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CUTTING TOOLS (TWIST DRILLS) WEAR EVALUATION VIA TORQUE

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Abstract**—**Development of process measuring systems for monitoring tools condition in real time is of utmost importance in contemporary production systems. The paper presents experimentally established correlations between torque, as a reliable bearer of tool wear information, and influential parameters in drilling steel of high hardness and strength (tempered steel). On the grounds of the established correlations, regression analysis was applied to result in a mathematical model which describes torque as the function of force.

Keywords**—**twist drill, durability, torque.

I. Introduction

BEING one of the most undetermined categories in the field of metal cutting, machinability represents an output resultant of the combination of a number of input parameters. Most often, it is evaluated by means of machinability criteria such as: tool durability, the quality of machined surface, cutting force, cutting temperature, the shape of borings, etc.

One of the basic functions of material machinability as well as one of the basic usability features of tools is the durability function defined as “the ability to maintain the cutting characteristics of tools during machining.” Durability is also a fundamental factor of cutting tools’ quality. It primarily depends on the intensity, nature and speed of wearing of certain cutting elements. Therefore, monitoring of the cutting elements wear provides for the most realistic picture of the tool wear in real time.

Monitoring of the tool condition in real time is of utmost importance due to the fact that the signals on the tool condition, which are generated, represent the main inputs for the systems of management and automation of machining and technological processes in production lines whereby the possibility of bad quality is being eliminated thus increasing the cost effectiveness of machining (cutting down on production costs).

The complexity of cutting process, conditioned by the influence of a number of influential and mutually collinear parameters, disables a reliable application of analytical methods and definition of mathematical models to predict mechanical, thermo-dynamical, tribological, chemical and other phenomena occurring in the cutting zone. Much more correct and reliable results, expressed in the form of a machinability function, are obtained by means of experimental-analytical method whereby the results of experiment (the established correlation between influential factors and the goal function) are used in regression analysis to introduce a mathematical (regression) modal of machinability function.

Direct out-process measuring methods in contemporary production lines are becoming a significantly limiting factor thus contributing to the development of online process measuring systems to be of supreme significance. The process methods most often in application are indirect methods whose basis comprises a set of various signals that originate from the units of a machining system (the machine, tools, workpiece) which correlate with wearing parameters. Researchers most often rely on cutting force, resistance and torque for information (signals) on tool wear. Thus, Spaić O., Krivokapić Z., and Ivanković R. [1] set up a mathematical model for cutting force as one of the most reliable information bearer on tool wear, on the basis of experimentally established correlation between axial cutting force and influential parameters (at drilling tempered steel) by applying regression analysis. The values of cutting force obtained in experimental butt milling, Tanakić D. and Manić M. [2] processed by means of regression analysis and aritificial neural netwroks. Lin J. T., Bahttacharya D. and Kecman V. [3] showed that measurement of cutting force can be applied in tool wear monitoring without interrepting cutting process. Using a comparative analysis of evaluation of tool wear on an 8mm diameter twist drill, Sanjay C., Neema M. L. and Chin C. W. [4] showed that modified regression equations could be used to evaluate tool wear values. In this paper, torque has been selected to be the bearer of information on tool wear phenomenon. On the grounds of the experimentally established correlations between torque, as a function of force, and influential parameters, regression analysis was applied to result in a mathematical model which describes tool condition in real time.

II. Experiment planning

Experimental research was conducted to establish correlations between torque, in the capacity of a function of force, and influential parameters. The Box-Wilson plan served as the basis with four-time repetition of experiment in the central plan point ($n_0 = 4$) according to the matrix plan of three-factor space [5], as illustrated in Table 1.

