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Torque and thrust force in drilling

KRZYSZTOF SZWAJKA
[1)]Faculty of Wood Technology, Warsaw University of Life Sciences – SGGW

Abstract: *Model torque and thrust force in drilling.* A theoretical model to predict thrust force and torque in drilling is presented. The method consists of determining the continuous distributions of thrust and torque along the lip and the chisel edge of a twist drill. The calculation uses the oblique cutting model for the lip and the orthogonal cutting model for the chisel edge. Thrust and torque are obtained in terms of the geometric features of the drill, the cutting conditions and the properties of the machined material.

Keywords: Theoretical model, drilling; thrust force, torque

INTRODUCTION

Drilling is probably the most important conventional mechanical process associated with chipboard processing. In the furniture industry, for instance, large quantities of holes have to be drilled due to the use of connections, handles and hinges. A considerable part of the current research effort in this field is still being devoted to major process-optimization issues such as the most appropriate cutting parameters or tool geometries.

Chipboard drilling require different process parameter optimization approaches: in the former process, the smoothness of the surface processed and tool wear are equally important; in chipboard drilling, the former parameter is prioritized over the latter given the difficulty to drill laminate without producing unacceptable cracks.

A suitable model would assist in a focused selection of the most appropriate feed rates, spindle speeds and geometrical cutting tool shapes. A detailed review of dynamic cutting models is provided in Ehmann et al. [1].

The study of drilling has often presented some difficulties which are linked to the complex geometry of the twist drill (Fig. 1). In practice, generally empirical equations are used to calculate thrust force and torque. These equations are very approximate, because they do not take all the cutting parameters into account. They often use only the feed speed and the diameter of the drill.

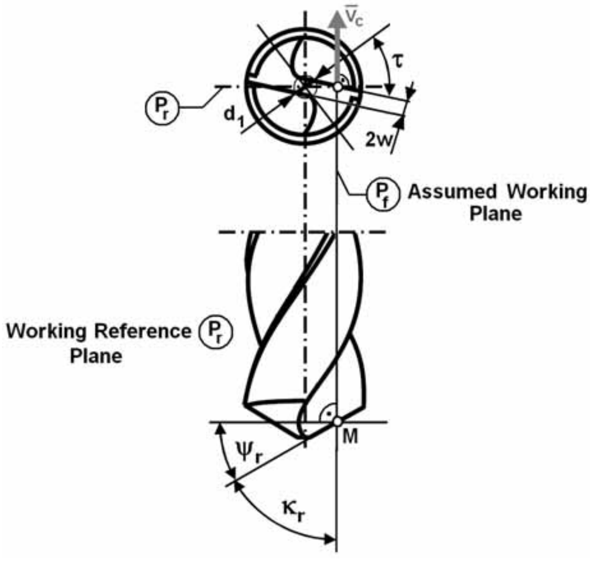

Figure 1. View showing geometric data of a twist drill.

Few theoretical works have been undertaken on drilling. Bera and Bhattacharya [2] described the first attempt to use a cutting model to determine torque and thrust in drilling. They analyzed the whole drill and considered that the chisel edge acted as an indenting tool and the lip as a cutting tool. They assumed that the resultant force per unit length of the lip is constant.

They assumed that the resultant force per unit length of the lip is constant. Williams [3] recognised the significance of the feed on the resultant velocity and on altering the cutting geometry. In making predictions of torque and thrust, Williams argued that a portion of the drill acted as an orthogonal cutting edge because the cutting velocity is assumed to be perpendicular to the cutting edge.

In 1972 Armarego and Cheng [4] proposed an approach to predict thrust and torque during drilling for a conventional drill and a modified drill in order to simplify the calculations. The method of calculation used the orthogonal cutting model and the oblique cutting model, and was also used in 1979 by Wiriyacosol and Armarego [5]. Basically, this method consists of dividing the cutting edges into a limited number of cutting elements. These elements were assumed to be oblique cutting edges on the cutting lip and orthogonal cutting edges on the chisel edge. The calculation used empirical equations established from orthogonal cutting tests. In most of the methods mentioned above, the major problem was to choose the number of cutting elements, and to determine the empirical equations for some cutting parameters.

