quad D_0g = 26.00$
$Web = 1.80 \quad Vg = 90.00$
$H_0 = 27.50 \quad Exg = 2.50$
$Rk \quad Rkg$

$R_k = R_kg \mid 48.0 \ (i) \quad 68.0 \ (ii)$

[Refer to Appendix 2: varying $R_k$ and $R_kg$]
Flute - conventional
Grinding - cylindrical

R₀ = 6.00
Web = 1.80
H₀ = 27.50
Rk = 59.00

D₀g
Vg = 90.00
Exg = 2.50
Rkg = 59.00

D₀g
20.0 (i)
32.0 (ii)

[Refer to Appendix 2: varying D₀g]
Flute - conventional cylindrical

R0 = 6.00  D0g= 26.00
Web= 1.80  Vg = 90.00
H0 = 27.50  Exg
Rk = 59.00  Rkg= 59.00
Exg  2.0 (i)
     3.5 (ii)

[Refer to Appendix 2: varying Exg]
Computer program for non-conventional (and conventional) flute generation.
General flute design according to the cutting angles along the drill lip (refer to Chapter 5).
This FORTRAN program uses subroutines from GINO and NAG libraries which are not listed here.
NON-CONVENTIONAL (AND CONVENTIONAL)
FLUTE GENERATION
GENERAL FLUTE DESIGN ACCORDING TO THE
CUTTING ANGLES ALONG THE DRILL LIP

DESIGNED, DEVELOPED AND IMPLEMENTED BY
MANUEL DOS SANTOS PAIS

IMPLICIT DOUBLE PRECISION (A-H, O-Z)
REAL XEEL(200), YEEL(200), XAXIS, YAXIS, XCOR, YCOR
REAL XCIRE(200), YCIRE(200), XCIRD(200), YCIRD(200)
REAL XCHIG(200), YCHIG(200), ZCHIG(200)
REAL XFLU(200), YFLU(200), XS(200), YS(200)
REAL XSTG(200), YSTG(200), ZSTG(200)
REAL XCHI2(200), YCHI2(200)
DIMENSION RU(7), TIPR(200), T2PR(200), STEPXY(7), WW(400)
DIMENSION WS(3,7), REAU(200), REAUX(200)
DIMENSION VAR(3)
DIMENSION DF2(3), C12(4), C21(7)
DIMENSION STEPMX(4), W(120)
DIMENSION SSS(200)
DIMENSION FJAC(4,4), SMON(4), V(4,4), IW(1), WE0(120)
COMMON/BL00/XFLU, YFLU, CWEDGE, RCA, ETACHA, XSTG, YSTG, ZSTG
COMMON/BL01/NPOINT, MAXCAL, TIPR, T2PR, NLOOP
COMMON/BL02/DFDX, DFDY, DFDZ, C1, C2, C3
COMMON/BL03/PA, REVAB, VG, RKG, EXG
COMMON/BL04/SVGA, CSVG, SNKOI, CSKOI
COMMON/BL05/BETA, CGSAMA, VVCG, SGAMA, GAMA, GAMA
COMMON/BL06/DISCC, GAMA, GAMA, ETAA, VVCA
COMMON/BL07/RADI, T211, SS
COMMON/BL08/HA, CONS, R8, WEB, R8G, IWRITE, PI
COMMON/BL09/C12, C21
COMMON/BL10/PR0TOL, D0
COMMON/BL11/numero, PR0TOL
COMMON/BL15/JINSTNS, J
COMMON/BL20/XST0, YST0, ZST0, R0
COMMON/BL21/XS, YS

C READING DATA
WRITE(1, 73)
73 FORMAT('READ R8,WEB, R8, EXG, VG, RKG, R8G/'
'FOR DRILL BODY AND POINT ARCHITECTURE')
READ(1, 10) R8, WEB, R8, EXG, VG, RKG, R8G
WRITE(1, 71)
71 FORMAT('READ NUMBER OF POINTS ON THE LIP')
READ(1, * ) NPOINT
NLOOP = * NPOINT
C
PI = 3.14159265
CONS = 3.141593/180.
R8 = R8*CONS

C CONVENTIONAL PROFILE - FOR COMPARISON
C

DO 9147 NS = I, NLOOP
RSTAN = R8 - FLOAT(NS - 1)*(R8 - WEB/2.)/(NLOOP - 1)
W2R = WEB/2./RSTAN
IF (W2R .GE. 1.) GO TO 79
PHST = DATAN(W2R/DSQRT(1. - W2R**2)) + DSQRT(RSTAN**2 -
(WEB/2.)**2)*DSIN(H0)/DCOS(H0)/R8*CSKOI/SNKOI
GO TO 80
79 PHST = PI/2.
80 XST = RSTAN*OCOS(PHST)
YST = - RSTAN*DSIN(PHST)
XS(NS) = XST
YS(NS) = YST
9147 CONTINUE
C
Z0 = DSQRT((2.*R0G)**2 - (EXG - WEB/2.)**2)/DSIN(RKG*CONS)
C REFERENCE POINTS
C
YCE = WEB/2.
XCE = DSQRT(R8**2 - YCE**2)
C
AXX = CSVG**2 + (CSKOI**2)*(SNVG**2)
BY = CSVG**2 + (CSKOI**2)
CX = 2.*CSVG**2 + (CSKOI**2)*(SNVG**2)
CXY = 2.*CSVG**2 + (CSKOI**2)*(SNVG**2)
C
POZ1 = (-2.*CSKOI*CSKOI*SNVG)*XCE
POZ2 = (-2.*SNKOI*CSKOI*CSVG)*YCE
POZ3 = (2.*EXG)*CSVG + 2.*Z0*SNKOI*CSKOI*SNVG)*XCE
POZ4 = (2.*EXG)*CSVG + 2.*Z0*SNKOI*CSKOI*CSVG)*YCE
POZ5 = EXG**2 + 2.*R0G**2 + Z0**2*SNKOI**2
POZ6 = -2.*Z0*SNKOI**2
C
POZ2 = SNKOI**2
POZ2 = POZ1 + POZ2 + POZ6
POZ2 = AXX + CXY**2 + BY + YCE**2 + CXY + YCE + XCE + POZ3 + POZ4 + POZ5
C
POZ10=(-POZB+DSQRT(POZB**2-4.*POZA*POZC))/2./POZA
POZ20=(-POZB-DSQRT(POZB**2-4.*POZA*POZC))/2./POZA
POZ1=-POZB+POZ2
POZ2=POZ1
ZCORN=POZ20
C OUTER CORNER
C ==================================================
POX=XCE
POY=YCE
POZ=ZCE
POZA=SNKOI**2
POZB=POZ6
POZC=POZS
POZ10=(-POZB+DSQRT(POZB**2-4.*POZA*POZC))/2./POZA
POZ20=(-POZB-DSQRT(POZB**2-4.*POZA*POZC))/2./POZA
C CHISEL POINT - DEAD CENTRE
C ==================================================
POX=XCE
POY=YCE
POZ=ZCE
PQZA=SNKOI**2
POZB=POZ6
POZC=POZS
POZ10=(-POZB+DSQRT(POZB**2-4.*POZA*POZC))/2./POZA
POZ20=(-POZB-DSQRT(POZB**2-4.*POZA*POZC))/2./POZA
ZCORN=POZ20
C CHISEL EDGE
C ==================================================
DO 5 I=1,NLOOP
ZCHI=ZCORN-FLOAT(I-1)/FLOAT(NLOOP-1)*(ZCORN-ZXY0)
C CALL GRIN(ZCHI,Z0,AXX,BYX,CXY,DDX,EY,FF)
C CHI1=BYX+(EY/DDX)**2*AXX-AXX*EY/DDX+CXY
NCHI=1
IF(-FF/CHI1 .GE. 0.0) GO TO 408
WRITE(1,410)NCHI
410 FORMAT("CHI1=",14(E1),/)
GO TO 405
408 YCHI2(I)=+DSQRT(-FF/CHI1)
XCHI2(I)=-YCHI2(I)*EY/ODX
XCHI2(I)=DABS(XCHI2(I)
YCHI2(I)=DABS(YCHI2(I)
5 CONTINUE
405 CONTINUE
C INITIAL CONDITIONS TO THE PROFILE TO BE FOUND
C ==================================================
SS=0.8
XST=XCE
YST=YCE
ZST=ZCE
C READING WEDGE ANGLE
C READ MAXCAL, IFAIL, IWRITE
READ(1,*)MAXCAL, IFAIL, IWRITE
READ(1,*)BAFTOL,XTOL,ETA,IPRINT
WRITE(1,77) /CONVENTIONAL FLUTE INSTEAD /
READ(1,*)ISTINS
C PARAMETERS TO SUBROUT E84FCF
C ==================================================
M4F=4
N4F=4
LJ=4
LV=4
LIN=1
LW=120
CPOZ10=(-POZB+DSQRT(POZB**2-4.*POZA*POZC))/2./POZA
POZ20=(-POZB-DSQRT(POZB**2-4.*POZA*POZC))/2./POZA
ZC=EPOZ20
C CHISEL EDGE
C ==================================================
DO 5 I=1,NLOOP
ZCHI=ZCORN-FLOAT(I-1)/FLOAT(NLOOP-1)*(ZCORN-ZXY0)
C CALL GRIN(ZCHI,Z0,AXX,BYX,CXY,DDX,EY,FF)
C CHI1=BYX+(EY/DDX)**2*AXX-AXX*EY/DDX+CXY
NCHI=1
IF(-FF/CHI1 .GE. 0.0) GO TO 408
WRITE(1,410)NCHI
410 FORMAT("CHI1=",14(E1),/)
GO TO 405
408 YCHI2(I)=+DSQRT(-FF/CHI1)
XCHI2(I)=-YCHI2(I)*EY/ODX
XCHI2(I)=DABS(XCHI2(I)
YCHI2(I)=DABS(YCHI2(I)
5 CONTINUE
405 CONTINUE
C INITIAL CONDITIONS TO THE PROFILE TO BE FOUND
C ==================================================
SS=0.8
XST=XCE
YST=YCE
ZST=ZCE
C READING WEDGE ANGLE
C READ MAXCAL, IFAIL, IWRITE
READ(1,*)MAXCAL, IFAIL, IWRITE
READ(1,*)BAFTOL,XTOL,ETA,IPRINT
WRITE(1,77) /CONVENTIONAL FLUTE INSTEAD /
READ(1,*)ISTINS
C PARAMETERS TO SUBROUT E84FCF
C ==================================================
M4F=4
N4F=4
LJ=4
LV=4
LIN=1
LW=120
c

PHIl~OATAN(YST/XST)

113

PHI=PHII-ZST!Re*OSIN(H0)/OCOS{H0)
XSTG (1 )z:XST
YSTG (1 )=YST
WRITE(l,1l3)
FORMAT(/'CALLING E04FCF'/)

C

c

c
C
C

CALL E04FCF(M4F,N4F, RESID. MONIT. IPRINT.MAXCAL.ETA.XTOL,
SSTEP,CI2,FE.RE,FJAC,LJ,SMON,V,LV.NITER,NF,IW,LIW,WE0,LW,
SIFAIL)
CALL EXIT
END
SUBROUTINES
=D===========a~==========E=Z:============Z=========