Table 1 - The matrix plan of there-factor space

Experimental points	Coded values								Real values			Output vector [M]
	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	d [mm]	n [rev/min]	s [mm/rev]	
1.	+1	-1	-1	-1	+1	+1	+1	-1	6.0	250	0.027	M_1
2.	+1	+1	-1	-1	-1	-1	+1	+1	10.0	250	0.027	M_2
3.	+1	-1	+1	-1	-1	+1	-1	+1	6.0	500	0.027	M_3
4.	+1	+1	+1	-1	+1	-1	-1	-1	10.0	500	0.027	M_4
5.	+1	-1	-1	+1	+1	-1	-1	+1	6.0	250	0.107	M_5
6.	+1	+1	-1	+1	-1	+1	-1	-1	10.0	250	0.107	M_6
7.	+1	-1	+1	+1	-1	-1	+1	-1	6.0	500	0.107	M_7
8.	+1	+1	+1	+1	+1	+1	+1	+1	10.0	500	0.107	M_8
9.	+1	0	0	0	0	0	0	0	7.75	355	0.053	M_9
10.	+1	0	0	0	0	0	0	0	7.75	355	0.053	M_{10}
11.	+1	0	0	0	0	0	0	0	7.75	355	0.053	M_{11}
12.	+1	0	0	0	0	0	0	0	7.75	355	0.053	M_{12}

2.1. Experiment conditions

The experiment involved drilling of a blind hole, depth *L=3d* in test tubes made of Cro-Mo alloyed tool steel for enhancement Č.4732, thermally treated to 43-45 HRC hardness, with twist drills (TD) DIN 338 made of high-speed steel with 8% Co produced by conventional technology (S2-9-1-8) with cruciform blade.

The TD was designed in line with recommendations from respective references in relation to drilling poorly machinable materials – tempered steels – and on the grounds of gained experience. The drills were produced by grinding technology. The geometrical parts of TD are shown in references [5].

Cutting regimes were set up to follow the referred recommendations for drilling steel of high hardness and strength thus fulfilling the following conditions:

$d_{sr}^2 = d_{\min} \cdot d_{\max}$, $n_{sr}^2 = n_{\min} \cdot n_{\max}$ i $s_{sr}^2 = s_{\min} \cdot s_{\max}$.

For cooling and lubrication, the 8% H/VR s teolin solution was used in the quantity of 1 l/min.

For measurement of torque, the 3D dynamometer was used – “Kistler”, TYP 8152B2 – integrated with a conventional milling machine, TYP FGU-32, and connected to the software Global Lab for data acquisition in the laboratory at the Faculty of Mechanical Engineering in Podgorica, as illustrated in Figure 1.

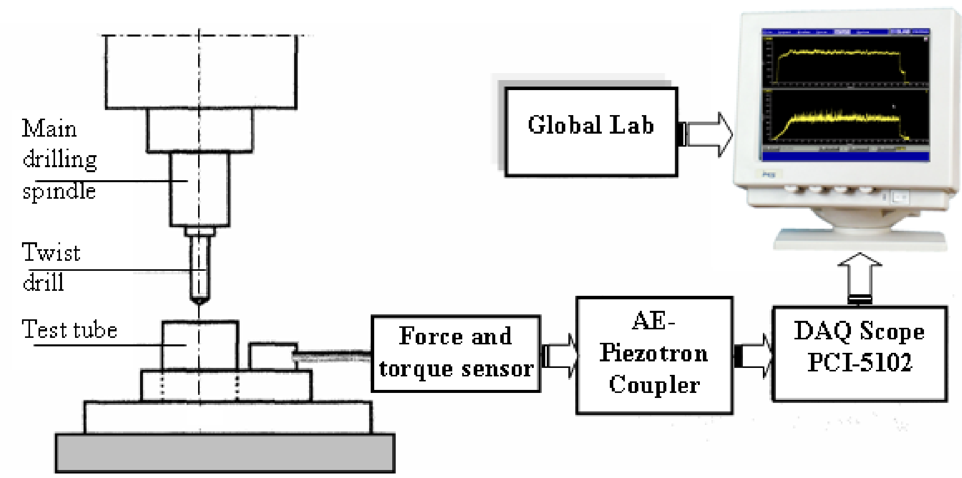

Fig. 1- Axial force and torque measurement scheme during experiment [5]

III. EXPERIMENT RESULTS

Torque measurement was conducted according to the plan matrix with the achieved drilling lengths stated below (in mm) whereby TD wear achieved the following maximally allowed (defined in advance) values:

- for TD Ø6.0 mm – 0.25 mm,
- for TD Ø7.75 mm – 0.30 mm, and
- for TD Ø10.0 mm – 0.35 mm.