More recently Watson [6–10] initially used practically the same method, with a different geometry. He developed a model for the chisel edge and the lip from the orthogonal cutting model and the oblique cutting model, respectively. The author initially used the same principle which consisted of dividing drill edges into a number of elementary cutting edges. Watson [7] recognised that the chips front the lips and the chisel edges are continuous across their width and that continuity imposes a restriction on the possible variation of the chip flow angle across those edges.

Other works have been interested in particular drilling operations, such as deep hole drilling [11,12], using an experimental model, and drilling with a three-cutting-edge drill [13,14]. Most of the models for drilling presented above were based on experimental measurements.

MODEL OF DRILLING

The model that will be studied in this work uses the geometry of a conventional twist drill. It is based on an analysis of the thrust and the torque continuity, from the force distribution along the cutting edges. It uses no preliminary experimental results. The purpose of the study is to establish predictive formulae to calculate thrust amid torque of drilling.

This theoretical model is based on the development of the shear zone model established by Oxley [15] for the cutting of metals, in the two cutting parts of a twist drill via the lip and the chisel edge. It is a purely analytical method, which makes it possible to determine thrust and torque according to the geometry of the tool and the cutting conditions. Although several investigations on drilling [2,3] have used the orthogonal cutting model to describe the deformation of the machined material about the lip and the chisel edge, other authors [4,5] have shown that the oblique cutting model gives a better approximation of the cutting mechanism for the lip. Concerning the chisel edge, its geometry does not set any major problem for the modelling of thrust and torque, except for the zone situated in the vicinity of the drill centre which will be discussed further in the article.

Before developing this model, it is necessary to give a geometrical characterization of a standard twist drill. Indeed, the form of a standard twist drill is characterized by the symmetry around its axis, and the type of sharpening. The three sharpening types most used for twist drills are described in the work of Armarego and Wright [16]. They are defined by geometrical parameters which depend on the cutting geometry of the two active parts of the twist drill, the lip and the chisel edge. These parameters are: $2\kappa_r$: point angle, τ: chisel edge angle, $2w$: lip spacing.

Parameters defined above are illustrated by Figure 1; they constitute the basic data for the determination of the necessary parameters used in the drilling force calculations.

The method used for the calculation of thrust and torque on the cutting lip of the drill consists of determining the element of the thrust dF_l, and the element of the torque dM_l for an element dl of the lip at an arbitrary point M on the edge, situated at a radius r from the drill axis. Force distributions along the lip are obtained using geometrical parameters, cutting conditions and properties of the machined material. Because of the symmetry around the drill axis the study will be done for one lip. The cutting geometry at a point M (Fig. 2) is such that the cutting speed and the tangent to the cutting edge at this point are not perpendicular. Consequently, an analysis using oblique cutting is a better approach to describe the cutting process on this part of the drill.

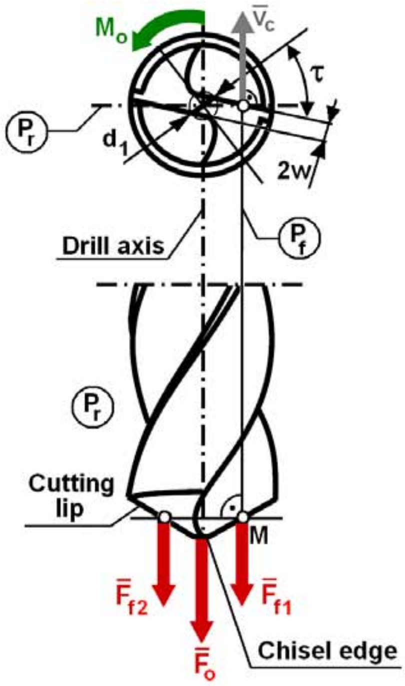

Figure 2. Edge geometry at a cutting point on the lip.

