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A new methodology for designing a curve-edged twist drill with an arbitrarily given distribution of the cutting angles along the tool cutting edge

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ABSTRACT

The present study aims at the development of a new methodology for designing a curve-edged twist drill with an arbitrarily given distribution of the cutting angles along the tool cutting edge. The new methodology consists of 81 major mathematical equations and is developed using a method of mapping relevant planes and straight lines of a cutting tool (such as the cutting plane and the cutting edge) as corresponding image points and image lines on a projection plane. The developed methodology is used to intuitively and graphically analyze and determine the relationship between the orientation of the cutting edge and the cutting angles at each point on the cutting edge. A set of image points and image lines is established to calculate the cutting angles on the cutting edge of a twist drill, including the working tool rake angle, the working tool inclination angle, the working cutting edge angle, and the working normal rake angle. Three computer case studies are provided to show curved cutting edges that correspond, respectively, to a linear distribution of the working tool rake angle, a combined linear and uniform distribution of the working tool rake angle, and a linear distribution of the working tool inclination angle along the tool cutting edge. Finally, a set of metal drilling experiments is performed to compare the drilling torque and the thrust force between a conventional straight-edged twist drill and a new curve-edged twist drill that has a combined linear and uniform distribution of the working tool rake angle along the tool cutting edge. The experimental results show that the new curve-edged drill reduces the drilling torque by 28.5% and the thrust force by 24.6% on average.

1. Introduction

The geometrical shape and dimensions of the cutting edges (lips) of a twist drill significantly affect the cutting performance, such as the cutting forces, tool wear, cutting dynamics, and the quality of drilled holes [1–3]. A poorly designed tool cutting edge often results in an undesired (or non-optimized) distribution of the cutting angles along the tool cutting edge [4–7], hence deteriorating the cutting performance and even causing a complete loss of the cutting ability of a drill.

A conventional twist drill usually has two straight cutting edges [8,9]. In developing a mathematical model for straight-edged twist drills, Galloway [10] calculated the cutting angles along the tool cutting edge and concluded that the cutting angles at a general point on the cutting edge varied with its radial position. As the center of a drill was approached, the rake angle decreased. A very large negative rake angle existed on the part of the cutting edge that was close to the drill core. This large negative rake angle could significantly increase the cutting forces and tool wear [11,12]. Fugelso [13] also studied the cutting angles on the straight cutting edge of a conical drill and found a very small flank angle on the part of the cutting edge near the drill core. He concluded that in order to solve that flank angle problem, the straight cutting edge of a drill had to be slightly curved.

Studies [14–16] have shown that the cutting performance of a straight-edged twist drill can be significantly improved by changing the geometrical shape and dimensions of the tool cutting edge. Either a standard or a non-standard technique can be used to grind the tool flank face, therefore a desired distribution of the cutting angles along the tool cutting edge can be obtained. One example can be found on the well-known multifacet drill [17–20], which uses the combination of a circular arc edge and a straight edge, instead of a single straight edge, to improve the drilling performance. Another example is a curve-edged twist drill developed by Shi et al. [21] on which the orientation of the cutting edge was controlled by grinding the tool flank face using a non-standard grinding method. The tool rake angle at each point along the tool cutting edge took its maximum allowable value. Compared to a conventional straight-edged twist drill, that curve-edged drill [21] reduced the drilling torque by 12–20% and the thrust force by 40% and improved tool life by 2–9 times. Using the