The maximal tool wear value was taken to be the mean value of the wear belt in the back area ($B \approx 0.04d$) at the border of regular area which is at 0.25mm distance from outside fibres (Fig. 2).

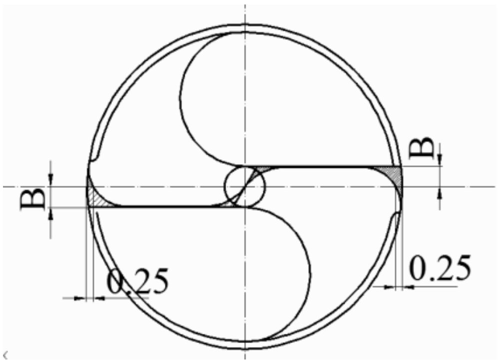

Figure 2 - Twist drill wear

At different cutting regimes (the nominal diameter, the number of turns, and the feed) the TDs reached the maximally allowed wear value at different drilling lengths. The torque values measured at maximal wear size are shown in Table 2.

Table 2 - The torque values at maximal TD wear size

Exp. No	d [mm]	n [rev/min]	s [mm/rev]	l_{max} [mm]	M_{max} [Nmm]
	6.0	250	0.027	610.00	166.00
2.	10.0	250	0.027	1100.00	239.34
3.	6.0	500	0.027	3690.00	107.30
4.	10.0	500	0.027	5800.00	185.80
5.	6.0	250	0.107	2700.00	294.25
6.	10.0	250	0.107	3820.00	550.60
7.	6.0	500	0.107	5850.00	283.44
8.	10.0	500	0.107	800.00	490.43
	7.75	355	0.053	2750.00	186.30
	7.75	355	0.053	2336.63	211.70
	7.75	355	0.053	2336.63	196.60
	7.75	355	0.053	2336.63	236.20

IV. ANALYSIS OF THE RESULTS

By means of experimental-analytical method, that is, the experiment planning theory and the regression analysis theory, torque can be expressed in the form of an exponential function:

$$M = Q \cdot \prod_{j=1}^{k} x_j^{q_j} \qquad (1),$$

where:

x_j – (j = 1,2,...,k) - are input paramaters influencing cutting process,

Q – is the coefficient of other factors' influence on cutting process, and

q_j (j = 1,2,...,k) – are the exponents of input parameters' influence on cutting process.

Torque M being the information bearer on the size of wear at drilling, provided other conditions are unaltered, is in the function of cutting regime (TD nominal diameter, the number of turns and the feed):

$M = f(d, n, s)$, as illustrated in Figure 3.

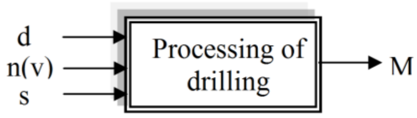

Figure 3 - Torque dependence on cutting regime

According to the equation (1), the twist drills' torque can be described by means of an empirical model in the following form:

$$M = C_M \cdot d^x \cdot n^y \cdot s^z \text{ [Nmm]} \qquad (2),$$

where:

d – is the twist drill nominal diameter [mm],

n – is the number of turns [rev/min],

s – is the feed [mm/rev],

C_M – is the coefficient of measurable parameters' influence,

x, y and z – are the exponents of measurable parameters.