The geometry described in the work of Wiriyacosol and Armarego [5] for a conventional twist drill will be used to determine, according to the position of the cutting point M, trigonometrical relationships between the different angles. The speed of any point M on the edge situated at a radius r from the drill axis is also determined. The drilling investigations [4–10] have used existent models of orthogonal cutting and oblique cutting. Those models were based on the same technique of dividing the edges of the drill into elementary cutting edges, and applying thereafter on those edges, the oblique cutting model and the orthogonal cutting model.

The model proposed in this work was inspired by the previously mentioned works and takes the whole cutting edge into account. The notion of the number of elements is suppressed, as well as the preliminary experimental tests, which were necessary in the works mentioned above. This new model is continuous and predictive.

Determination of necessary parameters for the calculation of thrust and torque

Increments of thrust dF_{pr} and torque dM_{pr} are determined by supposing that the cutting geometry is approximately static ($f < 2\pi r$) along the cutting edges. Inclination angle i and rake angle γ_n at cutting point M are given by the following equations:

$$\lambda = \arcsin\left(\sin\omega \sin\kappa_r\right) \tag{1}$$

$$\gamma_n = \gamma_r - \eta \tag{2}$$

where κ_r is the half point angle of the tool. γ_r, ω and η are intermediate angles, and are calculated from the geometrical parameters of the drill by:

$$\omega = \arcsin\frac{w}{r} \tag{3}$$

$$\eta = arctg\left(tg\omega \cos\kappa_r\right) \tag{4}$$

and

$$\gamma_r = \frac{tg\,\delta \cos\omega}{\sin\kappa_r - \cos\kappa_r\, tg\,\delta \sin\omega} \tag{5}$$

where w is half of the distance between the two lips, and δ is the helix angle at point M, given by:

$$\delta = \frac{d}{2r} tg\,\delta_o \tag{6}$$

and δ_o is the helix angle at the periphery of the tool.
All the parameters quoted above depend only on radius r of point M from the drill axis and on the global drill geometry at this point. By using r and the geometry of the drill, an expression for the length of the lip can be obtained,

$$l = \frac{1}{\sin\kappa_r}\sqrt{\left(r^2 - w^2\right)} + \frac{d_1}{2}\cos\tau \tag{7}$$

where d_1 is the length of the chisel edge and τ is the angle between the chisel edge amid the lip d_1 and τ are shown in Figure 1. The differential element dl for the length of the cutting lip (Fig. 3) is given by:

$$l = \frac{1}{\sin\kappa_r}\frac{r}{\sqrt{\left(r^2 - w^2\right)}}dr \tag{8}$$

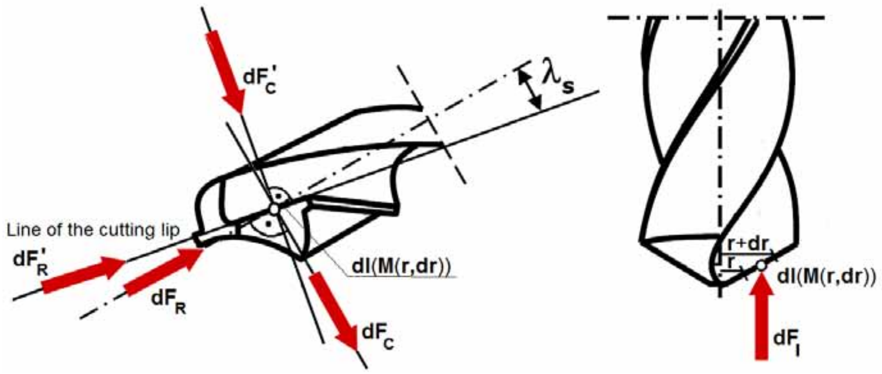

Figure 3. View of forces on the lip.