C

c
C

====;~=;~~;7;;D~~~~77;~~7~:;7~~;~~;;~;~7;=7~;~7;;;7~~)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
REAL RaN,R0P,XCOR,YCOR
EXTERNAL DERIV2
REAL XCIRE(2~~).YCIRE(20A),XCIRD(200},YCIRD(200)
REAL XEEL(200),YEEL(200),XAXIS,YAXIS
REAL XSTG(20A),YSTG(200),ZSTG(2~0)
REAL XCHIG(20A),YCHIG(20A).ZCHIG(2AA)
REAL XFLU(20~),YFLU(200),XS(200),YS(2~e)
REAL VERIG(2~~),RRG(200),GAMI(200)
REAL DINCC(200),WEDGE(2~0),RSINC(200)
REAL GAMAA(2~0),CLEAA(2~0),GAMAE(200)
DIMENSION EIX(100,S),FEAT(1~0,4),THETA(S,4),B(4),AM(S,5)
DIMENSION SOLU(4),C(100,S).IPIV(S),WKl(S.5),WK2(100)
DIMENSION WKS2(4),WKSl(32),SIGSQ(4)
DIMENSION XNMSD( 20l'l) , YNMSD( 20e), ZNMSD(200)
DIMENSION PHU(200).SENOEE(200)
DIMENSION CCEl(200),CCE2(200),CCE3(200)
DIMENSION A(3,3),DCOOR(3)
DIMENSION XSTGD{200),YSTGD(200),ZSTGD(200)
DIMENSION XNRAD(2P10),YNRAD(200),ZNRAD(200)
DIMENSION XFLUD(200),YFLUO(200)
DIMENSION XCHI2(200),YCHI2(200)
DIMENSION REAU(200),REAUX(200}
DIMENSION IW(1),WEA(120),WS(3,7)
DIMENSION VAR(3)
DIMENSION DF2(3),CI2(4),TIPR(200),T2PR(200)
DIMENSION RE(4),STEPMX(3),W(120),DDIS(200)
DIMENSION 5SS(200)
DIMENSION GAMN(200),GCD(200),AKCD(20A),HCD(20A)
DIMENSION RADI(20e),T211(200),ETAA(2A0).VVCA(2~A)
DIMENSION ETACHA( 200), RCA( 200), GEMEA( 200)
COMMON/BL00/XFLU,YFLU,CWEDGE,RCA,ETACHA.XSTG,YSTG,ZSTG

c

COMMON/BLOl/NPOINT,MAXCAL,TlPR.T2PR,NLOOP
COMMON/SL02/DFDX,OFDY,OFDZ,CE1,CE2,CE3
COHMON/SL03/PA,REVAB,VG,RKG,EXG
COMMON/BL04/SNVG.CSVG,SNKOI,CSKOI
COMMON/BLOS/SENETA,CSGAMA,VVCV,SGAMAE,GEMEA,SGAMA
COMMON/BL06/0INCC,GAHAA,CLEAA;GAMAE,ETAA,VVCA
COMMON/BL07/RADI,T211,SSS
COMMON/SL08/H0,CONS,R0,WEB,R0G,IWRITE,PI
COMMON/BLOll/OIDS,Z0
COMMON/BL012/SAFTOL
COMMON/BL014/XCE,YCE,ZCE,XCORN,YCORN,ZCORN,ZX0Y0
COMMON/BLOlS/ISTINS,J
.
COMMON/BL016/RPACE. PHPA, YPACEl
COMMON/BL017/COEA,COEB
COMMON/BL018/R0CHIP,HBCHIP,A
.. COMMON/BL019/RSTAR. PHSTAR, ZSTAR, XSTRDT, YSTROT, ZSTROT
COMMON/SL020/XST0,YST0,ZST0, RC0 .
COMMON/SL021/XS,YS

POZ"'ZCE
C SS IS THE LENGTH ALONG THE CUTTING EDGE.
e FROM THE OUTER CORNER
VARX=XCE
VAR(l )=0.0
VAR(2 )=YCE
VAR(3)=ZCE
DVARX=(XCE-XCORN)/FLOAT(NPOINT-2 )

c

114

42
43

NBAF=3
IFAUL""0
WRITE (1. 114)
FORMAT Ut STARTING LOOP 4A AND CALLING D02ABF' /)
DO 40 J""l,NPOINT
IF(J .GE. 2) GO TO 42
VARXl=XCE
VARX2=VARXl+0VARX
GO TO 43
VARXl=XCE-FLOAT(J-3}*DVARX
VARX2 a VARXI-OVARX
TOL=BAFTOL

C

CALL D02BAF(VARXl,VARX2,NBAF,VAR.TOL.DERIV2,
$WS,IFAUL)

c
SS=VAR( 1)
XST=VARX2
YST=VAR(2)
ZST=VAR(3)
PHIl=DATAN(YST/XST)
PHU(J)=PHIl
UUl=-DSIN(PHIl)
UU2-+DCOS (PHI 1)
UU3=/3.0
RR=DSQRT(XST*·2+YST**2)

W

---J

Ul


COTH=RA*DCOS(HA)/DSIN(HA)/RR
SENOI=C12(1)*(RR/RO)**2+C12(2)*RR/RO*C12(3)+C12(4)/RR
IF(ISTINS.EQ.1)SENOI=WEB/2./RR*SNOI
SENOE(J)=SENOI

C
CCE1(J)=CE1
CCE2(J)=CE2
CCE3(J)=CE3

C VECTOR NORMAL TO THE MACHINED SURFACE
XNMS=UU2*CE3
YNMS=UU2*CE1
ZNMS=UU2*CE2
SU=DSQRT(XNMS**2+YNMS**2+ZNMS**2)
DFD=DSQRT(DFDX**2+DFDY**2+DFDZ**2)
TCSCLEA=(XNMS*DFDX+YNMS*DFDY+ZNMS*DFDZ)/SU/DFD
TCSCLEA=DSQRT(1.-TCSCLEA**2)/TCSCLEA
CLEAR=DATAN(TCSCLEA)/CONS

XNMS=-XNMS
YNMS=-YNMS
ZNMS=-ZNMS

XNMSD(J)=XNMS
YNMSD(J)=YNMS
ZNMSD(J)=ZNMS

SALPHA=DABS(ZNMS/SU)
CALPHA=DSQRT(1.-SALPHA**2)

C RAKE ANGLE COMPUTATION
C
C
3300 AR2=DSQRT(XNRA**2+(YNRA**2+YNRA**2))
AR1=-AR2*YNRA/XNRA
BR1=YST/RR
BR2=YST/RR
CSBETA=ARI*BR1+AR2*BR2
SNBETA=DSQRT(1.-CSBETA**2)
TGBETA=DATAN(SNBETA/CSBETA)
SIGN=XR*XST*YNRA*YST
SIGN2=DABS(SIGN)
IF(SIGN2.GE.0.)GO TO 3001
YMS=XR/CONS
3001 SIGN=SIGN1/SIGN2
BETA=SIGN1*DABS(BETA)
TGBETA=DSQRT(1.-SENOI**2)*TGBETA
SMBETA=DATAN(TGBETA/CONS)
SIGN1=RY/CONS
SIGN2=DABS(SIGN1)
IF(SIGN2.GE.0.)GO TO 3001
YMS=RY/CONS
3003 FORMAT(' SIGN2= A.B')
CALL EXIT

3301 FORMAT(' XNRA IS NUL ')
CALL EXIT

C
C 196
C
C 3001 FORMAT(' SIGN2= A.B')
CALL EXIT

C VECTOR NORMAL TO RAKE FACE
XNRA=UU2*CE3-CE2*COTH
YNRA=CE1*COTH-UU1*CE3
ZNRA=UU1*CE2-UU2*CE1
XZM=DSQRT(XNRA**2+YNRA**2+ZNRA**2)
XNRA=XNRA/XZM
YNRA=YNRA/XZM
ZNRA=ZNRA/XZM
XNRA=XRAD(J)-XNRA
YNRA=XRAD(J)-YNRA
ZNRA=XRAD(J)-ZNRA
COSGN=(-XNRA*CE2+YNRA*CE1)/DSQRT(CE2**2+CE1**2)
GAMMA=DATAN(DSQRT(1.-COSGN**2)/COSGN)

C IF(XNRA.GE.0.)GO TO 3300
WRITE(1,3313)
3313 FORMAT(' XNRA IS NUL ')
CALL EXIT
ZSTGD(J)=ZST
SSS(J)=SS-SSS(2)
DINCC(J)=DINCC
GAMAA(J)=GAMA
GAMM(J)=GAMM/CONS
CLEAA(J)=CLEAR
GAMAA(J):GAMAA(2)
WEDGE(J)=90.-GAMA-CLEAR
HCID(J)=HC/CONS
ETACHA(J)=ETACH
DDIS(J)=DIDS*CONS
GAMIE''(SIN(DINCC(J)*CONS)**2+(COS(DINCC(J)*CONS})**2*
$SIN(GAMAA(J)*CONS)
GAMI(J)=ATAN(GAMIE/SORT{l.-GAMIE»/CONS
REAUX(l)=eI.0
205 FORMAT(7F7.2)
READ(1,*)SEPARA
C
C FINAL PARAMETERS TO INCLINATION ANGLE LAW
WRITE(1,921)C12(1),C12(2),C12(3)
921 FORMAT(/6X,'C12(1)=','F8.4,3X,'C12(2)=','F8.4,3X,/
$'C12(3)='.,2F8.4)
C
C NOW , PLOTS
WRITE(1,60)
60 FORMAT('/' GRAPHICS ?'/)
READ(1,*)IGRAF
IF(IGRAF .EQ. 0)CALL EXIT
935 CONTINUE
C
C WRITE(1,142)
142 FORMAT('/' T40I0(,),C10.5N(2) OR SE281(3) ?'/)
READ(1,*)IDEVIC
WRITE(1,232)
232 FORMAT('CHISEL EDGE ?')
READ(1,*)CHIH
IF(CHIH .EQ. 0)GO TO 112
C
C CHISEL EDGE COMPUTATION
C
C DO 5 I=1,NLOOP
ZCHI=ZCORN-FLOAT(I-1)/FLOAT(NLOOP-1)*(ZCORN-ZX3Y)
5
C
C CALL GRIN(ZCHI,AXX,SYY,CKY,ODX,EY,FF)
C
C RADIC=-FF*CHI
IF(RADIC .GE. 0.)GO TO 233
231 FORMAT('/' RADIC < 0')
233 CALL EXIT
C
C YCHI2(I)=YCHI(I)-YCHI2(I)**2*AXX-AXX-EY/DDX*CX
C
C RADIC=FF/CHI
IF(RADIC .GE. 0)GO TO 233
WRITE(1,231)
231 FORMAT('/' RADIC < 0')
C
C CALL EXIT
C
C WRITE(1,101)
101 FORMAT('/'CHISEL EDGE COMPUTED'/)
C
C Computing Flute Heel
WRITE(1,200)
200 FORMA1/7GRAPHICS ?7/
READ(1,*)IGRAF
IF(IGRAF .EQ. 0)CALL EXIT
233 FORMAT('/'CHISEL EDGE COMPUTED'/)
C
C CHISEL EDGE COMPUTATION
C
C DO 5 I=1,NLOOP
ZCHI=ZCORN-FLOAT(I-1)/FLOAT(NLOOP-1)*(ZCORN-ZX3Y)
5
C
C CALL GRIN(ZCHI,AXX,SYY,CKY,ODX,EY,FF)
C
C RADIC=-FF*CHI
IF(RADIC .GE. 0.)GO TO 233
231 FORMAT('/' RADIC < 0')
233 CALL EXIT
C
C YCHI2(I)=YCHI(I)-YCHI2(I)**2*AXX-AXX-EY/DDX*CX
C
C RADIC=FF/CHI
IF(RADIC .GE. 0)GO TO 233
WRITE(1,231)
231 FORMAT('/' RADIC < 0')
C
C CALL EXIT
C
200 FORMAT(/'READ ANGLE FOR HEEL')
READ(1,*) ANGLE
YEEL(I) = R0*SIN(ATAN(YFLU(2)/XFLU(2))) - PI + ANGLE*CONS
XEEL(I) = R0*COS(ATAN(YFLU(2)/XFLU(2))) - PI + ANGLE*CONS
RCORN = DSQR(XCORN**2 + YCORN**2)
PHICO = ZCORN/RCORN*SIN(HA)/COS(HA)
PHICOR = DATAN(YCORN/XCORN) - PHICO
YCOR = RCORN*SIN(PHICOR)
XCOR = RCORN*COS(PHICOR)
AEEL = (YEEL(I) - YCOR)/(XEEL(I) - XCOR)**2
BEEL = -2.*AEEL*XCOR
CEEL = YEEL(I) - AEEL*XCOR**2
DO 201 I = 1, NLOOP
     XEEL(I) = XEEL(I) + FLOAT(I-1)/FLOAT(NLOOP-1)*XCOR
     YEEL(I) = YEEL(I) + FLOAT(I-1)/FLOAT(NLOOP-1)*YCOR
     YCIRE(I) = YEEL(I) + FLOAT(I-1)/FLOAT(NLOOP-1)*YFLU(2)
     XCIRE(I) = XEEL(I) + FLOAT(I-1)/FLOAT(NLOOP-1)*XFLU(2)
201 CONTINUE
C
202 FORMAT(/'FLUTE CROSS SECTION ?')
WRITE(1,215)
215 FORMAT(/'FLUTE CROSS SECTION ?')
READ(1,*) IFLUSE
IF(IFLUSE .EQ. 0) GO TO 216
GO TO(207, 208, 209, 210). IDEVIC
C
206 FORMAT(/'INCLINATION ANGLE PLOTTING ?')
READ(1,*) INCANG
207 CALL T4010
XAXIS = 158.
YAXIS = 128.
GO TO 210
CALL C1051
XAXIS = 158.
YAXIS = 158.
GO TO 210
CALL SE281
XAXIS = 180.
YAXIS = 110.
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0, 50, 50, XAXIS, 1)
CALL AXIPOS(0, 50, 50, YAXIS, 2)
CALL AXISCA(2, 180, 0, R0, R0, 1)
CALL AXISCA(1, 120, 60, 2)
CALL AXIDRA(-2, -1.2)
C
218 FORMAT(/'WEDGE PLOTTING ANGLE ?')
READ(1,*) ISEPARA
WRITE(1, 220)
220 FORMAT(/'WEDGE PLOTTING ANGLE ?')
READ(1,*)IWE
IF(IWE .EQ. 0) GO TO 219

