DETERMINATION OF CUTTING FORCES AT DRILLING MEDIUM-ALLOY CARBON STEEL

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Abstract: *This paper presents the application of an experimental method for determining the numerical values of the machinability factors of medium alloy carbon steel in the drilling process. Research conditions are defined, including tools, machine, and machining parameters. The experiment was performed according to a two-factor orthogonal experimental plan, and the values of cutting forces were monitored using a dynamometer through other elements of the information measuring system. Cutting forces were also considered in relation to the drilling depth.*

Keywords*: DRILLING, CUTTING FORCES, MACHINABILITY, INFORMATION MEASUREMENT SYSTEM*

1. Introduction

Drilling is one of the most common cutting methods used in industrial production [1]. Despite the relatively simple appearance of the cutting tool and the scope of its use, the drilling process is not fully defined due to a large number of influencing parameters. For example, the cutting action is poor near the axis of the cutting tool (twist drill bit) due to the relatively low cutting speed. For a conventional twist drill, the action in the center is more extrusion (deformation) than a cutting process [2], therefore a greater axial force is required to enter the twist drill into the workpiece, so the amount of heat produced is significant. This heat depends on the type of material being drilled and it can have a favorable or unfavorable effect on the cutting process itself. In addition to the geometry of the twist drill, the drilling process itself is affected by a number of other variables such as the material of the drill bit, the material being drilled, the drilling machine, and the cooling and lubrication fluid used, etc. During the drilling process, the drill, as a double-edged tool, suffers high stress due to the effect of cutting force, significant additional deformations of the chip, and due to friction in contact with the chip and the hole surface. Knowing the cutting force plays an important role in determining the following procedures:

- evaluation and optimization of the cutting process through the criterion of tool wear, which is directly related to the cutting force,
- the behavior of the material and its workability,
- development and optimization of cutting tools,
- to determine the influence of forces on certain quality parameters of the finished product,
- to control machines and processes with adaptive feedback through the collection of these values in real-time.

Machinability is the suitability of a material to be machined by cutting. The term machinability of materials is complex and is considered simultaneously from several aspects and under different processing conditions. Thus, for example, a material with good machinability in drilling may have low machinability in drawing, etc. [3]. Machinability can be determined using several methods such as tool life monitoring, cutting force measurement, energy consumption measurement, machined surface roughness, and chip shape [4]. Machinability primarily depends on the physical and mechanical properties of the material, the chemical composition, and the structure of the material. Expressions for the main processing factors, which are determined experimentally, are most often used to evaluate the machinability of a material. Machinability constants express the influence of the primary group of factors (drill bit diameter and feed rate) on drilling torque M_c and axial drilling force – feed force F_f. They represent the main cutting forces during the drilling process [5], [6], and the values of these quantities are described by empirical expressions [7]:

$$M_c = C_M D^{x_1} f^{y_1} \quad (1)$$

$$F_f = C_F D^{x_2} f^{y_2} \quad (2)$$

Where D – drill diameter and f – feed rate are varied factors, ie input values, C_M and C_F machinability constants, and x_1, y_1, x_2, y_2 machinability parameters.

2. Defining research conditions

The workpieces used in this research are cylindrical in shape, base diameter, and height of 30 mm, made of medium alloyed carbon steel C45, hardness 210 HB (Figure 1). This alloy is widely used in industry in applications where a material with higher strength and anti-wear properties is needed in operation. Some of the products obtained from this alloy are gears, bolts, axles and shafts, connecting rods of ICE engines as well as many other machine elements.

Figure 1 shows the eight workpieces made based on the adopted experimental plan, four of which are used in the central points of the plan.

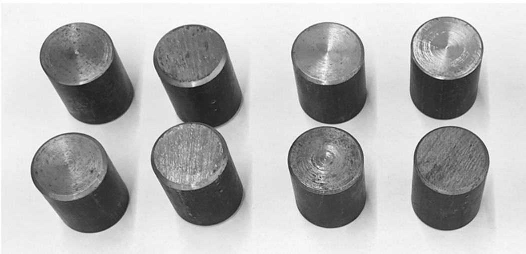

Fig 1 *Experimental workpieces made of medium alloyed carbon steel C45*

A cutting tool (twist drill) has several geometric design parameters such as point angle, chisel edge angle, web thickness, the angle of the helix, etc [8]. Each of these parameters affects the cutting force and the quality of drilled holes in different ways. In addition to the geometric parameters, important factors of the cutting tool are the material, the size of the twist drill, as well as the condition.

