ON THE DESIGN OF MILLING CUTTERS OR GRINDING WHEELS FOR TWIST DRILL MANUFACTURE.
A CAD APPROACH

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SUMMARY

Short series of special twist drills, which are often required by the motor industry, are manufactured by means of milling or form grinding. Trial and error procedures to design suitable milling cutters or grinding wheels, have been common practice. However, CAD methods can be a decisive help in the difficult case of subland drills.

A CAD method has been developed which is based on two geometrical transformations: that which produces the tool axial profile suited to obtain a drill of given cross-section profile, and that which produces the drill cross-section profile that would be actually obtained by using a tool-milling cutter or grinding wheel-of a given axial profile. Both transformations, which depend upon several geometrical parameters—distance and angle between drill and tool axes, lead of helix, and the “phase angle” of the drill cross-section—and the computer methods developed to cope with them are presented.

By interactive use of these transformations, drill cross-section modifications can be introduced in order to make it feasible by means of a single tool. An application case is presented to illustrate its use.

INTRODUCTION

Mass production methods for manufacturing twist drills are not well suited for short series of special twist drills, such as those required by the motor industry. Special drills are milled or form ground.

The design of the tool profile—milling cutter or grinding wheel—has widely relied on trial and error empirical methods so far. This fact derives from the practical experience of manufacturers, from the certain degree of freedom concerning the shape of the flutes cross-section, and from the complexity of the geometrical problem involved.

However, CAD methods can be a decisive help in the difficult case of the subland drills. As the tool design depends upon several geometrical manufacturing parameters, a large number of solutions can easily be explored by CAD methods in order to find the most suitable.

On top of this, it might not exist a suitable tool for a given drill cross-section profile—DCSP—in what follows—and in such a case the drill design should be modified. For this purpose an interactive process can easily be carried out by means of CAD methods.

In this paper, the direct problem: that of determining the tool profile to obtain a given DCSP, and the inverse problem: that of determining the DCSP to be obtained by means of a certain tool profile, are solved and used to develop an interactive CAD method.

ISO nomenclature concerning twist drills[1] is used.

THE DIRECT PROBLEM

Geometry of the manufacturing process

In the manufacturing process the drill blank is given an helicoidal movement along its axis while the tool rotates around a fixed axis. (Fig.1).

![Fig.1 Geometry of the manufacturing process.](image)

Geometrical parameters defining this process are:
- Distance $s$ and angle $\gamma$ between tool and drill axes, sign and lead of helix $h$, the DCSP $u(t)$, $v(t)$, (Fig.2), and its phase angle $\alpha_0$ at the axial position nearest to the tool axis, ($z=0$).

The value of $\alpha$ is usually taken roughly equal to the helix angle $\alpha$ at the helix angle, $D$ being the body diameter.
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It is assumed that a single tool must be able to machine one half of the DCSP, (Fig.3). The land (the outer land for subland drills) can be left because it is usually machined in a manufacturing step different from this in which it may be given a certain back taper. (Subland back taper, if needed, is introduced when the step of smaller diameter is machined).

Fig.4 External tool/drill surface tangency.

Solutions of eq.1, to be acceptable, must correspond to external tangency between tool and drill, i.e. the external normal vector \( \mathbf{e} = \mathbf{T} \mathbf{e} \) at the point of tangency must point towards the tool axis. If \( t \) increases monotonously as point \( P' \) goes round the DCSP in clockwise direction as seen from positive \( z \) axis, the condition of external tangency can be expressed, as shown in Ap.1, as,

\[
y = s \sin \phi + \zeta \cos \phi < 0
\]  

(2) where, \( \dot{\zeta} = \frac{du}{dt} \); \( \zeta = \frac{dv}{dt} \); and \( \dot{\phi} = \frac{2\pi}{h} \).

Fig.5 Tool profile.

Once an acceptable solution \( z \) has been found, the coordinates \( q,r \) of the corresponding point \( P'' \) of the tool profile, (Fig.5) are conveniently expressed by means of point \( P \) coordinates \( xyz \),

\[
q = \frac{r - z \cos \alpha}{r 
\] + \( z \sin \alpha \)  
\[ r = \frac{1}{1 + \frac{\cos \alpha}{r} + \frac{\sin \alpha}{z}} \]  

with, \( x = u \cos \phi - v \sin \phi \), \( y = u \sin \phi + v \cos \phi \).

Tool/drill-edge tangency

A drill edge is the intersection of two drill surfaces, for instance, the heel is the intersection of the flute and the body clearance surfaces. If it corresponds to a convex angular point and both neighbouring surfaces can be machined by means
of tool profiles determined as described in the preceding section, the edge would spontaneously arise. However a discontinuity usually appears between both profiles, and the problem arises of what profile must be used to link them, (Fig.6). A careless choice might make this part of the tool to interfere with the edge and remove it from the drill.