C
R0P=R0+1.
IRO=IROP
R0P=R0P
R0N=R0P
GO TO (211,212,213), IDEVIC
C
211 CALL T4O1O
XAXIS=158.
YAXIS=128.
GO TO 214
212 CALL C1851N
XAXIS=156.
YAXIS=156.
GO TO 214
213 CALL SE281
XAXIS=188.
YAXIS=128.
C
214 CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0,50,50,XAXIS,1)
CALL AXISCA(2,18,0,180,1)
CALL AXDRA(2,1,1)
CALL AXIDRA(-2,-1,2)
C
219 CONTINUE
READ(1,*)ISEPARA
WRITE(1,224)
C
224 FORMAT('EFFECTIVE RAKE PLOTTING ?'
READ(1,*)IRAKE
IF(IRAKE .EQ. 0) GO TO 223
R0P=R0P
IRO=IRO
R0N=R0N
GO TO 214
C
2705 CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0,50,50,180,1)
CALL AXISCA(3,180,0,180,1)
CALL AXDRA(2,1,1)
CALL AXIDRA(-2,-1,2)
C
231 CALL CHAMOD
READ(1,*)ISEPARA
WRITE(1,221)
C
221 FORMAT('MORE PLOTS ?'
READ(1,*)IPLOT
C
C PLOTTING DRILL LIP
IF(IPLOT .EQ. 1) GO TO 222
IF(IDEVIC .EQ. 2) GO TO 45
CALL T4416
GO TO 46
45 CALL C1851N
46 CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0,100,20,200,1)
CALL AXISCA(2,20,10,100,1)
CALL AXIDRA(2,1,1)
CALL AXIDRA(-2,-1,2)
C
C CALL GRACUR(XSTG(2),ZSTG(2),NPOINT)
C CALL CHAMOD
READ(1,*)ISEPARA
C
C CALL DEVEND
C
C SUBROUTINE DERIV2(XVAR,VAR,DF2)
C IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C DIMENSION VAR(3)
C DIMENSION DF2(3),C12(4),VERUF(2A0),C21(7)
C DIMENSION XSTG(2),ZSTG(2),NPOINT
C COMMON/BL02/DFDX,DFDY,DFDZ,CE1,CE2,CE3
C COMMON/BL03/PAR,A,VERAB,VG,RKG,EXG
C COMMON/BL04/SNGV,CSVG,SNKOI,CSKOI
C COMMON/BL05/H0,CONS,R0,WEB,R0G,IWRITE,PI
C COMMON/BLO12/C12,C21
C COMMON/BLO11/DIDS,Z0
C COMMON/BL01S/ISTINS,J
C XST=XVAR
I-wrap=VAR(2)
ZST=VAR(3)
C
C RR=DSQRT(XST**2+YST**2)
SENOI=C12(1)*(RR/R0)**2+C12(2)*RR/R0+C12(3)+C12(4)/RR
IF(DABS(SENOI) .LT. 1.) GO TO 230
C
C WRITE(1,231)
C
C 231 FORMAT('DABS(SIN(INC)) >= 1 ')
C CALL EXIT
230 IF(ISTINS .EQ. 0) THEN
PHII=DATAN(YST*XST)
UU1=DSIN(PHII)
UU2=DCOS(PHII)
UU(1)=0.0
IF(UU1 .NE. 0.0 .AND. RR .NE. 0.0) GO TO 1789
WRITE(1,1791)
1791 FORMAT(' UU1 OR RR IS NUL')
CALL EXIT
1789 CONTINUE
C
CALL GRIN(ZST,Z0,AXX,BYX,CXY,DDX,EY,FF)
C
DFDX=2.*XST*AXX+YST*CXY+DDX
DFDY=2.*YST*BYX+CXY*XST+EY
DFDZmXST*(-2.*SNKOI*CSKOI*SNVG)+YST*{-2.*SNKOI*
$*CSKOI*CSVG)+SNKOI**2*(-2.*SNK

C IF(UU1 .NE. 0.0) GO TO 7654
WRITE(1,7656)
7656 FORMAT(' UU1 = 0.0')
CALL EXIT
7654 COICE1=SENOI/UU1
COICE2=-UU2/UU1
COICE3=-DFDX*SENOI/(DFDZ*UU1)
COICE4=(DFDX*UU2)/(DFDZ*UU2)-DFDY/DFDZ
C
COTH=R0*DCOS(H0)/OSIN(H0)/RR
ACE2=1.+COICE1**2+COICE2**2
BCE2=2.*((COICE1*COICE1-1)*COICE3**2)
CCCE2=1.+COICE1**2+COICE3**2
RADICS=BCE2**2-4.*ACE2*CCCE2
IF(RADICS .LE. 0.0) GO TO 185
WRITE(1,187)RADICS
187 FORMAT('(187) RADICS IS NEGATIVE = ',F12.6)
185 CONTINUE
C
IF(ACE2 .NE. 0.0) GO TO 4100
WRITE(1,4009)
4009 FORMAT(' ACE2 IS NUL ')
CALL EXIT
4100 CE2=(-BCE2-DSQRT(RADICS))/(2.*ACE2)
CE1=COICE1+COICE1*CE2
CE3=COICE3*COICE3*CE2
C
DF2(1)=-1./CE1
DF2(2)=CE2/CE1
DF2(3)=CE3/CE1
C
IF(J .EQ. 10)DF2(1)=-DF2(1)
C
RETURN
C
C
C SUBROUTINE GRIN(Z,Z0,AXX,BYX,CXY,DDX,EY,FF)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/BLO4/SNVG,CSVG,SNKOI,CSKOI
COMMON/BLO8/H0,CONS.RR,WEB,RRG,WRITE,PI
C
AXX=CSVG**2+(CSKOI**2)*SNVG+CSKOI**2
BY=SNVG**2+CSVG**2*(CSKOI**2)
CXY=2.*SNVG*CSVG+2.*(CSKOI**2)*SNVG*CSVG
DDX=2.*EXG*CSVG-2.*(Z-Z0)*SNKOI*CSKOI*SNVG
EY=2.*EXG*SNVG-2.*(Z-Z0)*SNKOI*CSKOI*CSVG
FF=EXG**2-(2.*RRG)**2+(2.*(Z-Z0)**2)*SNKOI**2
C
RETURN
END
C
C SUBROUTINE GRIN(Z,Z0,AXX,BYX,CXY,DDX,EY,FF)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION C12(4),RE(4),FJAC(4,4),SMON,IR,ITER,
$NF,IR,W,RG,WE(120)
FE=RE(1)**2+RE(2)**2+RE(3)**2+RE(4)**2
WRITE(1,20)ITER,FE
20 FORMAT('AFTER',I4,' ITERATIONS',2X,'THE SUM OF SQ. IS',$.F9.3)
WRITE(1,22)C12(1),I=1,4
22 FORMAT('AT THE POINT',4F10.4)
RETURN
END
C
C
C *END*END*END*END*END*END*END*END*END*END*END*END*END*END*END*END*END*
APPENDIX 7

Wear loss at points 2, 3, 4 and 5 (outer corner) along the drill lips for both tested drilling conditions. For point 1 refer to Chapter 6.
Wear loss at point 2 of each drill lip
Wear loss at point 2 of each drill lip
Wear loss at point 2 of each drill lip
Wear loss at point 2 of each drill lip

- Conventional flute
- New flute

118 deg point
1140 RPM
157 RPI
Wear loss at point 2 of each drill lip
Loss at point 2

optical divisions
eyepiece graticule

Wear loss at point 2 of each drill lip

No of holes X101

[Graph showing data points and lines for drill wear loss]
134 deg point
820 RPM
157 RPI

Wear loss at point 2 of each drill lip
Wear loss at point 2 of each drill lip.
Wear loss at point 3 of each drill lip

- Conventional Flute
- New Flute

118 deg point
820 RPM
240 RPI

No of holes: 0, 1, 2, 3

Optical divisions per eye piece, graticule

Wear loss at point 3 of each drill lip
Wear loss at point 3 of each drill lip
Wear loss at point 3 of each drill lip

- Conventional Flute
- New Flute

118 deg point
820 RPM
157 RPI

No of holes

Optical divisions
Eyesight graticule

Loss at point 3

392
Wear loss at point 3 of each drill lip

- Conventional flute
- New flute

118 deg point
1140 RPM
157 RPI
Wear loss at point 3 of each drill lip
Wear loss at point 3 of each drill lip

- Conventional flute
- New flute

- 134 deg point
- 1140 RPM
- 240 RPI
Wear loss at point 3 of each drill lip

- Conventional Flute
- New Flute

- 134 deg point
- 820 RPM
- 157 RPI
Wear loss at point 3 of each drill lip
Wear loss at point 4 of each drill lip

- Conventional Flute
- New Flute

118 deg point
820 RPM
240 RPI
Wear loss at point 4 of each drill lip

- Conventional flute
- New flute

118 deg point
1140 RPM
240 RPI
Wear loss at point 4 of each drill lip

- Conventional Flute
- New Flute

118 deg point
820 RPM
157 RPI
Wear loss at point 1 of each drill lip

- Conventional Flute
- New Flute

118 deg point
1140 RPM
157 RPI
o conventional flute
+ new flute

134 deg point
820 RPM
240 RPI

Wear loss at point 4 of each drill lip
No of holes

Wear loss at point 4 of each drill lip

134 deg point
1140 RPM
240 RPI

o conventional Flute
+ new Flute
Wear loss at point 4 of each drill lip

- Conventional flute
- New flute

134 deg point
820 RPM
157 RPI
Wear loss at point 4 of each drill lip

- Conventional flute
- New flute

- 134 deg point
- 1140 RPM
- 157 RPI
Wear loss at point 5 - outer corner - of each drill lip
Wear loss at point 5 - outer corner - of each drill lip

- Conventional flute
- New flute

118 deg point
1140 RPM
240 RPI
Wear loss at point 5 - outer corner - of each drill lip
Wear loss at point 5 - outer corner - of each drill lip

- conventional flute
- new flute

- 118 deg point
- 1140 RPM
- 157 RPI
Wear loss at point 5 - outer corner - of each drill lip

- conventional flute
- new flute

134 deg point
820 RPM
240 RPI
Wear loss at point 5 - outer corner - of each drill lip

- conventional flute
- new flute

134 deg point
1140 RPM
240 RPI
No of holes  

Wear loss at point 5 - outer corner - of each drill lip
APPENDIX 8

Computer program for chip geometric simulation with any flute shape and any set of cylindrical grinding conditions providing for chip flow angle prediction, cutting ratio prediction and other chip related variables (refer to Chapter 8).
This FORTRAN program uses subroutines from GINO and NAG libraries which are not listed here.
CHIP SIMULATION FOR ANY SET OF CYLINDRICAL GRINDING CONDITIONS AND ANY FLUTE SHAPE

PROGRAM DESIGNED, DEVELOPED AND IMPLEMENTED BY MANUEL DOS SANTOS PAIS

SUBROUTINES FROM GINO AND NAG LIBRARIES ARE USED

IMPLICIT DOUBLE PRECISION(A-H,O-Z)
REAL ETARIG(100), SSS(100), CEL(100)
REAL XAXIS,YAXIS,R0P,R0F,R0N
REAL XPACGC10A), YPACGC100), ZPACC(100), RSTO(lOO)
REAL Xl(HH~), Yl(10A), Y1N(100), YIA(1U), XIA(1(0)
DIMENSION XIAN(100)
REAL TIMEU(100), T1WI(100), TIMAUC100)
REAL XFLU(100), YFLU(100), XCHIG(100), YCHIG(100), ZCHIG(100)
REAL RAKE(100), ANSAI(100), AINC(100), ANSI(100)
REAL RADI(100), XLS(100), YLS(100), ZLS(100), RSN(100), DL(100)
REAL RCHISE(100), CHIXA(100)
DIMENSION A(3,3), DCOORD(3), CAAR(3), EIX(4)
DIMENSION VERIF(100)
DIMENSION CLEAA(100), GAMEA(100)
DIMENSION GANN(100), GCD(100), ACKD(100), HCD(100)
DIMENSION RED(100), T21I(100), ETAA(100)
DIMENSION RCA(100), GAMA(100)
DIMENSION XCHI(100), YCHI(100)
DIMENSION ZSTGD(100), XSTGD(100), YSTGD(100)
DIMENSION XNRAI(100), YNRAI(100), ZNRAI(100)
DIMENSION RCHISE(100), CHIXA(100)
DIMENSION DER(14), EREST(14), COEF(20)
DIMENSION XNHU(100), YNHU(100), ZNHU(100)
DIMENSION XL(100), YL(100), DERIV(100), RELIEF(100)
DIMENSION RSTFL(40), PSTFL(40), COFL(40), MSTFL(40)
DIMENSION YHSTFL(40)
DIMENSION CCE1(100), CCE2(100), CCE3(100), CCEP(100)
DIMENSION MDLD(100), VUD(100)
DIMENSION 2TCHG(100), HEU(100), ETAS(100), WIETA(100)
IF(S .EQ. 0) RSTAN1 = WEB/2. + 1.E-6
RSTAN2 = R0 + 1.
HRAB = 1.E-5
NCH1 = NPOINT
ZCL1 = 2.
ZCL2 = 1.2*RA
DMAR = 0.35