Cutting forces are defined through the resulting force of material to cutting. When machining by drilling, as well as when machining by turning, the blade of the cutting wedge acts with the resulting cutting force that can be broken down into three components (Fig 2).

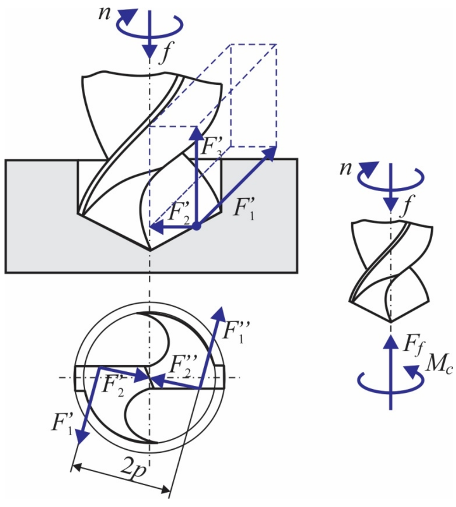

Fig 2 *Cutting forces at drilling*

The main cutting forces F_1' and F_1'' during drilling create a torsional load (drilling torque M_c), the passive forces F_2' and F_2'' are on the same line and in the opposite direction, so they are balanced, and the auxiliary movement forces for both blades are collinear, so add up and their resulting force is called feed force F_f [9].

When conducting experimental research, the diameter of the twist drill varied according to the adopted experimental plan, and the adopted twist drills were with a cylindrical handle and a point angle of 118 °.

Figure 3 shows the cutting tools used (twist drills with a diameter of Ø12 mm, Ø8.5 mm, and Ø6 mm made of high-speed steel - HSS).

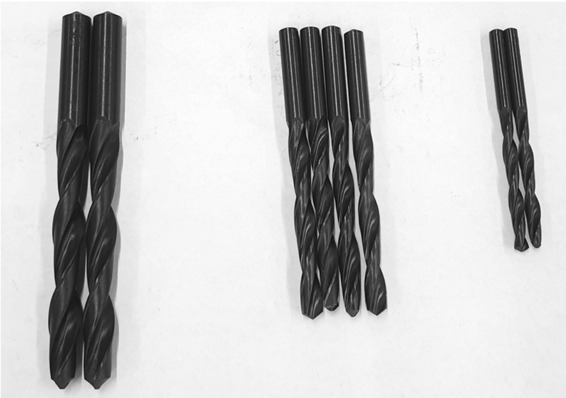

Fig 3 *Twist drills made from HSS*

The machine used in the experimental research is a drill press BD-40. The power of the machine is 3 kW, the height of the working space is 710 mm, and the length of the riser is 200 mm. The machine has 9 degrees of the main movement in the range between 63 rpm and 1000 rpm, as well as 9 degrees of auxiliary movement in the range between 0.08 mm/rpm and 1.25 mm/rpm.

3. Experimental research

In order to obtain the values of the constants and machinability parameters for the given material, it was necessary to carry out experimental research according to the experimental plan with the monitoring of the values of the forces using an information measuring system.

3.1 Information measurement system

The information measurement system includes several components of modern measuring equipment, the joint effect of which ensures reliable results. The block diagram of this measuring system is given in Figure 4.

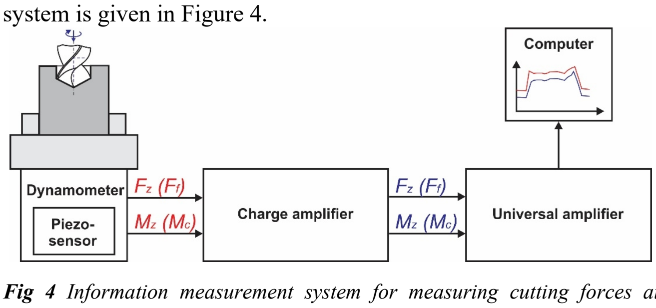

Fig 4 *Information measurement system for measuring cutting forces at drilling*

Dynamometer (Kistler 9271A) – works on the principle of the piezoelectric effect and provides a dynamic and quasi-static measurement of two components of drilling force, drilling torque (M_c) and auxiliary movement force (F_f). The dynamometer has high stiffness and therefore a high natural frequency. Its high resolution enables even the smallest dynamic changes in the large forces that the device measures. The measuring range of the vertical force is from -5 kN to 20 kN, while the drilling torque is in the measuring range from -150 Nm to 150 Nm.

