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PREDICTION OF THE MAIN CUTTING FORCE IN DRILLING BY KIENZLE EQUATION

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ABSTRACT
Drilling is one of the processes most used in the metal industry and was one of the first machining operations to be carried out historically. In the optimization of drilling, the techniques of modeling and simulation are important. The analysis of cutting forces in machining processes is very important for optimization of cutting parameters, power, costs and the cutting tool geometry. However, because of the high geometrical complexity of twist drills and the drilling process characteristics, analysis of cutting forces and their distribution along the cutting edges and other geometrical elements, are very difficult. This paper discusses prediction of the main cutting force in drilling by Kienzle equation. The study shows that values of the specific cutting force and Kienzle coefficient can be determinated during drilling tests.
Keywords: drilling, the main cutting force, Kienzle equation

1. INTRODUCTION
Drilling still remains one of the commonly used machining processes, whereby the operation involves making holes in a variety of materials. The main characteristic of drilling is the combination of both cutting and extrusion of metal, at the chisel edge, in the centre of the cutting tool. Therefore, accurate force models are a necessity for estimating the components of the force system acting on the drill's cutting edges in order to find optimized designs for new tool geometries, to improve quality, and to increase productivity.
There are more models which can be used for cutting forces calculation in drilling. One of them is Kienzle model which was developed 1952 [1]. Originally this model was developed for cutting forces calculation in turning process. After some time Kienzle model has been started to use for drilling process but coefficients of the Kienzle equation have been obtained through turning tests. This approach is only partially correct because each machining process has its own characteristics.In this paper a model for drilling forces was developed, which allows the use of the Kienzle equation for prediction of the main cutting force with coefficients which were obtained through drilling tests.

2. CUTTING FORCE MODEL FOR DRILLING
The drilling model here proposed simulates the main cutting force based on the specific force of the drilling process determined with the Kienzle model. Kienzle equation is empirical relationships that relate the cutting forces to the undeformed chip geometry. This can be defined by the following formula:

$$F_v = k_{v1.1} \cdot b \cdot h^{1-m_v} \qquad (1)$$

where F_v, the main cutting force (N); $k_{v1.1}$, specific cutting force is the specific cutting force required to detach a chip of undeformed chip width b=1 mm and undeformed chip thickness h=1 mm (N/mm^2); $1\text{-}m_v$, exponent which designates the gradient of the straight line $F_v=f(h)$ in the double logarithmic system [1]. .

Figure 1. shows cutting force components and cross-section of undeformed chip in drilling.

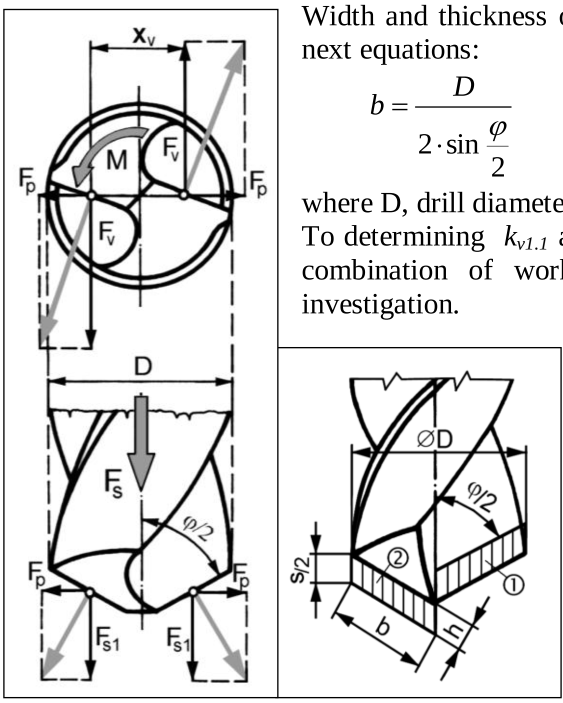

Figure 1. Cutting force components and cross-section of undeformed chip in drilling

Width and thickness of undeformed chip in drilling can be calculated by next equations:

$$b = \frac{D}{2 \cdot \sin \frac{\varphi}{2}} \qquad (2) \qquad\qquad h = \frac{f}{2} \cdot \sin \frac{\varphi}{2} \qquad (3)$$

where D, drill diameter (mm); f, feed (mm); φ, drill-point angle (°).

To determining $k_{v1.1}$ and $1\text{-}m_v$, cutting experiments are carried out for the combination of workpiece material and cutting tool material under investigation.