C WRITE(1,813)
813 FORMAT(‘READ RPM AND RPI’)
READ(1,*) RPM, RPI

C PI = 3.14159265
CONS = PI/180.
H0 = H0*CONS

C CSVG = DCOS(VO*CONS)
SVVG = DSIN(VO*CONS)
CSKO = DCOS(RK*CONS)
CSKO = DCOS(RK*CONS)
SNKO = DSIN(RK*CONS)

C DIST = DSQRT((2.*RKG)**2 - EXG**2)
Z0 = DSQRT((2.*RKG)**2 - (WEB/2./RA)**2)/DSIN(RKG*CONS)

C WRITE(1,8004)
8004 FORMAT(‘DATA FOR THE COMPUTATION THE CHISEL CORNER’)
WRITE(1,8000)
8000 FORMAT(‘PRINT (-1)-NO CALL / (1)-EACH ITERATION’)
READ(1,*) IPRT
FTOL = 1.E-7
XTOL = 1.E-6

C CHISEL CORNER - STARTING POINT
CORN(1) = WEB/2.
CORN(2) = WEB/2.
CORN(3) = 1.
WRITE(1,8002)

8002 FORMAT(‘READ STEP FOR CHISEL CORNER CALCULATION’)
READ(1,*) STEP
MAXCAL = 1000

C WRITE(1,8005)
8005 FORMAT(‘SELECT POINT STEP FOR PRINTING’)
READ(1,*) NSALTO

C WRITE(1,7010)
7010 FORMAT(‘ANGULAR DIFFERENCE MARGIN/HEEL’)
READ(1,*) DPHIEL
DPHIEL = DPHIEL*CONS
WRITE(1,8009)

8009 FORMAT(‘MAIN DATA READ’)

C WRITE(1,7015)
7015 FORMAT(‘ VERY OPEN HEEL ?’)

READ(1,*) IHILST

WRITE(1,734)
734 FORMAT(‘WRITE INTO FILE ? IF YES READ 6’)
READ(1,*) IFILE

C EPS = 1.E-7
EPS1 = 1.E-7
EPV = 1.E-7

IF(S .NE. 1.) GO TO 15
DO 284 IM = 1, NP
READ(5,*) XL(I), YL(I)
284 CONTINUE
WRITE(1,1286) (XL(I), YL(I), I = 1, NP)
WRITE(1,217) EPS, EPS1, EPV, EPV, IFAIL
IFAIL = 0
IF(S .NE. 1.) GO TO 15
DO 219 I = 1, NP
READ(5,*) XL(I), YL(I)
219 CONTINUE

DO 610 I = 1, NP
XL(I) = XL(I)*DCOS(SISANG) + YL(I)*DSIN(SISANG)
YL(I) = XL(I)*DSIN(SISANG) + YL(I)*DCOS(SISANG)
610 CONTINUE

C NON-CONV. FLUTE SECTION
CALL E02ACF(XL, YL, NP, COEF, NCOEF, REF)
C DETERMINING THE CHISEL CORNER
CALL E04FCF(M, N, RESID, MONIT, IPRINT, MAXCAL, ETA, XTOI, STEP,
$CORN, FE, RE, PJAC, JJ, SMON, V, LV, NTER, NF, IW, LIW, WE0, LW, IFAIL)
C

GO TO B014

C B011 CALL E04FCF(M,N,RESUD,MONUT,IPRINT,MAXCAL,ETA,XTOL,STEP,
SCORN,PH,RI,PFAC.LJ,SMON,LY,NITER,NI,LI,WE,LW,IFAIL)

C B014 CONTINUE

C DETERMINING THE OUTER CORNER
P0X=DSQRT(R0**2-(WES/2.)**2)
P0Y=-WES/2.
P0Z=PAX*CSKOI/SNXOI
ZOUT=P0Z
XCORN=CORN(1)
YCORN=CORN(2)
ZCORN=CORN(3)
ZOUT1=P0Z-2.
ZOUT2=P0Z+2.
CALL C05ACF(ZOUT1,ZOUT2,EP,EV,FOUTCZ0,ZOUT,IFAIL)
ZEB=ZCORN
ZEM=ZOUT

C COMPUTING LIP AND FLUTE SURFACE
DO 38 I=1,NPOINT-1
II=i
NLIP=i
II=I
Z=ZOUT-FLOAT(I-1)*(ZOUT-ZCORN)/FLOAT(NPOINT-1)
38 ALPHAI=R0*DSIN(H0)/DCOS(H0)
ZSTG(I)=Z
ZSTGD(I)=Z
IF(S.EQ.1.)GO TO 30
CALL C05ACF(RSTAN1,RSTAN2,EP,EV,FUN,RSTAN,IFAIL)
GO TO 32
30 CALL C05ACF(RSTAN,RSTAN2,EP,EV,FAN,XST,IFAIL)
YST=0.
DO 75 J=1,NCOEF
YST=YST+COEF(J)*XST**(J-1)
75 CONTINUE
GO TO 34
C

32 W2=WEB/2./RSTAN
PHST=(RSTAN/WR)/DSQRT(1.-W2**2))+DSQRT(RSTAN**2-(WEB/2.)**2
*SUSIN(H0)/DCOS(H0)*R0*CSKOI/SNKOI
XFLU(I)=RSTAN*DCOS(PHST)
YFLU(I)=RSTAN*DSIN(PHST)
XFLUD(I)=RSTAN*DCOS(PHST)
YFLUD(I)=RSTAN*DSIN(PHST)
IF(I.EQ.1.)XFLUEE=RSTAN*DCOS(PHST)
IF(I.EQ.1.)YFLUEE=RSTAN*DSIN(PHST)
PHST=PHST+ALPHA
XST=RSTAN*DCOS(PHST)
YST=RSTAN*DSIN(PHST)
XSTGD(I)=XST
YSTGD(I)=YST
ZSTG(I)=Z
ZSTGD(I)=Z
ZED=ZCORN
ZEM=ZOUT
C

RRN(I)=RSTAN
RADI(I)=RSTAN
GO TO 36
C

34 RSTAN=DSQRT(XST**2+YST**2)
XFLU(I)=XST
YFLU(I)=YST
XFLUD(I)=XST
YFLUD(I)=YST
IF(I.EQ.1.)XFLUEE=XST
IF(I.EQ.1.)YFLUEE=YST
RRN(I)=RSTAN
RADI(I)=RSTAN
PHST=DATAN(YST/XST)
PHST=PHST+ALPHA
XST1=RSTAN*DCOS(PHST)
YST1=RSTAN*DSIN(PHST)
XSTGD(I)=XST1
YSTGD(I)=YST1
GO TO 36
C