At each cutting point M, the cutting depth is obtained in terms of the feed speed f and the cutting geometry at this point. The following formula for t_1 can be established:

$$t_1 = \frac{f \sin\kappa_r \cos\eta}{2} \tag{9}$$

Calculation of the thrust force and the torque distributions

Determination of the increments dF_l and dM_{pr} at point *M* (Fig. 3) is undertaken using the oblique cutting model established by Oxley [15]. The basis of this model is to analyze the stresses along the shear plane and the tool/chip interface so that the resultant force transmitted by the shear plane and the interface are in equilibrium. The thrust force element dF_l and the torque dM_{pr} are determined in terms of the differential force dF_C in the direction parallel to the cutting speed V_c, the differential force dF_T in the direction perpendicular to the cutting speed and to the cutting edge at point M, and the differential force dF_R in the direction perpendicular to dF_C and dF_T as shown by Fig. 3. The differential element of shear force dF_s is given for an element of the lip dl by:

$$dF_s = \frac{k_s t_1 dl}{\sin\phi_n} \tag{10}$$

where, ϕ_n is the normal shear angle and k_s is the shear flow stress along the shear plane. ϕ_n and k_s are calculated using the model of Oxley [15]. Replacing t_1 and dl by their respective expression given in Eqs. (8) and (9), gives the following formula:

$$dF_s = k_s \frac{f \cos\eta}{2\sin\phi_n} \frac{r}{\sqrt{r^2 - w^2}} dr \tag{11}$$

Then it is possible to determine force components $dF_C^{'}$, $dF_T^{'}$, $dF_T^{'}$ (Fig. 3):

$$dF_C^{'} = dF_s \frac{\cos(\phi_n - \gamma_n)}{\sin\theta_n} \tag{12}$$

$$dF_T^{'} = dF_s \frac{\sin(\phi_n - \gamma_n)}{\cos\theta_n} \tag{13}$$

and

$$dF_R^{'} = \left(dF_C^{'2} + dF_T^{'2}\right)\frac{1}{2} \sin\lambda_n \, tg\,\eta_c \tag{14}$$

where $dF_C^{'}$ is normal to the cutting edge and situated in the plane of the cutting edge and the cutting speed, $dF_T^{'}$ is normal to the machined surface and $dF_R^{'}$ is normal to $dF_C^{'}$ and $dF_T^{'}$. Elements of force dF_C, dF_T and dF_R are then given by the following formulae:

$$dF_C = dF_C^{'} \cos\lambda + dF_R^{'} \sin\lambda \tag{15}$$

$$dF_T = dF_T^{'} \tag{16}$$

and

$$dF_R = dF_R^{'} \cos\lambda - dF_C^{'} \sin\lambda \tag{17}$$

where dF_C and dF_R are perpendicular and situated in the plane of $dF_C^{'}$ and $dF_R^{'}$. dF_C and dF_R make respectively an angle λ with $dF_C^{'}$ and $dF_R^{'}$. Elements of forces dF_T and $dF_T^{'}$ are identical. From these elements of forces at point *M*, the thrust force element dF_l and the torque element dM_{pr} are found from the following formulae:

$$dF_l = \left(dF_T^2 + \left(dF_C^2 \cos\lambda + dF_R^2 \sin\lambda\right)^2\right)\frac{1}{2} \sin(\lambda_n - \gamma_n - \eta)\sin\kappa_r - \left(dF_C \sin\lambda - dF_R \cos\lambda\right)\cos\kappa_r \tag{18}$$

$$dM_l = r dF_C \tag{19}$$

Substituting for the various force elements, the following formulae are obtained.

$$\frac{dF_l}{dr} = k_s \frac{f\, cos\,\eta}{2\, sin\,\phi_n\, cos\,\theta_n} A_1 \frac{r}{\sqrt{r^2 - w^2}} \tag{20}$$

with $A_1 = sin(\lambda_n - \gamma_n - \eta) sin\,\kappa_r - tg\,\eta_c\, sin\,\lambda_n\, cos\,\kappa_r$ and

$$\frac{dM_l}{dr} = k_s \frac{f\, cos\,\eta}{2\, sin\,\phi_n\, cos\,\theta_n} A_2 \frac{r}{\sqrt{r^2 - w^2}} \tag{21}$$

with $A_2 = cos\,\lambda\, cos(\phi_n - \gamma_n) + tg\,\eta_c\, sin\,\lambda_n\, sin\,\lambda$.