If linearized, model (2) can be expressed in the form of a first order regression model:

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \qquad (3),$$

where:

$$\hat{y} = \ln M,\ b_0 = \ln C_M,\ x_1 = \ln d,\ x_2 = \ln n,\ x_3 = \ln s.$$

Model (3) can undergo application of the first order orthogonal plan with constant members whereby coding is performed by means of transformation in the form of equations:

$$x_1 = 1 + 2 \cdot \frac{\ln d - \ln d_{max}}{\ln d_{max} - \ln d_{min}},$$

$$x_2 = 1 + 2 \cdot \frac{\ln n - \ln n_{max}}{\ln n_{max} - \ln n_{min}},$$

$$x_3 = 1 + 2 \cdot \frac{\ln s - \ln s_{max}}{\ln s_{max} - \ln s_{min}} \qquad (4).$$

Determination of the model parameters' values was based on the following equations:

$$b_0 = \frac{1}{M}\sum_{u=1}^{M} x_{0u} \cdot y_u,$$

$$b_i = \frac{1}{N}\sum_{u=1}^{N} x_{iu} \cdot y_u,\ i = 1\text{-}3 \qquad (5),$$

where:
$M = 2^k + n_0$ – total number of measurements,
$N = 2^k$ – number of measurements on hypercube vertex as shown in Table 3.

Table 3 - Model parameters

Model parameters	b_0	b_1	b_2	b_3
	5.471	0.261	-0.105	0.418

4.1. Evaluation of the significance of coefficients

Evaluation of the significance of model parameters, i.e. verification of the null hypothesis, that the deviation of given paramater from zero is a result of the action of accidental paramaters and not of the measurable and controlable ones, was performed by means of Student's criterion as follows [6]:

$$t_j = \frac{|b_j|}{s_{bj}},\ j = 1\text{-}3 \qquad (6),$$

where:
s_{bj} – is the assessment of model paramaters' variances.
In the light of the fact that the experimental research was conducted in line with Box-Wilson's plan of the first system repetition whereby one measuring is performed in each plan point except for the central point in which the experiment is repeated n_0 times, the values of dispersion of experiment results were defined as follows:

$$s_y^2 = \frac{S_E}{f_E} = \frac{1}{n_0 - 1}\sum_{i=1}^{n_0}\left(y_{i0} - \bar{y}_0^2\right)^2,$$

$$s_y^2 = 0.010558 \qquad (7),$$

where:
S_E – is the sum of squared measurings deviation in the central plan point,
$\bar{y}_0$ – is the mean value of measurement results in the central plan point,
$f_E = n_0 - 1 = 3$ – is the number of freedom degree at the assessment of variance, and
y_{i0} – are the results of measuring in the central plan point.

Assessment of the variances for b_0 was performed on the basis of the reults of measurings in all plan points in line with the model:

$$s^2(b_0) = \frac{1}{M}s_y^2,$$

$$s^2(b_0) = 0.0008798 \qquad (8),$$

and for the paramater b_j on the basis of the results of measurings in the points along the vertices of hypercube:

$$s^2(b_j) = \frac{1}{N}s_y^2,$$

$$s^2(b_j) = 0.00132 \qquad (9).$$

The relevant freedom degrees are:
$f_{b0} = M - 1 = 11$ i $f_{bi} = N - 1 = 7$.
For the adopted level of significance $\alpha = 5\%$ and respective numbers of freedom degrees from the Student's distribution table [6], the table values of Student's quantities are the following:
$t_{b0,1-q/3,11} = 2.20$ i $t_{bi,1-q/3,7} = 2.36$.
By applying model (6), the values of t_j were calculated and assessments shown in Table 4.

Table 4 - Student's quantities and assessment of significance

St. squar.	t_{b0}	t_{b1}	t_{b2}	t_{b3}
	184.46	7.19	2.81	11.52
Assessment of sign.	sign.	sign.	insign.	sign.

Given the $t_{b0} > t_{b0,1-q/3,11}$, $t_{b1} > t_{b1,1-q/3,7}$ i $t_{b3} > t_{b3,1-q/3,7}$, the null hypotheses on evaluation of the regression coefficient t_{b0}, t_{b1} i t_{b3} were not verified. The model paramaters t_{b0}, t_{b1} i t_{b3} are significant and sustained in the model. The null hypothesis related to paramater t_{b2} was verified due to $t_{b2} < t_{b2,1-q/3,7}$, thus rendering parameter b_2 insignificant and possible to be excluded from the model.