By analyzing the plan of cutting forces in drilling (Fig 1.) it is possible to conclude that the twist drill is affected by the following loads: torque, which is the result of the two partial main cutting forces F_{v1}, and thrust force as the sum of the two partial feed forces F_{s1}. The sum of penetration forces F_p is zero, only if two main cutting lips are identical and are symmetrical upon the drill axis. Measurement of the partial main cutting forces with dynamometer in drilling is technically unfeasible, because they cancel each other out (Fig 1.). The main cutting force F_v cannot be determined from the torque M because its leg x_v is not known.

The model that will be studied in this work is based on the assumption that there are three distinct cutting edges on a typical twist drill: the main cutting edges, the chisel edge and the margin of cutting edges. Various investigators have studied contribution of these cutting edges to the thrust force and torque. Their results are very different.

In this model, the cutting forces in drilling are composed of three elements: the force is generated by the main cutting edges, the force is generated by the chisel edge and the force is generated by margin of cutting edges.

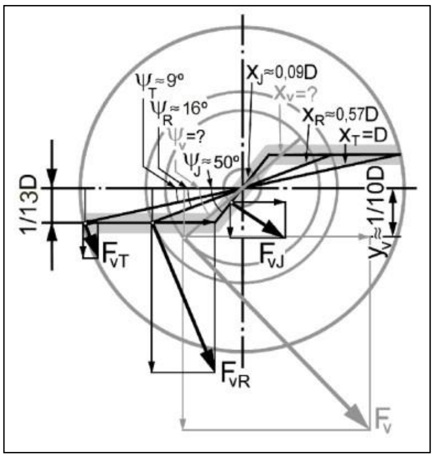

Figure 2. A plan of cutting forces on twist drill [2]

2.1. Determination of the main cutting force

The main cutting force F_v in drilling can be divided (similar to torque M) on the friction force F_{vT} (on the margin cutting edge), the real cutting force F_{vR} (on the main cutting edge) and the chisel edge force F_{vJ} (on the chisel edge) as it is shown in Figure 2. Values of these forces can be calculated from the previously determined partial torques and legs of force. Thus, friction force is $F_{vT} = M_T : x_T$, the real cutting force is $F_{vR} = M_R : x_R$ and the chisel edge force is $F_{vJ} = M_J : x_J$.

The main cutting force cannot be determined by simply adding components F_{vT}, F_{vR}, F_{vJ} because they don′t have the same direction as shown in Figure 2. Therefore, these cutting forces are projected on to the two mutual normal directions:

$$F_v \cos\psi_v = F_{vT} \cos\psi_T + F_{vR} \cos\psi_R + F_{vJ} \cos\psi_J \qquad (4)$$

$$F_v \sin\psi_v = F_{vT} \sin\psi_T + F_{vR} \sin\psi_R + F_{vJ} \sin\psi_J \qquad (5)$$

If partial cutting forces express by the torques which they make, equations will get the following form:

$$\frac{M}{x_v} cos\,\psi_v = \frac{M_T}{x_T} cos\,\psi_T + \frac{M_R}{x_R} cos\,\psi_R + \frac{M_J}{x_J} cos\,\psi_J \tag{6}$$

$$\frac{M}{x_v} sin\psi_v = \frac{M_T}{x_T} sin\psi_T + \frac{M_R}{x_R} sin\psi_R + \frac{M_J}{x_J} sin\psi_J \tag{7}$$

Values of partial torques can be expressed by the total torque, therefore $M_T = p_T \cdot M$, $M_R = p_R \cdot M$ and $M_J = p_J \cdot M$. Parameters p_T, p_R and p_J present participation of partial torques in the total torque. Partial torques can be determined sequentially by means of step drill experiments, as shown in Fig. 3.

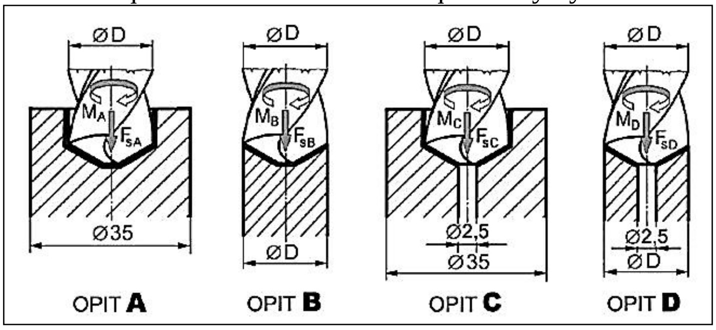

Figure 3. Experiment plan with four sub-experiments

Friction torque can be determined by experiments A and B, using $M_T = M_A - M_B$, the real cutting torque is given by experiment D so it is: $M_R = M_D$, and finally the torque from chisel edge was obtained from experiments A and C like: $M_J = M_A - M_C$.