Besides the geometrical data of the drill and the cutting parameters at point *M*, it is necessary to know the normal friction angle λ_n, between the tool and the chip, the normal shear angle ϕ_n, the chip flow angle η_c and the relationship between the chip thickness and the cutting depth. The determination of these parameters is made from the shear zone model in oblique cutting [15]. Each parameter is a linear or non linear function of radius *r* which defines the distance from the cutting point to the drill axis. At each cutting point, tile oblique cutting model is applied. An iterative calculation is used to obtain tile normal shear angle ϕ_n. The convergence of the iteration allows the determination of the parameters quoted above. This operation is undertaken for all values of *r* in the range [$d_1/2$, $d/2$] so as to cover the entire lip.

Calculation of the total thrust force and the total torque

In calculating the shear angle, cutting forces etc. at a point *M*, the given information will be the tool normal rake angle λ_n, the cutting speed V_c, and the thickness t_1, together with the thermal and flow stress properties of the work material and the initial temperature of the work. The method of calculation uses the same iterations on the shear angle ϕ_n and the temperature along the shear zone T_{AB} as in the model of Oxley [15]. Knowing those elements of force and torque determined previously, which are given according to the position of point *M*, the total cutting force and torque are obtained by integrating the dM_l and dF_l expressions, from the boundary between the lip and the chisel edge to the periphery of the drill.

$$F_l = 2\int_{\frac{d_1}{2}}^{\frac{d}{2}} \frac{dF_l}{dr} dr \tag{22}$$

$$M_l = 2\int_{\frac{d_1}{2}}^{\frac{d}{2}} \frac{dM_l}{dr} dr \tag{23}$$

dF_l / dr, and dM_l / dr are replaced by their respective expressions, the following formulae are obtained:

$$F_l = 2\int_{\frac{d_1}{2}}^{\frac{d}{2}} k_s \frac{f\, sin\,\kappa_r\, cos\,\eta}{2\, sin\,\phi_n\, cos\,\theta_n} \left(sin(\lambda_n - \gamma_n - \eta) sin\,\kappa_r - cos\,\kappa_r\right) \frac{r}{\sqrt{r^2 - w^2}} dr \tag{24}$$

$$M_l = 2\int_{\frac{d_1}{2}}^{\frac{d}{2}} k_s \frac{f\, sin\,\kappa_r\, cos\,\eta}{2\, sin\,\phi_n\, cos\,\theta_n} cos(\phi_n - \gamma_n - \lambda) \frac{r}{\sqrt{r^2 - w^2}} dr \tag{25}$$

CONCLUSION

The idea of considering the lip as a series of elementary edges [3–9], which has been applied in the preceding works, does not take the mechanical reality of the cutting mechanism into account. Indeed, according to experimental observations, the chip is not fragmented along its width. For the cutting edges, the variation of the cutting parameters is significant, and cannot be neglected on an elementary cutting edge. Thus, the presented method is realistic and makes it possible to analyze the cutting process without any approximation that might introduce additional errors.

LITERATURE

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Streszczenie: *Model momentu i siły w procesie wiercenia*. W artykule przedstawiono teoretyczny model do przewidywania siły skrawania i moment przy wierceniu. Metoda polega na wyznaczeniu rozkładu siły i momentu wzdłuż krawędzi wiertła. Do obliczeń zastosowano model ortogonalnego skrawania. Siłę i moment uzyskuje się w zależności od cech geometrycznych narzędzia, warunków skrawania i właściwości obrabianego materiału. W nie uwzględniono wpływu ścina wiertła.

Corresponding author:

Krzysztof Szwajka
Faculty of Wood Technology
Warsaw Agricultural University
02-776 Warsaw
Nowoursynowska 159 str.
kszwajka@poczta.onet.pl