Integrator (Kistler 5806) – the charge produced by a piezoelectric sensor is a variable that is difficult to measure due to its nature. For this reason, an electronic device known as an integrator or charge amplifier is connected to the sensor, in order to convert the electric charge into a voltage signal. The charge amplifier converts the negative charge produced by the piezoelectric sensor when subjected to a force load into a positive voltage that is proportional to the charge and thus to the applied force. Due to their working principle, force sensors have a negative sensitivity and they produce a negative charge under load.

Universal measuring bridge (HBM QuantumX MX840B) – is a universal amplifier with 8 channels. It is a combination of an AD converter and an amplifier, which digitizes and amplifies the electrical voltage signal it receives. Each channel allows acquisition with over 15 different types of sensors. It uses as input connector fifteen-pin DSUB15HD. All channels are electrically isolated from each other and from the power inputs.

Computer – HBM Catman software package is installed on it for display and acquisition of data obtained from the universal amplifier.

3.2 Experimental design

For the design of the experiment, a two-factor orthogonal design was adopted with varying factors at two levels, with four repetitions at the central point of the design. The number of experimental points N, for the number of factors k, which in this case are the diameter of the drill D and the feed f, varied on n levels with the number of repetitions n_0 in the central point, is calculated according to the following expression:

$$N = n^k + n_0 \tag{3}$$

From this expression, we see that the number of experiments is for the adopted values $N = 8$.

The interval limits of the input factors are adopted according to the condition:

$$X_{0i}^2 = X_{ui} \cdot X_{li}, i = 1,2, \ldots, k \tag{4}$$

Based on preliminary research, processing parameters were adopted for the given medium-alloyed carbon steel (percentage of carbon $C = 0.44$ %), and a cutting speed of 21 m/min was adopted.

Table 1 shows the varied values of the cutting mode at three levels (upper, lower, and center).

Table 1: *Values of varied factors of the experimental plan*

Input factors	Upper level (+)	Lower level (-)	Center level (0)
$X_1 = D$	12	6	8.5
$X_2 = f$	0.22	0.11	0.16

Based on the relation $v = f(D,n)$, the values of the number of revolutions n, which are given in Table 2, were obtained and based on the defined values, the plan matrix of the experiment was adopted, which is given in Table 3.

Table 2: *The obtained values of the angular speed for the adopted cutting speed of* 21 *m/min*

Drill diameter mm	Adopted angular speed rpm
Ø6	1000
Ø8.5	710
Ø12	500

3.3 Conducting experimental research

As part of the experimental research phase, the cutting force was measured (force of auxiliary movement F_f and drilling torque M_c) in accordance with the adopted experimental plan. The execution of experimental points is taken in order from the experimental plan matrix. Experimental research was done in laboratory conditions, and the research site is shown in Figure 5, where modern research measuring equipment was installed on the BD-40 drill press. The drilling depth of the workpieces is defined and is 20 mm.