However, for the purpose of obtaining more correct results, the insignificant parameter b_2 was sustained in the model thus rendering the regression model in the coded coordinates:

$$\hat{y} = 5.471 + 0.261x_1 - 0.105x_2 + 0.418x_3 \qquad (10).$$

Returning to the initial coordinates, by means of equations of coding stated in Table 5 the mathematical model of the torque was specified as follows:

$$M = \frac{1030.65 \cdot d^{1.023} \cdot s^{0.608}}{n^{0.304}} \qquad (11).$$

Table 5 – Model parameters

Influence coefficient of immeasurable parameters	$\ln C_M = b_0 + b_1 + b_2 + b_3 - 2\cdot\left[b_1 \frac{\ln d_{\max}}{\ln \frac{d_{\max}}{d_{\min}}} + b_2 \frac{\ln n_{\max}}{\ln \frac{n_{\max}}{n_{\min}}} + b_3 \frac{\ln s_{\max}}{\ln \frac{s_{\max}}{s_{\min}}} \right]$		
Exponents of measurable parameters	$x = \frac{2b_1}{\ln \frac{d_{\max}}{d_{\min}}}$	$y = \frac{2b_2}{\ln \frac{n_{\max}}{n_{\min}}}$	$z = \frac{2b_3}{\ln \frac{s_{\max}}{s_{\min}}}$

4.2. Model adequacy verification

The model adequacy verification includes comparison of residual variance to the experimental one. Considering the fact that the central plan point is adjoined to the experiment plan within orthogonal plans with n_0 number of experiment repetitions in the central point, in Fisher's criterion of model verification it is necessary to replace residual dispersion with dispersion of mean values of the experimental results in relation to the regression line.

Therefore, it is necessary to calculate the residual sum of squared deviations of model values from experimental data:

$$s_R = \sum_{i=1}^{M} (y_i - \hat{y}_i)^2,$$

$$s_R = 0.202 \qquad (12).$$

The appropriate variance is:

$$s_R^2 = \frac{s_R}{M - (k+1)},$$

$$s_R^2 = 0.010 \qquad (13),$$

where $M-(k+1)=8$ is the number of freedom degrees, which equals the total number of observations M minus the number of coefficients k+1.

Applicable variance to verify the model is:

$$s_{ad}^2 = \frac{s_{ad}}{M - (k+n_0)},$$

$$s_{ad}^2 = 0.034 \qquad (14),$$

thus rendering the following variances ratio for evaluation of the model adequacy:

$$F = \frac{s_{ad}^2}{s_y^2} = \frac{0.034}{0.010} = 3.233 \qquad (15).$$

The calculated value $F = s_{ad}^2 / s_y^2 = 3.233$ being lesser than the table values $F_{1-0.005,5,3} = 9.013$ [7] the hypothesis on model adequacy is verified, that is, the introduced model adequately describes the observed response function.

Experimental and module values of the torque as well as deviation of module values from the experimental ones in the experiment points are shown in Table 6.

Table 6 – Module values of the torque

Exp. No.	Experimental values	Module values	Error %
1.	166.00	133.89	19.34
2.	239.34	225.70	5.70
3.	107.30	108.46	-1.08
4.	185.80	182.87	1.58
5.	294.25	309.18	-5.07
6.	550.60	521.32	5.32
7.	283.44	250.44	11.64
8.	490.43	422.29	13.89
9-12.	207.70	235.59	-13.43

The table shows the percentage of maximal deviation of module values from experimental values, 19.34%, at minimal values of influential measurable parameters, i.e. cutting regime.

V. CONCLUSION

The introduced mathematical model shows that cutting, being a highly complex process of physical-chemical actions of the tools and workpiece, in the conditions of disperison of features and properties of the technological system elements can be monitored via torque as one of the bearers of the wear information.

Cutting tools wear at machining steel of high hardness and strength (tempered steel) the intenisty, character and speed of which greatly influence durability of cutting tools, depends on all varied parameters: the nominal diameter, the number of turns, and the feed.

The torque, as one of the process indirect methods of measuring, can be successfully used in measuring cutting tools wear instead of direct measuring methods.

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