36 CONTINUE
C

CALL GRIN(Z,ZA,AXX,AYY,CXY,EY,FF)
C VECTOR NORMAL TO FLANK POINT - POINTING OUT
DFDX2=2.*XST*AXX+YST*CXY+DDX
DFDY2=2.*YST*AYY+CXY*XST+EY
DFDZ2=XST*-(2.*SNKOI*CSKOI*SNVG)+YST*-(2.*SNKOI*CSKOI*CSVG)+SNKor**2.*2.*XST*SNVG
DFZ=DSQRT(DFDX2**2+DFDY2**2+DFDZ2**2)
DFDX=DFDX/DF
DFDY=DFDY/DF
DFDZ=DFDZ/DF
IF(DFDX.GT.A.BL)GO TO 40
DFDX=-DFDX
DFDY=-DFDY
DFDZ=-DFDZ
C VECTOR ON THE FLANK AND NORMAL TO RADIUS
C POINTING IN VELOCITY DIRECTION
40 U1=DCOS(PHST)
U2=DSIN(PHST)
U3=0.
XFLNR=1.
YFLNR=U1/UR2*XFLNR
ZFLNR=(-XFLNR*DFDX-YFLNR*DFDY)/DFDZ
PLANR=DSQRT(XFLNR**2+YFLNR**2+ZFLNR**2)
XFLNR=XFLNR/PLANR
YFLNR=YFLNR/PLANR
ZFLNR=ZFLNR/PLANR
IF(YFLNR.GT.0.)GO TO 160
XFLNR=-XFLNR
YFLNR=-YFLNR
ZFLN=N-ZFLN
C VECTOR TANGENT TO THE FLUTE AT Z=ZSTGFL(I)
C POINTING OUT
160 CONTINUE
NDER=1
IF(S .EQ. 1.)GO TO 130
CALL D64AAP(RSTAN,NDER,HBASE,DER,EREST,FON,IPFAIL)
DYDX=DSIN(PHST)/DCOS(PHST)+RSTAN*DER(1)
DYDX=1.-RSTAN*DER(1)*DSIN(PHST)/DCOS(PHST)
DYDX=DYDX/DYDX
GO TO 140
130 XST=XFLUC(I)
YST=YFLU(I)
CALL D64AAP(XST,NDER,HBASE,DER,EREST,FIN,IPFAIL)
OYOXN2DSIN(PHST)/OCOS(PHST)+RSTAN*DER(1)
DYDX=DYDX/DYDX
GO TO 140
140 OYOXN=DATAN(DYOX)
XTG=OCOS(DYDXN)
YTG=OSIN(DYDXN)
ZTG=0.0
DERIV(I)=DYDXN/CONS
IF(XTG .GT. 0.0)GO TO 120
XTG=-XTG
YTG=-YTG
C VECTOR TANGENT TO THE HELIX POINTING UPWARDS
C ALSO HELIX ANGLE
120 XTCH=D SIN(PHST)
YTC=DCOS(PHST)
COTH=R3/RSTAN*DCOS(H0)/DSIN(H0)
XC=DSQRT(XTCH**2+YTC**2+COTH**2)
XTCH=XTCH/XC
YTC=YTC/XC
XTG=XTG/YTC
YTG=YTG/XTC
ZTG=COTH/XTCH
ZTGH=ZTGH/CONS
C VECTOR TANGENT TO THE HELIX POINTING UPWARDS
C ALSO HELIX ANGLE
2TGH1=DSQRT(1.-2TGH**2)
2TGHG(I)=DATA(2TGH1/2TGH)/CONS
C VECTOR NORMAL TO RAKE FACE
C POINTING UPWARDS
XNRA=YTG*2TGH
YNRA=XTG*2TGH
ZNRA=XTG*YTGH*XTC
YZN=XTG/XTC
XZ=XTG/XTC
YNN=YNRA/YNRA
ZNN=ZNRA/ZNN
IP(ZNRA .LT. 0.0)WRITE(L,45)
45 FORMAT(/'NORMAL TO RAKE FACE POINTING DOWNWARDS'/)
XNRA(I)=XNRA
YNRA(I)=YNRA
ZNRA(I)=ZNRA
C VECTOR TANGENT TO THE LIP
C POINTING TO THE OUTER CORNER
CE1=YNRA*DFDX-2NRA*DFDY
CE2=ZNRA*DFDY-YNRA*DFDX
CEE=DSQRT(CE1**2+CE2**2+CE3**2)
CE1=CE1/CEE
CE2=CE2/CEE
CE3=CE3/CEE
C
CCE1(I)=CE1
CCE2(I)=CE2
CCE3(I)=CE3
CCE3=DSQRT(1.-CE3**2)
CCE3P(I)=DATA(CCE3/CCE3)/CONS
IF(CCE(I) .LT. 0.0)CALL EXIT
C VECTOR ON THE RAKE FACE, NORMAL TO THE CUTTING EDGE
C POINTING IN THE VELOCITY DIRECTION
XTRA=1.
CSTA=-(YNRA*CE2-2YNRA*CE3)/(2NRA*CE2)
CSTA2=-(YNRA*XTRA*CE1-2YNRA*XTRA*CE2)/(2NRA*CE2)
XTRA=CE2*CE2/XTRA2/XTRA1
YTRA=-(2NRA*CE2-2YNRA*CE1)/CE2
TRA=DSQRT(XTRA**2+YTRA**2+ZTRA**2)
XTRA=XTRA/TRA
YTRA=YTRA/TRA
ZTRA=ZTRA/TRA
IF(YTRA .LT. 0.0)GO TO 55
XTRA=-XTRA
YTRA=-YTRA
ZTRA=-ZTRA
C ANGLE BETWEEN THE TANGENT TO THE HELIX AND THE
C NORMAL TO THE CUTTING EDGE ON THE RAKE FACE
55 AFLO1=XTGH*XTRA+YTGH*YTRA+ZTGH*ZTRA
AFLO2=DSQRT(1.-AFLO1**2)
HENR(I)=DATAN(AFLO1/AFLO2)/CONS
C VECTOR ON THE FLANK POINT, NORMAL TO THE CUTTING EDGE
C POINTING IN THE VELOCITY DIRECTION
XTFLA=1.
CZTRA1=(DFDZ*CE2-DFDY*CE3)/(DFDZ*CE2)
CZTRA2=(DFDY*XTFLA*CE1-DFDX*XTFLA*CE2)/(CE2*DFDZ)
XTFLA=CE2*XTFLA/CE2
YFLA=-(2TFLA*CE3-XTFLA*CE1)/CE2
FLA=DSQRT(XTRA**2+YTRA**2+ZTRA**2)
XTFLA=XTFLA/FI
YFLA=YFLA/FI
ZTFLA=ZTFLA/FI
IF(YFLA .LT. 0.0)GO TO 60
XTRA=-XTRA
YTRA=-YTRA
ZTRA=-ZTRA
C VECTOR NORMAL TO THE MACHINED SURFACE
C POINTING UPWARDS
VV1=2.0*PI*RP.M/60.*RSTAN*DSIN(PHST)
VV2=2.0*PI*RP.M/60.*RSTAN*DCOS(PHST)
VV3=25.4/PI*RP.M/60.
VV=DSQRT(VV1**2+VV2**2+VV3**2)
VVD(I)=VV
VV1=VV1/VV
C VECTOR ON THE MACHINED SURFACE
C NORMAL TO VELOCITY AND POINTING UPWARDS
88 XTSU1=CTU1*XTSU*YMSU1+U2-XTSU*U1*YMSU1
CTU2=YMSU1*U2-ZMSU1*U1
ZTSU=CTU1/CTU2
YTSU=(XTSU*YMSU1+ZTSU*ZMSU1)/YMSU1
ZTSU=DSQRT(XTSU**2+YTSU**2+ZTSU**2)
XTSU=XTSU/CTU3
YTSU=YTSU/CTU3
ZTSU=ZTSU/CTU3
IF (ZTSU.CT. 0.0) GO TO 111
XTSU=-XTSU
YTSU=-YTSU
ZTSU=-ZTSU
C INCLINATION ANGLE
111 COSI=U1*CE1+U2*CE2
SINI=DSQRT(1.-COSI**2)
AIN=DATAN(SINI/COSI)
AIN=PI/2.-AIN
AINC(I)=AIN/CONS
C NORMAL RAKE ANGLE
COSRA=XVCE*XTRA+YVCE*YTRA+ZVCE*ZTRA
SINR=DSQRT(1.-COSRA**2)
SIGN1=XVCE*XTRA+YVCE*YTRA+ZVCE*ZTRA
SIGN2=OABS(SIGN1)
SIGN1=SIGN2/SIGN2
RAK=DATAN(SINR/COSRA)
RAK=SIGN*RAK
RAKE(I)=RAK/CONS
8867 ETA=DATAN(I./(DCOS(RAK)+DSIN(RAK))*DSIN(AIN)/DCOS(AIN))
8869 ETAS(I)=ETA/CONS
RN=RSN
IF (1 .EQ. 1) GO TO 498
DL(I)=0.
DL(I)=DSQRT((XTGD(I)-XTGD(I-1))**2+(YSTGD(I)-YSTGD(I-1))**2+(ZSTGD(I)-ZSTGD(I-1))**2)
SS=SS+DL(I)
SSS(I)=SS
498 RESQ=RSTAN
C CHIP COMPUTATION
C READ CHIP AXIS TO A GUESS
WRITE(1,119)
FORMAT('READ XEB,YEB,XEM,YEM,RCl')
READ(1,*XEB,YEB,XEM,YEM,RCl)
C VECTOR ON THE MACHINED SURFACE
C POINTING IN THE VELOCITY DIRECTION
XNMSU=-(U2*CE3+U3*CE2)
YNMSU=-(U3*CE1+U1*CE3)
ZNMSU=-(U1*CE2+U2*CE1)
SU=DSQRT(XNMSU**2+YNMSU**2+ZNMSU**2)
XNMSU=XNMSU/SU
YNMSU=YNMSU/SU
ZNMSU=ZNMSU/SU
C VECTOR NORMAL TO CUTTING EDGE AND VELOCITY
20 UU1=DSIN(PHST)
UU2=DCOS(PHST)
XVCE=1.
YVCE=-UU1/UU2*XVCE
ZVCE=(U2*CE2-YVCE)*CE3/CNMSU
VCE=DSQRT(XVCE**2+YVCE**2+ZVCE**2)
X=U1*XVCE/VCE
Y=U2*YVCE/VCE
Z=U3*ZVCE/VCE
IF (VCE.CT. 0.0) GO TO 110
XVCE=-XVCE
YVCE=-YVCE
ZVCE=-ZVCE
C CHIP COMPUTATION
110 XMSU1=-U2*CE3+U3*CE2
YMSU1=-U3*CE1+U1*CE3
ZMSU1=-U1*CE2+U2*CE1
SU1=DSQRT(XNMSU1**2+YNMSU1**2+ZNMSU1**2)
XNMSU1=XMSU1/SU1
YNMSU1=YMSU1/SU1
ZNMSU1=ZMSU1/SU1
C CHIP COMPUTATION
C READ CHIP AXIS TO A GUESS
WRITE(1,119)
FORMAT('READ XEB,YEB,XEM,YEM,RCl')
READ(1,*XEB,YEB,XEM,YEM,RCl)
WRITE(1,709)
709 FORMAT('READ CHIP LEAD AND CHIP DIAMETER')
READ(1,*,PA,RCH)
NL0=FIX(FLOAT(NPOINT)/3.)
EIX(1)=XEB
EIX(2)=YEB
EIX(3)=XEM
EIX(4)=YEM
N=8
LJ=8
LV=4
LW=120
IFAIL=0
MAXCAL=1000
WRITE(1,817)
817 FORMAT('READ IPRANT,STEP,XTOL AND ETA')
READ(1,*)IPRANT,STEP,XTOL,ETA

CALL E04FCF(M,N,RESAD,MONAT,IPRANT,MAXCAL,ETA,XTOL,STEP,EIX,FE,RE,FJAC,W,SMON,V,LV,NITER,UF,LW,IFAIL)
WRITE(1,819)XEB,YEB,ZEB,XEM,YEM,ZEM
819 FORMAT('XEB=',F10.5,'YEB=',F10.5,'ZEB=',F10.5,'XEM=',F10.5,'YEM=',F10.5,'ZEM=',F10.5)

DO 810 I=1,NPOINT
SEN0I=OSIN(AINC(I)*CONS)
CE1=CCE1(I)
CE2=CCE2(I)
CE3=CCE3(I)
XST=XSTGD(I)
YST=YSTGD(I)
ZST=ZSTGD(I)
PHI0=OATAN(YST/XST)
XNRA=-XNRAD(I)
YNRA=-YNRAD(I)
ZNRA=-ZNRAD(I)
XMSU=XMSU(I)
YNMSU=YMSU(I)
ZNMSU=ZMSU(I)

C COMPUTATION FOR CHIP VELOCITY
DBM=DSQRT((XEM-XEB)**2+(YEM-YEB)**2+(ZEM-ZEB)**2)
AAA=(XEM-XEB)/DBM
BBB=(YEM-YEB)/DBM
CCC=(ZEM-ZEB)/DBM
REVB=3.
WAA=2.*PI*REVB
V1=REVB*PA
ABC1=BBB*(ZST-ZEM)-CCC*(YST-YEM)
ABC2=CCC*(XST-XEM)-AAA*(YST-YEM)
ABC3=AAA*(YST-YEM)-BBB*(XST-XEM)
VC1=AAX*V1+WAA*ABC1
VC2=BBB*V1+WAA*ABC2
VC3=CCC*V1+WAA*ABC3
VC=DSQRT(VC1**2+VC2**2+VC3**2)
VC1=VC/VC
VC2=VC2/VC
VC3=VC3/VC
V1=2.*PI*RAN(I)
VVC=VC/VV
IF(ABC1.LE.0.8) GO TO 9148
WRITE(1,9149)
9149 FORMAT( 'ABC1 IS NUL')
CALL EXIT
C FINDING CHIP RADIUS AT EACH POINT OF THE LIP
9150 ZEXEAC=-ABC3/ABC1*AAA+BBB
YEXEAB=-ABC2/ABC1*AAA+BBB
ZEXEAC=-ABC3/ABC1*AAA+BBB
ZEXEAC=-ABC3/ABC1*AAA+BBB