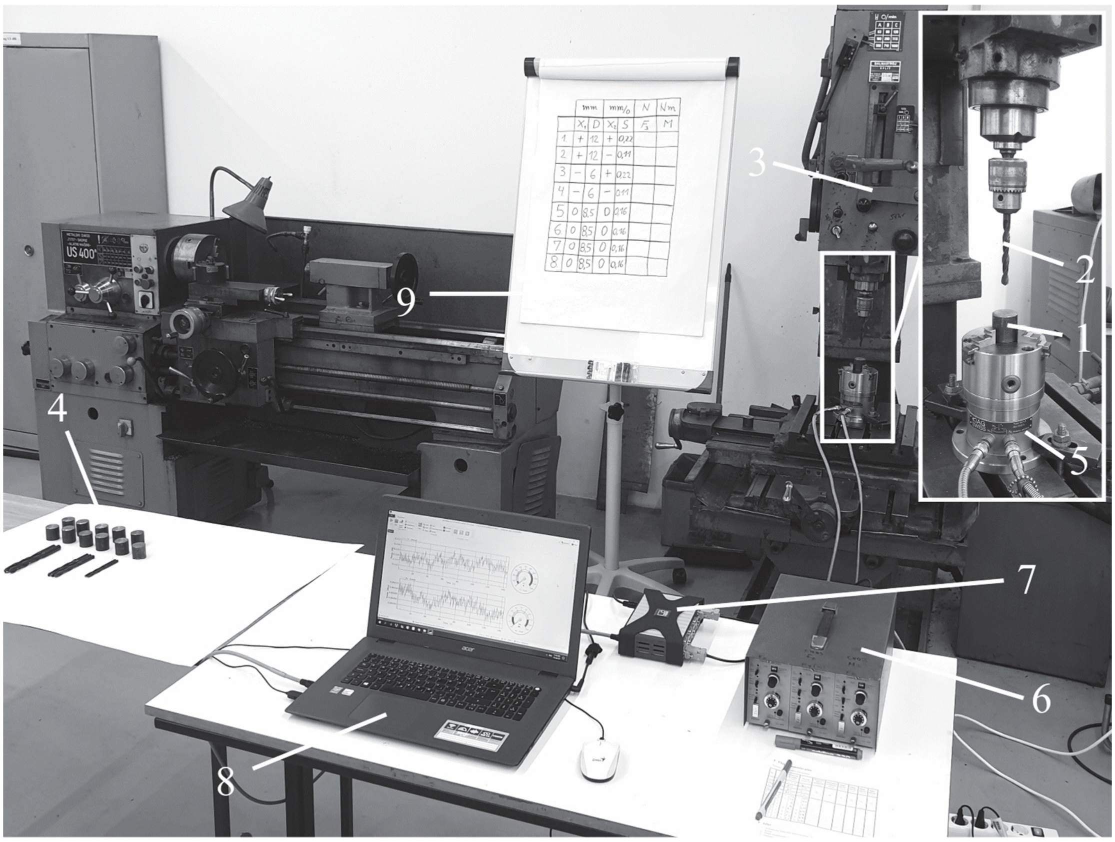

Fig 5 *Research site: 1 – workpiece, 2 – cutting tool (twist drill), 3 – machine (drill press BD-40), 4 – workpieces and tools for experimental points, 5 – sensor (piezo-electric dynamometer), 6 – charge amplifier, 7 – universal amplifier, 8 – a computer with acquisition software, 9 – experiment matrix plan*

The obtained form of the functional relationship of the cutting force on the varied parameters, as the output data of the information measuring system, is given in Figure 6. The maximum displayed value during the measurement was considered.

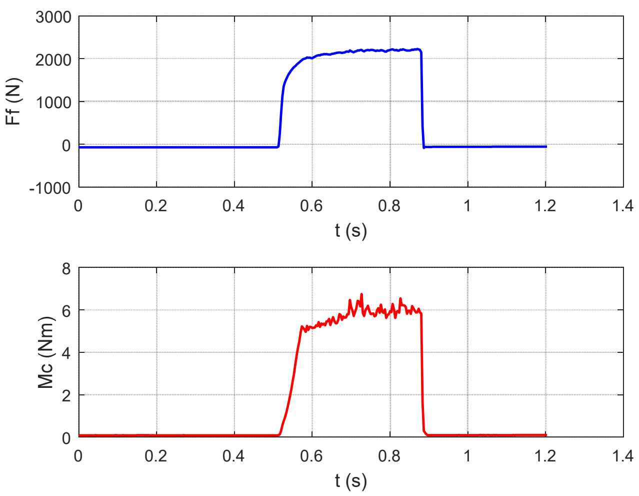

Fig 6 *Cutting forces values at the point of the experimental plan number 7..*

The diagram shows an increase in cutting force in proportion to the increase in drilling depth up to the final value of 20 mm.

Figure 7 shows drilled samples with corresponding chips obtained for parameters and tool diameters selected according to the experimental plan. The samples are arranged in such a way that the upper left sample belongs to Experimental Point 1, etc.