The profile of the surface generated by rotating the edge around the tool axis determines a linking curve that cannot be trespassed. If the actual profile goes below it, its corresponding tool surface will not touch the edge.

![Fig.6 Tool profile for a convex edge of the drill.](image)

Be $E_a^o$ and $E_b^o$, (Fig.6), the tool profile points that correspond to point $E'$ depending on $du/dv$ be taken at side $a$ or $b$, and be $E_a$ and $E_b$, (Fig.7), their corresponding points of tool/edge tangency. Points $E_i^o$ of the linking curve are found by projecting intermediate points $E_i$ of the drill edge over the tool axis. Coordinates $q_i$ and $r_i$ are defined by eqs. (3) for $z_i$ values lying in the interval $(z_a, z_b)$.

![Fig.7 Defining the linking profile.](image)

Edges that correspond to concave angular points cannot be machined unless $z_a = z_b$, because the tool surface cannot physically keep tangency along a span of the edge. $z_a = z_b$ implies that $E_a^o = E_b^o$ in the tool profile, and this can only happen if the tool axis and the edge at the tangency point $E_a = E_b$ are orthogonal.

![Fig.8 Tool profile for a concave edge of the drill.](image)

If $z_a \neq z_b$, the profiles that correspond to sides $a$ and $b$, cross each other, (Fig.8), and consequently the tool is not feasible.

**Tool feasibility**

The tool, to be feasible, must have a single valued profile $r(q)$.

For a given DCSP, parameters $a_a$ and $\phi_0$ of the manufacturing process can be modified in order to fulfill external tool/drill tangency condition for all its points. If this proves not to be possible, some spans of the tool profile will be missing. In consequence some redesigning of the drill is needed. Besides this, some redesigning of the drill is also needed if the obtained profile is not single valued.

This redesigning can derive from modifications introduced in the tool profile. Splines can fill the missing spans, and a single value -usually the lower- can be chosen at the multi-valued points.

From this modified tool, the inverse problem determines the DCSP that would be obtained. In this way an interactive design process can be carried out.

**THE INVERSE PROBLEM**

To a tool profile $r(q)$ always corresponds a DCSP. It can be found by applying the tool/drill tangency condition to each of its points.

For a given value of $q$ the normal to the tool surface at the point $P$ of the circle of radius $r$ passes through a point $Q$ of the tool axis, (Fig.9).

![Fig.9 Situation of point Q.](image)
The condition of orthogonality between $\vec{q}$ and $\vec{T}$ (Fig.10), leads to the equation,

$$g(q,r,\rho,\psi,\alpha,\theta) = 0 \quad ; \quad \frac{\alpha}{\theta} = \frac{dr}{dq} \tag{4}$$

function $g$ being defined by eq.11.3 of Ap.11. From eq.4, angles $\psi$ of tool/drill contact points can be found.

Once the value of $\psi$ has been obtained, coordinates of point $P$ are,

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} q \cos \psi + r \sin \psi \\ -q \sin \psi + r \cos \psi \end{bmatrix} \tag{5}$$

and from them, coordinates $u,v$ of the DCSP are readily expressed as,

$$u = q \cos \phi + r \sin \phi$$
$$v = -q \sin \phi + r \cos \phi$$

If there is a point $P'$ of the tool profile with a different slope at each side, two points $Q_a$ and $Q_b$ will be found (Fig.11). Be $\phi_a$ and $\phi_b$ the solutions of eq.4 and $P_a'$ and $P_b'$ the points of the DCSP that correspond to $Q_a$ and $Q_b$. The span of the DCSP that links $P_a'$ and $P_b'$ is determined from values of $\psi$ lying between $\phi_a$ and $\phi_b$.

**Informatic Treatment**

**The direct problem**

A spline $u(t),v(t) \ (2)$ is used to define each span of DCSP between angular points. Parameter $t$ is taken to roughly represent the length along the profile.

For a given span, equation I.9 is solved for a set of values of $t$, $z$ values to verify it are located in the intervals $0 \leq \psi \leq \frac{\pi}{2}$ and $-\psi_{max} \leq \psi \leq \frac{\pi}{2}$, $\psi_{max}$ is taken to be proportional to the drill body diameter. In each interval only the first physically possible solution is obtained, and usually no solution is found in one of the intervals.

The spans of the tool profile that correspond to angular points are found by applying eq.3 to $z$ values in the interval $(z_a,z_b)$ defined by the solutions $z_a$ and $z_b$ derived from both sides.