C COMPUTATION FOR CHIP FLOW ANGLE
HC=DATAN(2.*PI*RC/PA)
C VERIFICATION FOR ETA
SENETA=VC1*CE1+VC2*CE2+VC3*CE3
COSETA=DSQRT(1.-SENETA**2)
TGETA=SENETA/COSETA
ETA=DATAN(TGETA)/CONS
T2A=DCOS(AINC(I)*CONS)/VVCV/COSETA
T211(I)=T2A
I
VERIF1=VC1*YHRA
VERIF2=VC2*YHRA
VERIF3=VC3*ZIRA
C COSV=VERIF1+VERIF2+VERIF3
VER=DATAN(DSQRT(1.-COSV**2)/COSV)
VER=PI/2.-VER/CONS
IF(VER .GT. 90.)VER=VER-180.
VERIF(I)=VERI
VERIG(I)=VERI
AKCD(I)=AKC/CONS
GEMEA(I)=GEME
HCD(I)=HC/CONS
ETARIG(I)=ETACH
C ETAA(I)=ETA
RCA(I)=RC
RCAG(I)=RC
GAME(I)=GAME
VVCA(I)=VVCV
810 CONTINUE
C [REL]=
DO 735 I=1,NPOINT
T2PR(I)=T211(I)/T211(IREL)
TIPR(I)=VVC(I)/VVCA(IREL)
735 CONTINUE
GO TO (715,716), IEI
715 CALL AXISCA(2,12,.0.68,.1)
GO TO 717
716 CALL AXISCA(2,18,.0,.88,.1)
717 CONTINUE
CALL AXISCA(2,18,.0,.98,.2)
CALL AXIDRA(2,1.1)
CALL AXIDRA(-2,-1.2)
C
GO TO (718,719), IEI
718 CALL GRACUR(AINC,ETARIG,NPOINT)
CALL GRAMOV(0.,0.)
CALL BROKEN(1)
CALL GRALIN(AINC(NPOINT),AINC(NPOINT))
CALL CHAMOD
C
GO TO 720
719 CALL GRACUR(CEL,ETARIG,NPOINT)
CALL BROKEN(1)
CALL GRACUR(CEL,AINC,NPOINT)
CALL CHAMOD
720 CONTINUE
READ(1,*)SEPARA
WRITE(1,713)
713 FORMAT(/'MORE GRAPHS ?')
READ(1,*)IGR
IF(IGR .NE. 0) GO TO 738
C
2331 WRITE(1,2032)
2032 FORMAT(/'SECTIONS ON A ROTATING PLANE FOR INTERF ?')
READ(1,*)ISEPAR
IF(ISEPAR .EQ. 0) GO TO 109
109 CONTINUE
WRITE(1,712)
712 FORMAT(/'CHANGE CHIP DATA ?')
READ(1,*)ICH
IF(ICH .NE. 0) GO TO 708
708 CONTINUE
READ(1,2033)
2033 FORMAT(/'READ ROTATION OF THE PLANE ') READ(1,*)HOT
PHIC1=45.*CONS
PHIC2=89.*CONS
C
EPS=1E-8
EPV=1E-8
IFAIL=0
C
COORDINATES TRANSFORMATION
C TRANSFORMATION MATRIX
A(1,1)=AAA
A(2,1)=BBB
A(3,1)=CCC
A(2,2)=1.
C
A(1,2)=A(2,1)*A(2,2)/A(1,3)
A(3,2)=0.
AT=DSQRT(1.+A(1,2)**2+A(3,2)**2)
C
A(1,2)=A(1,2)/AT
A(2,2)=A(2,2)/AT
A(3,2)=A(3,2)/AT
C
A(1,1)=1.
A(2,1)=A(1,1)*A(2,1)/A(2,2)
A(3,1)=A(1,1)*A(3,1)/A(3,2)
C
ATT=DSQRT(A(1,1)**2+A(2,1)**2+A(3,1)**2)
C
A(1,1)=A(1,1)/ATT
A(2,1)=A(2,1)/ATT
A(3,1)=A(3,1)/ATT
C
DCOORD(K)=YSTGD(K)-YEB
DCOORD(2)=ZSTGD(1)-ZEB
XSTAR=0
YSTAR=0
ZSTAR=0
C
DO 102 K=1,3
XSTAR=XSTAR+A(K,1)*DCOORD(K)
YSTAR=YSTAR+A(K,2)*DCOORD(K)
ZSTAR=ZSTAR+A(K,3)*DCOORD(K)
102 CONTINUE
C
IF(XSTAR .EQ. 0 .AND. YSTAR .GT. 0) PHSTAR=PI/2.
IF(XSTAR .EQ. 0 .AND. YSTAR .LT. 0) PHSTAR=-PI/2.
C
IF(XSTAR .EQ. 0) GO TO 808
C
PHSTAR=DATAN(YSTAR/XSTAR)
IF(PHSTAR .LT. 0 .AND. YSTAR .GT. 0) PHSTAR=PI+PHSTAR
IF(PHSTAR .GT. 0 .AND. YSTAR .LT. 0) PHSTAR=-(PI-PHSTAR)
C
RSTAR=DSQRT(XSTAR**2+YSTAR**2)
C
PHROT=PHSTAR+ROT*CONS
XROT=ROCCHIP*DCOS(PHROT)
YROT=ROCCHIP*DSIN(PHROT)
ZROT=ZSTAR+(PHROT-PHSTAR)*ROCCHIP*DCOS(ROCCHIP)/DSIN(ROCCHIP)
CAAR(1)=XROT
CAAR(2)=YROT
CAAR(3)=ZROT
C
XOUTR=0.
YOUTR=0.
ZOUTR=0.
DO 1 I=1,3
XOUTR=XOUTR+A(I,1)*CAAR(I)
C
PHLOS=PHSTAR+HOT*CONS
XROT=ROCHIP*DCOS(PHLOS)
YROT=ROCHIP*DSIN(PHLOS)
ZROT=ZSTAR+(PHLOS-PHSTAR)*ROCHIP*DCOS(ROCHIP)/DSIN(ROCHIP)
CAAR(1)=XROT
CAAR(2)=YROT
CAAR(3)=ZROT
C
XOUTR=0.
YOUTR=0.
ZOUTR=0.
DO 1 I=1,3
XOUTR=XOUTR+A(I,1)*CAAR(I)
YOU3R=YOU3R+A(2.I)*CAAR(I)
YOU3R=YOU3R+A(3.I)*CAAR(I)
CONTINUE
C XOUTR=XOUTR+XEB
YOUTR=YOUTR+YE3
ZOUTR=ZOUTR+ZEB
C COEA=BBB*(YOU3R-ZEH)-CCC*(YOU3R-YEH)
COEB=CCC*(YOU3R-XEH)-AAA*(ZOUTR-ZEM)
COEC=AAA*(YOU3R-YEH)-BBB*(XOUTR-XEM)
COED=-XEM*COEA-YEM*COEB-ZEM*COEC
CONTINUE
XOUTR=XOUTR+XEB
YOUTR=YOUTR+YE3
ZOUTR=ZOUTR+ZEB
C YOUTR=YOUTR+A(2,I)*CAAR(I)
ZOUTR=ZOUTR+A(4.I)*CAAR(I)
CONTINUE
XOUTR=XOUTR+XEB
YOUTR=YOUTR+YE3
ZOUTR=ZOUTR+ZEB
C COEA=BBB*(YOU3R-ZEH)-CCC*(YOU3R-YEH)
COEB=CCC*(YOU3R-XEH)-AAA*(ZOUTR-ZEM)
COEC=AAA*(YOU3R-YEH)-BBB*(XOUTR-XEM)
COED=-XEM*COEA-YEM*COEB-ZEM*COEC
CONTINUE
DO 2834 I=1,NPOINT
DCOOR(I)=XSTCD(I)-XEB
DCOOR(2)=YSTCD(I)-YEB
DCOOR(3)=ZSTGD(I)-ZEB
XSTAR=.0
YSTAR=.0
ZSTAR=.0
DO 826 K=1,3
XSTAR=XSTAR+A(K,I)*DCOOR(K)
YSTAR=YSTAR+A(K,2)*DCOOR(K)
ZSTAR=ZSTAR+A(K,3)*DCOOR(K)
CONTINUE
IF(XSTAR.EQ.0.AND. YSTAR.GT.0)PHSTAR=PI/2.
IF(XSTAR.EQ.0.AND. YSTAR.LT.0)PHSTAR=-PI/2.
IF(XSTAR.EQ.0)GO TO 827
PHSTAR=DATAN(YSTAR/XSTAR)
IF(PHSTAR.LT.0.AND. YSTAR.GT.0)PHSTAR=PI+PHSTAR
IF(PHSTAR.GT.0.AND. YSTAR.LT.0)PHSTAR=(PI-PHSTAR)
RSTAR=DSQRT(XSTAR**2+YSTAR**2)
DZ=(PHROT-PHSTAR)*RCHIP*DCOS(HCHIP)/DSIN(HCHIP)
ZSTAR=ZSTAR+DZ
ZRIGG(I)=ZSTAR
RPACE=DSQRT(XSTGD(I)**2+YSTGD(I)**2)
PHPA=DATAN(YSTGD(I)/XSTGD(I))
WRITE(1,1701)
2PASTE=1701
CALL CBSACF(PHPAC1,PHPAC2,EPF,EPV,GPACE,GPAEC,IFAIL)
DCOOR(I)=XPACE-XEB
DCOOR(2)=YPACE-YEB
DCOOR(3)=ZPACE-ZEB
XSTAR=.0
YSTAR=.0
ZSTAR=.0
DO 828 K=1,3
XSTAR=XSTAR+A(K,1)*DCOOR(K)
YSTAR=YSTAR+A(K,2)*DCOOR(K)
ZSTAR=ZSTAR+A(K,3)*DCOOR(K)
CONTINUE
RSTO(I)=RSTOR
IF(I.GT.1.AND. RSTO(I).GT.RSTO(I-1))RSTO(I)=-RSTO(I)
XPACG(I)=XSTAR
YPACG(I)=YSTAR
ZPACG(I)=ZSTAR
CONTINUE
IF(IGRAPH.EQ.1)GO TO 737
WRITE(I,940)
FORMAT('IF GRAPHICS ONLY, READ 1')
READ(I,*)IGRA
IF(IGRA.EQ.1)GO TO 935
C TABLES
WRITE(1,1887)
FORMAT(3X,'SS ',3X,' X ',3X,' Y ',3X,' Z ',3X,'XFLU',
DO 41 J=1,NPOINT
READ(J,3)SEPARA
WRITE(1,92)SS(J),XSTG(J),YSTG(J),ZSTG(J),XFLU(J),YFLU(J)
$AISC(J),RAKE(J),GAMN(J),ETAS(J)
FORMAT(18F7.2)
41 CONTINUE
READ(I,*)SEPARA
WRITE(1,722)
722 FORMAT(//3X,'XNRA',3X,'YNRA',3X,'ZNRA'//)
DO 723 I=1,NPOINT
ANRA=ANRA-ATAN(SQRT(1.-XNRAD(I)**2)/XNRAD(I))/CONS
AYNRA=AYNRA-ATAN(SQRT(1.-YNRAD(I)**2)/YNRAD(I))/CONS
AZNRA=AZNRA-ATAN(SQRT(1.-ZNRAD(I)**2)/ZNRAD(I))/CONS
WRITE(1,724)ANRA,AYNRA,AZNRA
723 CONTINUE
724 FORMAT(3F7.2)
WRITE(1,7001)
7001 FORMAT(///'VERIF X SSS'///)
READ(I,*)IVER
IF(IVER.EQ.1)GO TO 70A2
RSP=1.2*K0
IRP=80
IRP=180
AXAXIS=120
CALL SC281
CALL PICCLE
CALL WINDO(2)
CALL AXIPOS(0.50.,120.,110.,1)
CALL AXIPOS(0.50.,170.,100.,2)
CALL AXISCA(2.180.,0.,45.,1)
CALL AXISCA(2.16.,-40.,48.,2)
C GRAPHICS
WRITE(1,886)
886 FORMAT(///'GRAPHICS FOR CHIP ?'///)
READ(I,*)IGRAF
IF(IGRAF.EQ.0)GO TO 815
935 CONTINUE
C =---------------------------------------------------------------C GRAPHICS
C =---------------------------------------------------------------C GRAPHICS
CALL AXIDRA(2.1,1)
CALL AXIDRA(-2,-1.2)
CALL GRACUR(CEL,VERIG,NPOINT)
CALL CHAMOD
READ(1,*),SEPARA
WRITE(1,805)
805 FORMAT('/CHIP INTERFERENCE ? '/)
READ(1,*),INTE
IF(INTE.EQ.0) GO TO 112
WRITE(1,713)
713 FORMAT('/READ XFACT AND YFACT '/)
READ(1,*)XFACT,YFACT
XAXIS=XFACT*S0.
YAXIS=YFACT*S0.
R0P=R0+1.
IR0=R0P
R0P=IR0
CALL SE281
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0.40.,100.,120.,1)
CALL AXIPOS(0.40.,100.,120.,2)
CALL AXISCA(2,IR0,0.,R0P,1)
CALL AXISCA(2,21.1,2)
CALL AXIDRA(-2,-1.2)
C
DO NOT PLOT AXES
C
737 CONTINUE
C
WRITE(1,106)
106 FORMAT('/MORE ROTATING SECTIONS ?'/)
READ(1,*),IROT
IF(IROT.EQ.1) GO TO 107
WRITE(1,112)
112 FORMAT('/RELATIVE CUTTING RATIO ?'/)
READ(1,*),IRELCR
IF(IRELCR.EQ.0) GO TO 815
R0P=R0P+1.
IR0=IR0
R0P=IR0
CALL SE281
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(0.40.,100.,130.,1)
CALL AXIPOS(0.40.,100.,130.,2)
CALL AXISCA(2,IR0,0.,R0P,1)
CALL AXISCA(2,21.1,2)
CALL AXIDRA(2,1,1)
CALL AXIDRA(-2,-1.2)
C
737 CONTINUE
C
CHANGE PEN COLOUR
CALL PENS(2,3,4)
CALL GRAPOL(RSTO(I),ZPACG(I),NPOINT)
CALL GRACUR(CEL,ZPACG,NPOINT)
CALL DASHED(2,6.,3.,5)
CALL GRAMOV(-.2,-.2)
CALL GRALIN(-.2,-.2)
CALL BROKEN(I)
CALL CHAMOD
C
READ(1,*),SEPARA
WRITE(1,815)
815 FORMAT('/ZCHI=20-DSQRT((2.*R0G)**2-EXG**2)/SNKOI**2)
DO 580 I=1,NPOINT
580 ZCHI(I)=ZCHI(I)+5.*(ZCHI(I)-ZPACG(I))
CONTINUE
WRITE(1,1965)
1965 FORMAT('/RCHISE(I)=DSQRT(ZCHI(I)**2+YCHI(I)**2)')
FORMAT('LOOP 588 FINISHED')

CHEEL CORNER ELEVATION

PHII = DATA(YSTGO(1)/XSTGO(1))

1FL = 0.1

CALL CS5ACP(ZCLE1, ZCLE2, EPS, EPV, FLANK, ZCLE, IFAIL)

C

4

CALL CS5ACP(ZCLE1, ZCLE2, EPS, EPV, FLANK, ZCLE, IFAIL)

CONTINUE

CONTINUE

IF (IYLN .EQ. 1) GO TO 7017

RHEEL = 8*R0

RHEEL = 1.1*R0

7017 CALL CS5ACP(RHEEL1, RHEEL2, EPS1, EPV1, FLANK, RHEEL, IFAIL)

RHEEL = 8*RHEEL

RHEEL = 1.2*RHEEL

IF (IFAIL .LT. WEB/2.) RHEEL = WEB/2.