The legs of partial cutting forces can be calculated by geometric dimensions of twist drill (Fig. 2), hence x_T=D, x_J=0,09·D and x_R=0,57·D. As illustrated in Fig. 2, angles between legs of partial cutting forces and drill axis which parallel on the main cutting edges can also be determined by drill geometry (ψ_T=9°, ψ_R=16°,ψ_J=50° or 52°). Angle ψ_v can be calculated using the equation below:

$$tg\psi_v = \frac{p_T \cdot sin\psi_T + 1/_{0,57} \cdot p_R \cdot sin\psi_R + 1/_{0,09} \cdot p_J \cdot sin\psi_J}{p_T \cdot cos\,\psi_T + 1/_{0,57} \cdot p_R \cdot cos\,\psi_R + 1/_{0,09} \cdot p_J \cdot cos\,\psi_J} \tag{8}$$

The leg x_v can be expressed as the function of component torques within the total torque (eq. 6), as is expressed below:

$$0,99 \cdot p_T + 1,69 \cdot p_R + 7,14 \cdot p_J = \frac{cos\,\psi_v}{k_1} \tag{9}$$

where, $k_1 = x_v/D$

3. EXPERIMENTAL RESULTS

The drilling tests were performed on Index GU600 machine tool. The development of the force model for drilling is based on C15 steel as the cutting material and standard twist drill with a diameter of 10 mm as the tool, both widely applied in industry, under different cutting conditions (six different feed rates were used; spindle speed was kept constant at 22,3 m/min). During the experiments, the torque was measured using Kistler dynamometer and sampled using a PC based data acquisition system with LabVIEW software.

The structure of total torque was determined from experiments A, B, C and D. Using the previously mentioned structure of total torque, partial torques were determined ($M_T = 0,19 \cdot M$, $M_R = 0,73 \cdot M$, $M_J = 0,08 \cdot M$). The values of angle ψ_v=28° and leg x_v=0,443·D were determined by Eq. (8) and Eq. (9).

By applying the values of the angle ψ_v, ψ_T, ψ_R, ψ_J and legs of partial cutting forces with relationship $F_{vT} = M_T : x_T$, $F_{vR} = M_R : x_R$, $F_{vJ} = M_J : x_J$, the Eq. (4) for calculating of the main cutting force will be:

$$F_v \approx 1,12 \cdot F_{vT} + 1,09 \cdot F_{vR} + 0,73 \cdot F_{vJ} \tag{10}$$

Values of the main cutting force were determined on the basis of the measurement results of the experiments A, B, C, D and Eq. (10). Width of undeformed chip was determined by Eq. 2 (D=10 mm, b=5,833 mm). The values $k_{v1.1}$ and 1-m_v were determined by graphical method. The requiered specific cutting force characteristic parameter $k_{v1.1}$ was determined by extrapoling the undeformed chip thickness to h=1 mm. The tangent of the angle between the straight line and the x-axis is the desired gradient value $1-m_v$. The results for Kienzle constants were $k_{v1.1}=1639,05$ N/mm^2 and $1-m_v=0,75$.

Comparison of empirical and experimental results of the main cutting force are summarized in Table 1, too. The empirical force values were calculated by using Kienzle equation.

Table 1. Values of the measured and calculated the main cutting force

f, mm/rev	h, mm (Eq. 3)	The main cutting force F_v, N		
		experimental	Kienzle equation (Eq. 1)	Error, %
0,056	0,0240	557,64	583,10	4,57
0,071	0,0304	677,30	696,71	2,86
0,089	0,0381	776,63	825,37	6,28
0,1125	0,0482	916,61	983,95	7,35
0,143	0,0612	1099,48	1177,9	7,13
0,179	0,0767	1395,23	1393,95	-0,09
Average error: 4,71 %				

4. CONCLUSION

The main cutting force cannot be measured directly by using dynamometer in drilling process. The paper presents a new approach for calculating the main cutting force in drilling. This approach includes contribution of the three distinct cutting edges of drill to the main cutting force. By applying the experiment plan with four sub-experiments were determined values of the main cutting force in drilling. These results were enabled determining of Kienzle constants through drilling tests. The Kienzle predicted cutting force values show a good comparison with those obtained experimentally. It is evidence that the Kienzle constants can be determined directly from drilling process. The method can be applied to other material combinations in order to obtain specific cutting force data for drilling operations with a minimum experimental effort.

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