**The inverse problem**

The single valued tool profile $z(q)$ is defined as a set of points. Equation I.3 is solved for each value of $q$, values to verify it are looked for in the intervals $0 \leq \psi \leq \frac{\pi}{2}$ and $-\psi_{max} \leq \psi \leq \frac{\pi}{2}$. In each interval only the first solution is obtained. If a solution is obtained in each interval, usually only the smaller one defines a point of the actual DCSP.

The spans of the DCSP that correspond to angular points are found by applying eqs.5-6 to $z$ values in the interval $(z_a,z_b)$ defined by solutions $z_a$ and $z_b$ derived from both sides. A point $P_a$ is considered to be angular if the angle between vectors $\vec{P}_{a-1}P_a$ and $\vec{P}_nP_{n+1}$ is greater than a certain value.

**Tool profile modifications**

Subroutines have been developed to introduce certain modifications in not satisfactory tool profiles. Missing spans are filled by splines defined to smoothly link the neighbouring spans. In multi-valued spans, minimum $r(q)$ values are chosen.

**ILLUSTRATIVE APPLICATION**

In Fig.12 the initial DCSP of a subland drill is shown. The lead of the helix is $h = 60 \text{ mm}$. Distance between tool and drill axes is taken to be $s = 24 \text{ mm}$ and, as usual, $a$ is taken to be roughly equal to the helix angle, in this case $a = 25^\circ$. To illustrate the strong influence of the phase angle $\phi_0$, the tool profile obtained for $\phi_0 = -30^\circ$ is shown in Fig.13(a), which proves to be quite unsatisfactory; multivalued occurs close to points $Q_a''$ and $Q_b''$. A better choice is $\phi_0 = 30^\circ$, that leads to the tool profile shown in Fig.13(b), in which there still appears some trouble near to points $Q_a''$ and $Q_b''$.

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**Fig.10** Geometry of the inverse problem.

**Fig.11** DCSP generated by an angular point of the tool profile.

**Fig.12** Initial DCSP.
The actual DCSP suggests the drill to be modified by a small displacement of the heel over the body clearance. Redesigned drill, shown in Fig.16, proves to be acceptable because a fully feasible tool can be obtained from its DCSP, as shown in Fig.17.

CONCLUSIONS

The problem of finding the tool profile needed to obtain a given drill cross section, and the problem of finding the drill cross section that will be obtained by means of a given tool profile have been solved.

Computer programs to apply these solutions have been developed, and they have proved to be useful to support an interactive process of tool and drill redesign to obtain a suitable tool profile from a geometrical point of view.

More research is needed for a better evaluation of tool suitability, taking into account the technological aspects of the cutting process.

REFERENCES

1. International standard: Twist drills - Terms, definitions and types. ISO 5419-1982(E/F)
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NOTATION

DCSP drill cross section profile
D drill body diameter
h lead of helix
N rotation matrix, defined by eq. I.2
\( \hat{N} \) dB/da
P point of tool/drill contact
P' point of the DCSP
P'' point of the tool profile
Q intersection point of tool profile and normal at P to drill and tool surfaces
Q' coordinates of the tool profile
Q'' axial coordinate of point Q
s distance between tool and drill axes
\( \psi, \phi \) spline parameter
u, v, w DSCP coordinates at z=0 and for \( \phi_0 = 0 \)
\( \psi, \phi \) coordinates of P
\( \alpha = (\pi/2) - \alpha \) angle between tool and drill axes
\( \phi_0 + 2\pi / h \) phase angle of the drill cross section at z=0, Fig.2
\( \psi \) see Fig.10. \( r, v, q \) are cylindrical coordinates of P
\( \hat{U}, \hat{V}, \hat{\psi} \) normal vector to drill surface
\( \hat{p} \) vector tangent at P to the DCSP.
\( \hat{v} \) vector tangent at P to the helix.
\( \tau \) vector in the direction of positive tool axis.

APPENDIX I. THEORETICAL ANALYSIS OF THE DIRECT PROBLEM

Be \( u(t), v(t) \) the rectangular coordinates of the DCSP, Fig.2, and be t a parameter the value of which increases monotonously as point P' goes round the DCSP in clockwise direction as seen from positive z axis.