C

XHEEL (1) = XSTEE1

YHEEL (1) = YSTEE1

ZHEEL (1) = ZSTEE1

XHEEL (1) = XSTEE1

YHEEL (1) = YSTEE1

ZHEEL (1) = ZSTEE1

ZHEEL (1) = ZSTEE1

YHEEL (1) = YSTEE1

YHEEL (1) = YSTEE1

YHEEL (1) = YSTEE1

CONTINUE

CONTINUE

READ(I, *) NEX, NEX, NEX

CALL EA2ACF(XHSTFL, YHSTFL, NEX, COFL, NEX, REF1)

DO 7000 I = 1, NPOINT

Z = ZCLEE - (ZCLEE - ZCORN)/FLOAT(NPOINT - 1)

ALPHA = Z/R0*DSIN(H0)/DCOS(H0)

IF (I .NE. 1) GO TO 7014

RHEEL = 3

RHEEL = R0

CALL CS5ACP(RHEEL1, RHEEL2, EPS1, EPV1, FEEL, XEEL, IFAIL)

RHEEL = XEEL

RHEEL = YSTEE1

XHEEL (1) = XSTEE1

YHEEL (1) = YSTEE1

ZHEEL (1) = ZSTEE1

XHEEL (1) = XSTEE1

YHEEL (1) = YSTEE1

ZHEEL (1) = ZSTEE1

XHEEL (1) = XSTEE1

YHEEL (1) = YSTEE1

YHEEL (1) = YSTEE1

CONTINUE

CONTINUE

READ(I, *) SEPARA

ALPHA = OUT/R0*DSIN(H0)/DCOS(H0)

PHC = DATAN(YC0/XC0)

PHC = PHC + ALPHA

RXYC0 = DSQRT(XC0**2 + YC0**2)

ZEM = ZOUT

XEM = RXYC0*DCOS(PHC)

YEM = RXYC0*DSIN(PHC)

XC0 = XEM

YC0 = YEM

GO TO 7044

7000 CONTINUE

GO TO 7022

C

FUNCTIONS AND SUBROUTINES

C

FUNCTION FAN(XST)

IMPLICIT DOUBLE PRECISION(A-H,O-Z)

DIMENSION COEF(28)

COMMON/BLO1/R0, RG, WEB, H0, RKG

COMMON/BLO2/CONS, RACAM, EIG, VG

COMMON/BLO3/ALPHA, CSVG, SNVG, CKSO1, SNKO1, CSKOU, SNKOU

COMMON/BLO4/2, 20, ZNH

COMMON/BLO6/COEF, NCOEF, IIY, IYO

C

IF (IYLN .EQ. 1) WRITE(1,71)III

71 FORMAT(5X,14,'TH STEP IN COURSE (FUNCTION FAN)')
CALL GRIN(Z,Z0,AXX,BYX,CXY,DDX,EY,FF)
YST=0.0
DO 70 J=1,NCOEF
YST=YST+COEF(J)*XST**(J-1)
CONTINUE
PHST=DATAN(YST/XST)
RSTAN=DSQRT(XST**2+YST**2)
PHST=PHST+ALPHA
XST1=RSTAN*DCOS(PHST)
YST1=RSTAN*DSIN(PHST)

FUNCTION FEEL(XEEL)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20),COEEL(3),COFL(40)
COMMON/BLO1/R0,R0G,WEB,H0,RKG
COMMON/BL02/CONS,RCAM,EXG,VG
COMMON/BL03/ALPHA,CSVG,SNVG,CSKOI,SNKOI,CSKOU,SNKOU
COMMON/BL04/Z,Z0,ZHH
COMMON/BL05/S,NPOINT,NLAAP,ISEC
COMMON/BL06/COEF,NCOEF,III,IYN,IYO
COMMON/BLO8/XFLUEE,YFLUEE,DMAR,XSTEEL,YSTEEL,DPHEEL,YEEL
COMMON/BLO11/COFL,NSTFLI
PI=3.14159265
IF(IYO.EQ.1) WRITE(I,71) III
71 FORMAT(5X,I4,'TH STEP IN COURSE (FUNCTION FEEL)')

CALL GRIN(Z,Z0,AXX,BYX,CXY,DDX,EY,FF)
YEELDY+COEF(2)
IF(S.EQ.1) YEELDY=0.
XEEL1=WEB/2.
YEEL1=-YEEL
XEEL2=-XELLE
YEEL2=-YELLE
PHEEL=DATAN(YEEL2/XEEL2)
PHIL=PHEEL+DPHEEL
XELLE2=DSQRT(XEEL2**2+YEEL2**2)*DCOS(PHIL)
YEEL2=DSQRT(XEEL2**2+YEEL2**2)*DSIN(PHIL)
COEL(1)+YEEL1
COEEL(2)=YEELD
COEEL(3)=(YEEL2-XEEL2*COEEL(2)-COEEL(1))/XEEL2**2
IF(XEEL.EQ.0.0) GO TO 1
IF(S.EQ.1 .AND. XEEL.LT. 0.) GO TO 5
YEEL=0.

FUNCTION FIEL(RHEEL)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20),COEEL(3),COFL(40)
COMMON/BLO1/R0,R0G,WEB,H0,RKG
COMMON/BL02/CONS,RCAM,EXG,VG
COMMON/BL03/ALPHA,CSVG,SNVG,CSKOI,SNKOI,CSKOU,SNKOU
COMMON/BL04/Z,Z0,ZHH
COMMON/BL05/S,NPOINT,NLAAP,ISEC
COMMON/BL06/COEF,NCOEF,III,IYN,IYO
COMMON/BLO8/XFLUEE,YFLUEE,DMAR,XSTEEL,YSTEEL,DPHEEL,YEEL
COMMON/BLO11/COFL,NSTFLI
COMMON/BLO17/XEELA,YEELA,2WEB
PI=3.14159265

CALL GRIN(Z,Z0,AXX,BYX,CXY,DDX,EY,FF)
W2R=WEB/2./RHEEL
IF(RHEEL.LT.WEB/2.) GO TO 1
ANG=DATAN(W2R/DSQRT(1.-W2R**2))
PHST=ANG+DSQRT(RHEEL**2-(WEB/2.)**2)*DSIN(ANG)/DCOS(ANG)/R0
*$CKOU/SNKOU

RETURN

END
IF(Z \lt ZWEB) PHST = PI-PHST
GO TO 1

PHST = PI/2.
XEELA = RHEEL*DCOS(PHST)
YEELA = RHEEL*DSIN(PHST)

PHST = PHST + ALPHA
XST1 = RHEEL*DCOS(PHST)
YST1 = RHEEL*DSIN(PHST)
XSTEL = XST1
YSTEL = YST1

FINL = AXX*XST1**2+BYY*YST1**2+CXY*XST1*YST1+ODX*XST1
       +EY*YST1+FF
RETURN
END

FUNCTION FIN(XST)

IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20)
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
COMMON/BLO6/COEF,NCOEF,III,IYN,IYO
YST = '0.
150 CONTINUE

PHEST = DATAN(YST/XST)
RSTAN = DSQRT(XST**2+YST**2)
PHST = PHST + ALPHA
XST1 = RSTAN*DCOS(PHST)
YST1 = RSTAN*DSIN(PHST)
FINL = AXX*XST1**2+BYY*YST1**2+CXY*XST1*YST1+ODX*XST1
       +EY*YST1+FF
RETURN
END

FUNCTION FLANK(ZCLE)

IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20)
COMMON/BLO1/R0, R0G, WEB, H0, RKG
COMMON/BLO2/CONS, R0, R0G, WEB, H0, RKG
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
COMMON/BLO4/2, Z0, 2HH
COMMON/BLO6/COEF,NCOEF,III,IYN,IYO
COMMON/BLO7/XCLE,YCLE,IPL, IHLST, PHEIL
COMMON/BLO8/XFLUEE,YFLUEE, DMAR,XSTEEL, YSTEEL, DPHEEL, YEEL

IF(IHLST .LT. 11) GO TO 1

XEE2 = -YFLUEE
YEEL2 = DSQRT(R0**2-XEE2**2)
PHIEEL = DATAN(YEEL2/XEE2)
PHIL = PHIEEL + DPHEEL

W2R = WEB/2./R0
PHIL = DATAN(W2R/DSQRT(1.-W2R**2)) + DSQRT(R0**2-(WEB/2.)**2)

$ * DSIN(H0)/DCOS(H0)/R0*CSKOU/SNKOU

PHST = PHIL + ALPHA
XCLE = R0*DCOS(PHST)
YCLE = R0*DSIN(PHST)

PHEL = DATAN(YCLE/VCLE)
Z = ZCLE

CALL GRIN(Z, Z0, AXX, BY, CXY, DDX, EY, FF)

FLANK = AXX*XCLE**2+BY*YCLE**2+CXY*XCLE*YCLE+DDX*XCLE
       +EY*YCLE+FF
RETURN
END

FUNCTION FOUTCR(ZOUT)

IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/BLO1/R0, R0G, WEB, H0, RKG
COMMON/BLO2/CONS, R0, R0G, WEB, H0, RKG
COMMON/BLO3/ALPHA, CSVG, SNVG, CSKOI, SNKOI, CSKOU, SNKOU
COMMON/BLO4/2, Z0, 2HH
COMMON/BLO5/9, NPOINT, NLAAP, ISEC
COMMON/BLO21/XOUT, YOUT

ALPHA = ZOUT/R0*DSIN(H0)/DCOS(H0)
W2R = WEB/2./R0

PHEL = DATAN(W2R/DSQRT(1.-W2R**2)) + DSQRT(R0**2-(WEB/2.)**2)

$ * DSIN(H0)/DCOS(H0)/R0*CSKOU/SNKOU

PHST = PHIL + ALPHA
XST = R0*DCOS(PHST)
YST = R0*DSIN(PHST)

CALL GRIN(ZOUT, Z0, AXX, BY, CXY, DDX, EY, FF)

FOUTCR = AXX*XST**2+BYY*YST**2+CXY*XST*YST+DDX*XST
       +EY*YST+FF
FUNCTION FPACE(PHACE)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/B014/RACE, PHA, ZPACE1
C
YPACE=RPACE*DSIN(PHACE+PHPA) FPACE=YPACE-YPACE1
C
RETURN
END

FUNCTION FPACE(PHACE)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/B014/RACE, PHA, ZPACE1
C
YPACE=RPACE*DSIN(PHACE+PHPA) FPACE=YPACE-YPACE1
C
RETURN
END

FUNCTION FUN(RSTAN)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
INTEGER NPOINT
COMMON/B01/R0, R0G, WEB, H0, RKG
COMMON/B03/ALPHA, CSVG, SNV, CK01, SNK01, CSK01, SNK0U
COMMON/B05/2, RH, ZHH
COMMON/B07/S, NPOINT, NLAAP, ISEC
Common/B08/Z, Z0, Z02
W2R=WEB/2./RSTAN
PHST=-(DATAN(W2R/DSQRT(1.-W2R*·2»+DSQRT(RSTAN**2- 3(WEB/2.)**2)*DSIN{H0)/OCOS(H0)/R"*CSKOU/SNKOU)
PHST=PHST+ALPHA
XST=RSTAN*DCOS(PHST)
YST=RSTAN*DSIN(PHST)
CALL GRIN(Z, ZST, XST, YST)
FUN=AXX*XST**2+SYY*YST**2+CXY*XST*YST+DDX*XST$+EY*YST+FF
RETURN
END

SUBROUTINE GRIN(Z, Z0, AX, BX, CY, DY, EY, FF)
C
C
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/B01/R0, R0G, WEB, H0, RKG
COMMON/B02/CONS, RCAM, EXG, VG
COMMON/B03/ALPHA, CSVG, SNV, CK01, SNK01, CSK01, SNK0U
C
A.XX=CSVG**2+(CSKO1**2)*(SNVG**2)
BYY=SNVG**2+CSVG**2*(CSKO1**2)
CXT=-(CSVG**2+CSKO1**2)*SNVG
DXK=-(CSVG**2+CSKO1**2)*SNVG
EXY=-(EXG*SNVG)**2+(EXG**2)*SNVG
FF=EXG**2-(S*RK)**2+(Z-RK)**2*SNKO1**2
C
RETURN
END

SUBROUTINE MONAT(M, N, EX, RE, FJAC, LJC, SMON, IGR, NITER, NF, LW, $LIN, WEB, LW)
C
C
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION EX(4), RE(4), FJAC(3, 3)
SMON(3), IW(1), WEB(120)
IE=RE(1) +RE(2) *RE(3) +RE(4) *RE(5) *RE(6)
$+RE(7) *RE(8) *RE
WRITE(1, 20) NITER, IE
20 FORMAT('AFTER', 14, ' ITERATIONS', 2X, 'THE SUM OF SQ. IS'$.F12.6)
WRITE(1, 22)(EX(I), I=1, N)
22 FORMAT('AT THE POINT', 109.4)
RETURN
END

SUBROUTINE MONIT(M, N, CORN, RE, FJAC, LJC, SMON, IGR, NITER, NF, LW, $LIN, WEB, LW)
C
C
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION CORN(3), RE(3), FJAC(3, 3)
SMON(3), IW(1), WE0(120)
IE=RE(1) +RE(2) *RE(3)
WRITE(1, 20) NITER, IE
20 FORMAT('AFTER', 14, ' ITERATIONS', 2X, 'THE SUM OF SQ. IS'$.F9.3)
WRITE(1, 22)(CORN(I), I=1, N)
22 FORMAT('AT THE POINT', 109.4)
RETURN
END

SUBROUTINE MONRT(M, N, CORN, RE, FJAC, LJC, SMON, IGR, NITER, NF, LW, $LIN, WEB, LW)
C
C
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION CORN(3), RE(3), FJAC(3, 3)
SMON(3), IW(1), WEB(120)
IE=RE(1) +RE(2) *RE(3)
WRITE(1, 20) NITER, IE
20 FORMAT('AFTER', 14, ' ITERATIONS', 2X, 'THE SUM OF SQ. IS'$.F9.3)
WRITE(1, 22)(CORN(I), I=1, N)
22 FORMAT('AT THE POINT', 109.4)
RETURN
END