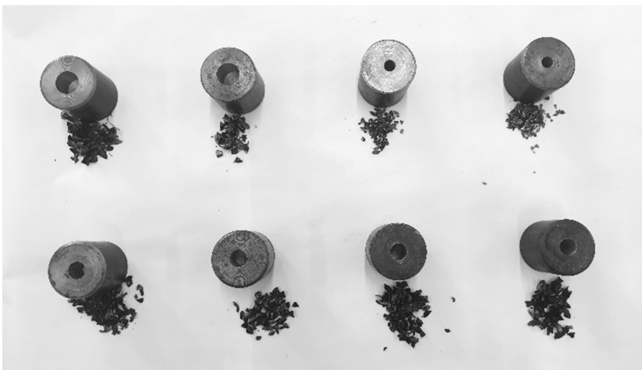

Fig 7 *Experimental samples drilled according to the points of the experimental plan*

Table 3: *Plan matrix of the experiment*

No.			Drill diameter mm		Feed rate mm/rpm		Feed force N	Drilling torque Nm
	X_0		$X_1 = D$		$X_2 = f$		Output vectors (y)	
X_{ui}	1		12		0.22		F_f	M_c
X_{li}	1		6		0.11			
X_{0i}	1		8.5		0.16			
1.	+	1	+	12	+	0.22	3913	13.38
2.	+	1	+	12	-	0.11	2368	8.09
3.	+	1	-	6	+	0.22	1294	4.4
4.	+	1	-	6	-	0.11	901	2.76
5.	+	1	0	8.5	0	0.16	2120	6.27
6.	+	1	0	8.5	0	0.16	2150	6.49
7.	+	1	0	8.5	0	0.16	2229	6.75
8.	+	1	0	8.5	0	0.16	2267	6.26

Using the regression analysis of the experimental results, the values of the coefficients and machinability parameters were determined. First, equations (1) and (2) were translated into logarithmic form, so we get equations of the form:

$$y = b_0x_0 + b_1x_1 + b_2x_2 \quad (5)$$

Where b_0, b_1, and b_2 linear regression coefficients are determined based on the expression:

$$b_o = \frac{1}{8} \cdot (y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7 + y_8) \quad (6)$$

$$b_1 = \frac{1}{4} \cdot (y_1 + y_2 - y_3 - y_4) \quad (7)$$

$$b_2 = \frac{1}{4} \cdot (y_1 - y_2 + y_3 - y_4) \quad (8)$$

Finally, the values of the constants and machinability parameters are determined from the expression:

$$lnC_F = b_o + b_1 + b_2 - 2 \cdot \left(b_1 \cdot \frac{lnD_{max}}{ln\,{}^{D_{max}}/_{D_{min}}} - b_2 \cdot \frac{lns_{max}}{ln\,{}^{f_{max}}/_{f_{min}}} \right) \quad (9)$$

$$x_i = 2 \cdot \frac{b_1}{ln\frac{D_{max}}{D_{min}}} \quad (10)$$

$$y_i = 2 \cdot \frac{b_2}{ln\frac{f_{max}}{f_{min}}} \quad (11)$$

The resulting values of the machinability parameters can be seen in the decoded version of the empirical equations for the Drilling torque in Nmm and Feed force in N in the drilling process:

$$M_c = 783.4D^{1.578}f^{0.699} \quad (12)$$

$$F_f = 259.8D^{1.495}f^{0.623} \quad (13)$$

4. Conclusion

Cutting processes belong to very complex stochastic processes with a large number of influencing parameters. The effect of parameters on the investigated quantities is non-linear and accompanied by complex interactions, so obtaining theoretical analytical models in a closed form, despite the efforts of a large number of researchers, is practically not possible. These laws are especially pronounced in the drilling process, which is the subject of our research.

For the process of drilling medium alloy carbon steel, based on the analysis of previous research and our own experiences, a model was proposed which is assumed to be able to adequately describe our researched process, i.e. to accurately approximate the unknown analytical form. The diameter of the drill bit *D* and the feed rate *f* are considered as input parameters, while the outputs of the analyzed process are the Feed force F_f and the Drilling torque M_c. The coefficients of the proposed model were determined by regression analysis of experimental data. The experiment was performed on the basis of a two-factor orthogonal experimental design. The results were obtained using an information measurement system that includes several interconnected components whose synergistic action obtained the results.

These results are very applicable to the investigated process, while the proposed methodology is applicable to a wide class of problems in cutting processing.

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