The drill surface is defined by,

\[
\{ \hat{Q} \} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} = H \begin{bmatrix} u \\ v \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} (I.1)
\]

with,

\[
H = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} ; \psi = \phi_0 + 2\pi / h (I.2)
\]

Vectors \( \hat{Q} \) and \( \hat{T} \), tangent at P to the DCSP and to the helix passing through it, Fig.4, are

\[
\{ \hat{Q} \} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = H \begin{bmatrix} \hat{u} \\ \hat{v} \\ 0 \end{bmatrix} (I.3)
\]

\[
\{ \hat{T} \} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \hat{N} \begin{bmatrix} u \\ v \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} (I.4)
\]

If tool and drill surfaces are tangent at P, the normal to them at P must intersect the tool axis. Be \( Q \) the intersection point. Condition of tangency can be expressed from the orthogonality between \( \hat{Q} \) and vectors \( Q \) and \( T \). \( \hat{Q} \) is,

\[
\{ \hat{Q} \} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} + \begin{bmatrix} -h \cos \alpha \\ -q' \cos \alpha \\ z \cos \alpha \end{bmatrix} (I.5)
\]

From

\[
\begin{align*}
\{ \hat{Q} \} \cdot \hat{Q} &= \begin{bmatrix} u \\ v \\ w \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} + \begin{bmatrix} -h \cos \alpha \\ -q' \cos \alpha \\ z \cos \alpha \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} = 0 \\
\hat{Q} &= 1 
\end{align*}
\]

the value of \( q' \cos \alpha \) can be found

\[
q' \cos \alpha = \frac{u \hat{u} + v \hat{v} + \hat{Q} (\hat{Q} \cdot \hat{Q}) - \hat{Q} (\hat{Q} \cdot \hat{T})}{\hat{Q} (\hat{Q} \cdot \hat{Q})} (I.7)
\]

And from

\[
\begin{align*}
\{ \hat{Q} \} &= \begin{bmatrix} u \\ v \\ w \end{bmatrix} H^T \begin{bmatrix} \hat{u} \\ \hat{v} \\ 0 \end{bmatrix} + \begin{bmatrix} -h \cos \alpha \\ -q' \cos \alpha \\ 0 \end{bmatrix} \begin{bmatrix} u \\ v \\ 0 \end{bmatrix} + \\
&+ z \cos \alpha = 0 
\end{align*}
\]

- \( H^T \) is an antisymmetric matrix which makes the first term vanish by substituting eq. I.7 in eq. I.6

the condition that must be verified by z results,

\[
z = \frac{u \hat{u} + v \hat{v} + (\hat{Q} (\hat{Q} \cdot \hat{Q}) - \hat{Q} (\hat{Q} \cdot \hat{T}))}{\hat{Q} (\hat{Q} \cdot \hat{Q})} - \\
- a (\hat{Q} (\hat{Q} \cdot \hat{Q}) - \hat{Q} (\hat{Q} \cdot \hat{Q})) (I.9)
\]

The external normal vector \( \hat{U} + \hat{V} \) must point towards the tool axis,

\[
\{ \hat{U} \} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \hat{U} + \begin{bmatrix} \hat{V} \\ \hat{W} \end{bmatrix} = \begin{bmatrix} -u' \\ v' \\ w' \end{bmatrix} \]

As points \( P \) of tangency are lower than the tool axis, \( \hat{U} \) must be positive and this implies that

\[
u' = \hat{U} (\hat{Q} (\hat{Q} \cdot \hat{Q}) - \hat{Q} (\hat{Q} \cdot \hat{Q})) < 0 (I.10)
\]

APPENDIX II. THEORETICAL ANALYSIS OF THE INVERSE PROBLEM

Be \( r(q) \) a single valued function defining the tool profile, and \( P \) a point of tool/drain tangency. Vectors \( \hat{Q} \) and \( \hat{T} \), that must be orthogonal, can be expressed by means of tool profile coordinates \( q, r \) and angle \( \psi \), Figs.9-10,

\[
\{ \hat{Q} \} = \begin{bmatrix} -\cos \psi \\ -\sin \psi \cos q \\ \sin \psi \sin q \end{bmatrix} (I.11)
\]

\[
\{ \hat{T} \} = \begin{bmatrix} (2h/q) \sin q \\ (2h/q) \cos q \\ 1 \end{bmatrix} (I.12)
\]

The orthogonality condition leads to,

\[
\sinq \left[ 1 + \frac{2\pi}{h} \tan \psi \right] + \cos \psi \frac{2\pi}{h} [q + r] = \\
- \frac{2\pi}{h} \hat{r} + \hat{r} \tan \psi = 0 (I.13)
\]

which must be verified by angle \( \hat{r} \). As points of contact are lower than the tool axis, \(- (\pi/2) < \psi < (\pi/2), \)

\[
\{ \hat{Q} \} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} + \begin{bmatrix} -h \cos \alpha \\ -q' \cos \alpha \\ z \cos \alpha \end{bmatrix} (I.5)
\]