SUBROUTINE GRIN(Z, Z0, AX, BY, CY, DX, EY, FF)
C
C
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
COMMON/B01/R0, R0G, WEB, H0, RKG
COMMON/B02/CONS, RCAM, EXG, VG
COMMON/B03/ALPHA, CSVG, SNV, CK01, SNK01, CSK01, SNK0U
C
A.XX=CSVG**2+(CSKO1**2)*(SNVG**2)
BYY=SNVG**2+CSVG**2*(CSKO1**2)
CXT=-(CSVG**2+CSKO1**2)*SNVG
DXK=-(CSVG**2+CSKO1**2)*SNVG
EXY=-(EXG*SNVG)**2+(EXG**2)*SNVG
FF=EXG**2-(S*RK)**2+(Z-RK)**2*SNKO1**2
C
RETURN
END

SUBROUTINE MONAT(M, N, EX, RE, FJAC, LJC, SMON, IGR, NITER, NF, LW, $LIN, WEB, LW)
C
C
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION EX(4), RE(4), FJAC(3, 3)
SMON(3), IW(1), WEB(120)
IE=RE(1) +RE(2) *RE(3) +RE(4) *RE(5) *RE(6)
$+RE(7) *RE(8) *RE
WRITE(1, 20) NITER, IE
20 FORMAT('AFTER', 14, ' ITERATIONS', 2X, 'THE SUM OF SQ. IS'$.F12.6)
WRITE(1, 22)(EX(I), I=1, N)
22 FORMAT('AT THE POINT', 109.4)
RETURN
END

SUBROUTINE MONIT(M, N, CORN, RE, FJAC, LJC, SMON, IGR, NITER, NF, LW, $LIN, WEB, LW)
C
C
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION CORN(3), RE(3), FJAC(3, 3)
SMON(3), IW(1), WEB(120)
IE=RE(1) +RE(2) *RE(3)
WRITE(1, 20) NITER, IE
20 FORMAT('AFTER', 14, ' ITERATIONS', 2X, 'THE SUM OF SQ. IS'$.F9.3)
WRITE(1, 22)(CORN(I), I=1, N)
22 FORMAT('AT THE POINT', 109.4)
RETURN
END

SUBROUTINE MONRT(M, N, CORN, RE, FJAC, LJC, SMON, IGR, NITER, NF, LW, $LIN, WEB, LW)
C
C
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION CORN(3), RE(3), FJAC(3, 3)
SMON(3), IW(1), WEB(120)
IE=RE(1) +RE(2) *RE(3)
WRITE(1, 20) NITER, IE
20 FORMAT('AFTER', 14, ' ITERATIONS', 2X, 'THE SUM OF SQ. IS'$.F9.3)
WRITE(1, 22)(CORN(I), I=1, N)

SUBROUTINE RESAD(IFLAG,M,N,EIX,RE,IW,LIW,WE0,LW)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION XSTGD(100),YSTGD(100),ZSTGD(100)
DIMENSION XNRAO(100),YNRAD(100),ZNRAD(100)
DIMENSION RRN(100),RCA(100)
DIMENSION VERIF(100),EIX(4),RE(8)
COMMON/BLO21/EB,YEB,EEM,SYM
COMMON/BLO24/PA,P1,RCA,RC1
COMMON/BLO25/XSTGD,YSTGD,ZSTGD
COMMON/BLO26/RN
COMMON/BLO27/XNRAO,YNRAD,ZNRAD
NLOO1=IFIX(NPOINT/3)
NLOO2=2*NLOO1
XEB=EIX(1)
YEB=EIX(2)
XEM=EIX(3)
YEM=EIX(4)
DO 1 J=1,5
   GO TO(10,11,12,13,14),J
10 I=1
   GO TO 14
11 I=NLOO1
   GO TO 14
12 I=NLOO3
   GO TO 14
13 I=NPOINT
   GO TO 14
15 I=NLOO3
14 CONTINUE
DBM=DSQRT((XEM-XEB)**2+(YEM-YEB)**2+(ZEM-ZEB)**2)
AAA=(XEM-XEB)/DBM
BBB=(YEM-YEB)/DBM
CCC=(ZEM-ZEB)/DBM
REVAB=3.
WAA=2.8*PI*REVAB
V1=REVAB*PA
ABCI=BBB*STGDI(I)-ZEM-CCC*YSTGD(I)-YEM
ABCI=CCC*YSTGD(I)-XEM-AAA*ZSTGD(I)-ZEM
VC1=AAA*W1+AAA*ABCI
VC2=BBB*V1+AAA*ABCI
VC3=CCC*V1+AAA*ABCI

VC=DSQRT((VC1**2+VC2**2+VC3**2)
VC1=VC1/VC
VC2=VC2/VC
VC3=VC3/VC
IF(ABC .NE. 0.0) GO TO 9148
WRITE(1,9149)
9149 FORMAT(' ABC IS NULL')
CALL EXIT
9148 XEXEAC=ABCI/ABC1+AAA*CCC
XEXEAB=ABCI/ABC2+AAA*BBB
IF(YEXEAB .NE. 0.0) GO TO 9151
WRITE(1,9152)
9152 FORMAT(' YEXEAB IS NULL')
CALL EXIT
9151 XEXEAC=ABCI/ABC2+YEXEAB=ABC1-ABC3/ABC1
YEXEAC=2.*YEXEAC**2+ZEXEAC+YEXEAB)**2
CONSTA=(XEB-XSTGD(I))*YEXEAC-(YEB-YSTGD(I))
ZEXEAC=YEXEAB+(ZEB-ZSTGD(I))
IF(ZEYESE .NE. 0.0) GO TO 9153
WRITE(1,9154)
9154 FORMAT(' ZEYESE IS NULL')
CALL EXIT
9153 VN3=CONSTA-ZEYESE
VN2=2*ZEEX=K*YEXEAB+V3
VN1=2*YEXE=K*VN3
RCA(I)=DSQRT(VN1**2+VN2**2+VN3**2)
VERIF=VC1*XNRAO(I)
VERIF2=VC2*YNRAD(I)
VERIF3=VC3*ZNRAD(I)
COSW=VERIF1*VERIF2*VERIF3
VERI=PI/2.-VERI
IF(VERI .GT. PI/2.)VERI=VERI-PI
VERI=VERI
1 CONTINUE
RE(1)=RCA(1)-RC1
RE(2)=VERIF(1)
RE(3)=VERIF(NLOO1)
RE(4)=VERIF(NLOO2)
RE(5)=VERIF(NPOINT)
RE(6)=VERIF(NLOO3)
RE(7)=VERIF(NLOO2)
RE(8)=RCA(NPOINT)-RC1
C RETURN
END
SUBROUTINE RESID(IFLAG,M,N,CORN,RE,IW,LIW,WE0,LW)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION XSTGD(100),YSTGD(100),ZSTGD(100)
DIMENSION RRN(100),RCA(100)
DIMENSION VERIF(100),EIX(4),RE(8)
COMMON/BLO21/EB,YEB,EEM,SYM
COMMON/BLO24/PA,P1,RCA,RC1
COMMON/BLO25/XSTGD,YSTGD,ZSTGD
COMMON/BLO26/RN
COMMON/BLO27/XNRAO,YNRAD,ZNRAD
NLOO1=IFIX(NPOINT/3)
NLOO3=4
NLOO2=2*NLOO1
XEB=EIX(1)
YEB=EIX(2)
XEM=EIX(3)
YEM=EIX(4)
DO 1 J=1,5
   GO TO(10,11,12,13,14),J
10 I=1
   GO TO 14
11 I=NLOO1
   GO TO 14
12 I=NLOO3
   GO TO 14
13 I=NPOINT
   GO TO 14
15 I=NLOO3
14 CONTINUE
DBM=DSQRT((XEM-XEB)**2+(YEM-YEB)**2+(ZEM-ZEB)**2)
AAA=(XEM-XEB)/DBM
BBB=(YEM-YEB)/DBM
CCC=(ZEM-ZEB)/DBM
REVAB=3.
WAA=2.8*PI*REVAB
V1=REVAB*PA
ABCI=BBB*STGDI(I)-ZEM+AAA*(YSTGD(I)-YEM)
ABCI=CCC*(YSTGD(I)-YEM)+AAA*(ZSTGD(I)-ZEM)
VC1=AAA*V1+AAA*ABCI
VC2=BBB*V1+AAA*ABCI
VC3=CCC*V1+AAA*ABCI

VC=DSQRT((VC1**2+VC2**2+VC3**2)
VC1=VC1/VC
VC2=VC2/VC
VC3=VC3/VC
IF(ABC .NE. 0.0) GO TO 9148
WRITE(1,9149)
9149 FORMAT(' ABC IS NULL')
CALL EXIT
9148 XEXEAC=ABCI/ABC1+AAA+CCC
XEXEAB=ABCI/ABC2+AAA+BBB
IF(YEXEAB .NE. 0.0) GO TO 9151
WRITE(1,9152)
9152 FORMAT(' YEXEAB IS NULL')
CALL EXIT
9151 XEXEAC=ABCI/ABC2+YEXEAB=ABC1-ABC3/ABC1
YEXEAC=2.*YEXEAC**2+ZEXEAC+YEXEAB)**2
CONSTA=(XEB-XSTGD(I))*YEXEAC-(YEB-YSTGD(I))
ZEXEAC=YEXEAB+(ZEB-ZSTGD(I))
IF(ZEYESE .NE. 0.0) GO TO 9153
WRITE(1,9154)
9154 FORMAT(' ZEYESE IS NULL')
CALL EXIT
9153 VN3=CONSTA-ZEYESE
VN2=2*ZEEX=K*YEXEAB+V3
VN1=2*YEXE=K*VN3
RCA(I)=DSQRT(VN1**2+VN2**2+VN3**2)
VERIF=VC1*XNRAO(I)
VERIF2=VC2*YNRAD(I)
VERIF3=VC3*ZNRAD(I)
COSW=VERIF1*VERIF2*VERIF3
VERI=PI/2.-VERI
IF(VERI .GT. PI/2.)VERI=VERI-PI
VERI=VERI
1 CONTINUE
RE(1)=RCA(1)-RC1
RE(2)=VERIF(1)
RE(3)=VERIF(NLOO1)
RE(4)=VERIF(NLOO2)
RE(5)=VERIF(NPOINT)
RE(6)=VERIF(NLOO3)
RE(7)=VERIF(NLOO2)
RE(8)=RCA(NPOINT)-RC1
C RETURN
END
COMMON/BLO3/ALPHA, CSVG, SNVG, CSK0I, SNKOI, CSKOU, SNKOU
COMMON/BLO4/2, 20, 21H

PI=3.14159265
XCORN=CORN(1)
YCORN=CORN(2)
ZCORN=CORN(3)

RSTAN=DSQRT(XCORN**2+YCORN**2)
ALPHA=ZCORN/R0*DSIN(H0)/DCOS(H0)
IF(RSTAN.LE.WEB/2.)GO TO 1
W2R=WEB/2./RSTAN
PHSTY=-DATAN(YCORN/XCORN)
CALL GRIN(ZCORN,Z0,AXX,BYY,CXY,DXX,EY,FF)

RE(1)=AXX*XCORN**2+BYY*YCORN**2+CXY*XCORN*YCORN+DXX*XCORN
S+EY*YCORN+FF
RE(2)=AXX*XCORN**2+BYY*YCORN**2+CXY*XCORN*YCORN-DXX*XCORN
S-EY*YCORN+FF
RE(3)=PHST+PHSTY+ALPHA
RETURN
END

FUNCTION ROTAC(XLK)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20)
COMMON/BLO1/R0, R0G, WEB, H0, RKG
COMMON/BLO6/COEF, NCOEF, III, IY, IYO
COMMON/BLO15/XLB, YL0

YLK=0.
DO 75 J=1,NCOEF
YLK=YLK+COEF(J)*XLK**(J-1)
75 CONTINUE
R=DSQRT(XLK**2+YLK**2)
ROTAC=R0
XLO=XLK
YLO=YLK
RETURN
END

SUBROUTINE RESUO(IFLAG,M,N,CORN,RU,IW,LIW,WE0,LW)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION COEF(20), RU(IW)
COMMON/BLO1/R0, R0G, WEB, H0, RKG
COMMON/BLO6/COEF, NCOEF, III, IY, IYO
COMMON/BLO15/XLB, YL0

XCORN=CORN(1)
YCORN=CORN(2)
ZCORN=CORN(3)

CALL GRIN(ZCORN,Z0,AXX,BYY,CXY,DXX,EY,FF)

RSTAN=DSQRT(XCORN**2+YCORN**2)
PHSTY=-DATAN(YCORN/XCORN)
ALPHA=ZCORN/R0*DSIN(H0)/DCOS(H0)
PHST=PHSTY+ALPHA
XST1=RSTAN*DCOS(PHST)
YST1=RSTAN*DSIN(PHST)
YST=0.0
DO 70 J=1,NCOEF
YST=YST+COEF(J)*XST1**(J-1)
70 CONTINUE