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Nomenclature

$\boldsymbol{a}$, $\boldsymbol{b}$	possible image lines of the cutting edge curve at the point O
A, B, C	three planes, C also stands for the intersection point of the cutting edge and the drill outer corner
$\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$	image points of planes A, B, and C
A_1, A_2, A_3	homogeneous coordinates of the image point $\boldsymbol{A}$
B_1, B_2, B_3	homogeneous coordinates of the image point $\boldsymbol{B}$
C_1, C_2, C_3	homogeneous coordinates of the image point $\boldsymbol{C}$
d	tangent line to the cutting edge
$\boldsymbol{d}$	image line of the cutting edge tangent d
d_0	line perpendicular to the image line $\boldsymbol{d}$
d_1, d_2, d_3	homogeneous coordinates of the image line $\boldsymbol{d}$
$\boldsymbol{d}_i$	image line of the cutting edge tangent at the ith point
d_{i1}, d_{i2}, d_{i3}	homogeneous coordinates of the image line $\boldsymbol{d}_i$
D	drill diameter
$\boldsymbol{e}$	image line $\boldsymbol{P}_e\boldsymbol{F}$
$\boldsymbol{e}''$	new position of the image line $\boldsymbol{P}_e\boldsymbol{F}$
$\boldsymbol{e}_1''$, $\boldsymbol{e}_2''$, $\boldsymbol{e}_3''$	homogeneous coordinates of the image line $\boldsymbol{e}''$
f	drill feed
$\boldsymbol{F}$	image point of the assumed feed plane
F_x, F_y	Cartesian coordinates of the image point $\boldsymbol{F}$
H	pitch of the drill flute helicoid
$\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$	unit vectors in the direction of x-, y- and z-axis, respectively
k	constant
k_1, k_2	slope of lines l_1' and l_2'
l_1', l_2'	straight lines shown in Fig. 5
l_1'', l_2''	lines parallel to l_1' and l_2'
N	rotational speed of the spindle, or the cutting edge normal plane
$\boldsymbol{N}$	image point of the cutting edge normal plane N
N_{ex}, N_{ey}	Cartesian coordinates of the image point $\boldsymbol{N}$
N_1, N_2, N_3	homogeneous coordinates of the image point $\boldsymbol{N}$
O	origin of the coordination system
P_e	working base plane
$\boldsymbol{P}_e$	image point of the working base plane P_e
$\boldsymbol{P}_e'$, $\boldsymbol{P}_e''$	new positions of $\boldsymbol{P}_e$
P_{ex}, P_{ey}	Cartesian coordinates of the image point $\boldsymbol{P}_e$
P_{e1}, P_{e2}, P_{e3}	homogeneous coordinates of the image point $\boldsymbol{P}_e$
P'_{e1}, P'_{e2}, P'_{e3}	homogeneous coordinates of the image point $\boldsymbol{P}'_e$
P_i, P_{i+1}	neighboring points on the tool rake face
$\boldsymbol{Q}$	image point of the tangent plane to the tool rake face at the point P_i
Q_x, Q_y	Cartesian coordinates of the image point $\boldsymbol{Q}$
$\boldsymbol{Q}''$	new position of $\boldsymbol{Q}$
Q_1, Q_2, Q_3	homogeneous coordinates of the image point $\boldsymbol{Q}$
Q''_1, Q''_2, Q''_3	homogeneous coordinates of the image point $\boldsymbol{Q}''$
Q_x'', Q_y''	Cartesian coordinates of $\boldsymbol{Q}''$
r	radial distance between the center of the drill core and a point on the tool rake face
r_{i+1}	radial distance of the point P_{i+1} from the drill core
r_n	radial distance of the point P_n from the drill core f
R_e	working orthogonal plane
$\boldsymbol{R}_e$	image point of the working orthogonal plane R_e
R_{ex}, R_{ey}	Cartesian coordinates of the image point $\boldsymbol{R}_e$
R_{e1}, R_{e2}, R_{e3}	homogeneous coordinates of the image point $\boldsymbol{R}_e$
$2R_0$	diameter of the drill core
t	variable parameter
T_e	working cutting plane
$\boldsymbol{T}_e$	image point of the working cutting plane T_e
T_{ex}, T_{ey}	Cartesian coordinates of the image point $\boldsymbol{T}_e$
T_{e1}, T_{e2}, T_{e3}	homogeneous coordinates of the image point $\boldsymbol{T}_e$
$\boldsymbol{v}$	rotational speed vector
$\boldsymbol{v}_e$	cutting velocity vector
v_{e1}, v_{e2}, v_{e3}	homogeneous coordinates of the image point $\boldsymbol{v}_e$
$\boldsymbol{v}_f$	feed speed vector
x, y, z	Cartesian coordinates
x_1, y_1	Cartesian coordinates defined by Eqs. (47) and (48)
x_2, y_2	Cartesian coordinates defined by Eqs. (47) and (48)
x_i, y_i, z_i	Cartesian coordinates of the point P_i
x_{i+1}, y_{i+1}, z_{i+1}	Cartesian coordinates of the point P_{i+1}
β_0	the lead cutting edge angle at the drill outer corner
δ	rotational angle
ε	infinitesimal positive number
2ϕ	drill point angle
γ_{ne}	working normal rake angle
γ_{0e}	working tool rake angle
γ_{0ei}	working tool rake angle at the ith point P_i
γ_{0emax}	maximum working tool rake angle
κ_{re}	working cutting edge angle
λ_{se}	working tool inclination angle
λ_{semax}	maximum working tool inclination angle
θ	helix angle, or the angle between the positive direction of the x-axis and the line P_iP_{i+1}
$\theta_{\boldsymbol{ACB}}$	non-Euclidean angle formed by the image points $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$
$\theta_{\boldsymbol{FP}_e\boldsymbol{T}_e}$	non-Euclidean angle formed by the image points $\boldsymbol{Q}$, $\boldsymbol{P}_e$, and $\boldsymbol{T}_e$
$\theta_{\boldsymbol{QNP}_e}$	non-Euclidean angle formed by the image points $\boldsymbol{Q}$, $\boldsymbol{N}$, and $\boldsymbol{P}_e$
$\theta_{\boldsymbol{QR}_e\boldsymbol{P}_e}$	non-Euclidean angle formed by the image points $\boldsymbol{Q}$, $\boldsymbol{R}_e$, and $\boldsymbol{P}_e$
$\theta_{\boldsymbol{QT}_e\boldsymbol{P}_e}$	non-Euclidean angle formed by the image points $\boldsymbol{Q}$, $\boldsymbol{T}_e$, and $\boldsymbol{P}_e$
σ	rotational angle
Δx, Δy, Δz	step size taken in three perpendicular directions
Δx_1, Δx_2	two values of Δx given by Eq. (79)

same strategy of intentionally changing the cutting angles along the tool cutting edge, Chen and Fuh [14] and Fuh and Chen [15] developed a thick web twist drill with curved cutting edges, which reduced the torque, the thrust force, and tool wear and hence provided a better cutting ability and longer tool life.

In the development of the curve-edged, maximum-rake-angled twist drill [21], a unique and powerful method [22,23] of mapping relevant planes and straight lines of a cutting tool (such as the cutting plane and the cutting edge) onto a projection plane was employed to analyze and determine, both intuitively and graphically, 3D complex tool geometry. A twist drill, especially a curve-edged drill, has a very complex geometrical structure. Its cutting angles are formed by 3D spatial surfaces, curves, and oblique planes. It is difficult to use the conventional, orthogonal projection-based mechanical drawing method to show many cutting angles in a clear way. It is also time-consuming to use the conventional mathematical tools (such as solid geometry, spatial analytical geometry, differential geometry, and vector calculus) to intuitively analyze and calculate 3D complex tool geometry.

The mapping method [22,23] was based on an isomorphism principle that establishes correlation between the angular relationship in a 3D Euclidean space and the distance relationship on a 2D projection plane. By mapping 3D planes and lines as image points and image lines on a 2D projection plane, the complex calculation of geometric angles in a 3D space is converted to the simpler calculation of geometric angles and