Bulletin of the *Transilvania* University of Braşov
Series I: Engineering Sciences • Vol. 5 (54) No. 1 - 2012

MATHEMATICAL MODEL FOR DRILLING CUTTING FORCES OF 40CrMnMoS8-6 STEEL

I. BĂDAN[1] Gh. OANCEA[1] M. VASILONI[1]

Abstract: *The paper presents the methodology for obtaining a mathematical model which calculates the drilling cutting forces, based on experimental researches. The experimental research aims to determine the influence of the cutting parameters: cutting depth, cutting speed and feed rate, on the drilling thrust force, for 40CrMnMoS8-6 steel using HAM 280 Superdrill solid carbide drills. The mathematical model is based on a power regression modelling, dependent on the three above mentioned parameters.*

Key words: *manufacturing engineering, drilling, thrust force, cutting parameters, 40CrMnMoS8-6 Steel.*

1. Introduction

It is well known that the steel processing and metallic materials are made of over 100 years [4], [9], [11]. During this time, were developed both methods for obtaining the metallic materials and, especially, processing methods. If the obtaining processes of metallic materials have not changed much over the years, the processing methods of these had a spectacular evolution. This is due to the need to produce cheaper, faster and at higher quality in the shortest time [3].

During the last century, many researchers have conducted experiments in order to obtain the optimum drilling cutting parameters regarding the metallic materials processing. [1], [4-7], [9], [11].

Based on experimental researches were obtained mathematical models of drilling thrust force. These models involve three factors: cutting depth [mm], cutting speed [m/min] and feed [mm/rev] [3], [4], [9]. Besides these factors, the mathematical models contain a large number of constants and coefficients, which correct the mathematical models, referring on the material characteristics, tool characteristics etc. If a mathematical model is dependent on so many coefficients and constants, it is difficult to assess whether it matches with a whole range of materials and tools.

In this context, was intended to determine a mathematical model for a particular material, with a particular tool, using a superior technological infrastructure, as a result of an experimental research.

Because the 40CrMnMoS8-6 alloyed steel is widely used in industry, was selected to design a new mathematical model to determine the main cutting force in drilling. In the following are presented the steps that led to the new mathematical model.

[1] Manufacturing Engineering Dept., *Transilvania* University of Braşov.

2. Research Methodology

To obtain a calculating mathematical model, as a result of an experimental research, is necessary first to be established the factors (dependent and independent factors) whose influence is studied [11].

In literature [3], [9-11], the most influence factors on the drilling thrust force, are considered to be: cutting depth [mm], cutting speed [m/min] and feed [mm/rev]. Along with these three factors very important elements are involved, such as: material properties, the tools used etc.

In the present research was studied the effects of the cutting depth (materialized by the drill diameter), the cutting speed (and the spindle speed by default) and the feed rate, on the drilling thrust force. The feed rate factor [mm/min] was chosen in replacement of feed factor [mm/rev], because the parameter which is introduced in the NC program is the feed rate, parameter that can be produced by the CNC machine whatever its value, as long its value is part of the CNC range.

The values for the feed rate factor [mm/min] were obtained starting from a set of values for feed [mm/rev]. These were converted considering the corresponding spindle speed values. The obtained values are presented in Table 1.

The experiment was designed based on the above dependent and independent variables.

The resulted experimental data were filtered, and introduced into a MathCAD *Regression Modeling* software application [8]. The output is a mathematical model for calculating the drilling thrust force, dependent on the three above mentioned factors.

2.1. Design of experiments

The experimental plan was designed based on a model of a classical experiments plan, because the association of the three independent factors did not allow the selection of another experiments plan type. After analyzing the experiments plans used by many researchers [2], [7], [11] was concluded that optimal plans are the factorial fractionated experiment ones. These plans substantially reduce the number of tests and, of course, the cost of the experiment. This type of experiment is not compatible with the subject of this research, because can not be done tests with a feed rate corresponding, for example to a Ø12 mm drill diameter, using a Ø4 mm drill diameter, because it would rise problems in terms of tool resistance. Consequently, it was necessary that the values of independent factors to be adapted to the drill diameter, which does not allow a fractional factorial experiments plan.

The values of independent factors, on which the experiment was conducted, are shown in Table 1, where n reflects the cutting speed [rev/min], and v_f reflects the feed [mm/rev].

The spindle speed values n [rev/min] was established based on Equation (1), starting from the cutting speed:

$$n = \frac{1000 \cdot v}{\pi \cdot d}, \tag{1}$$

where: n - spindle speed [rev/min]; v - cutting speed [m/min]; d - drill diameter [mm].

Starting from a whole value of cutting speed, the corresponding spindle speed was calculated, then the spindle speed was rounded to a whole value and after that the cutting speed was recalculated. Further, using the last value of the spindle speed, have resulted the values which are presented in Table 1.

Input data of the experiment were:

- Material: 40CrMnMoS8-6 steel (Tables 2 and 3);
- Victor VCENTER55 NC milling;
- HAM 280 Superdrill Solid carbide drills with the next values for diameter [mm]: 4, 6, 8, 10 and 12;

- KISTLER data acquisition and analysis system;
- PC for DynoWare software and Measurement COMPUTING computer board PCIM-DAS 1602/16 installing and data operating.

The independent factors values Table 1

Drill diameter, d [mm]	Spindle speed, n [rev/min]	Feed rate, v_f [mm/min]	Cutting speed, v [m/min]
4	3200	384	40.21
4	3600	432	45.24
4	4000	480	50.27
4	4400	528	55.29
4	4800	576	60.32
6	2160	392	40.72
6	2430	441	45.80
6	2700	490	50.89
6	2970	539	55.98
6	3240	588	61.07
8	1600	320	40.21
8	1800	360	45.24
8	2000	400	50.27
8	2200	440	55.29
8	2400	480	60.32
10	1280	320	40.21
10	1440	360	45.24
10	1600	400	50.27
10	1760	440	55.29
10	1920	480	60.32
12	1040	312	39.21
12	1170	351	44.11
12	1300	390	49.01
12	1430	429	53.91
12	1560	468	58.81

The 40CrMnMoS8-6 steel was chosen because it is widely used in industry. It is specially used for the manufacture of active plates for injection of plastic molding industry, which contains a high number of holes.

In Tables 2 and 3 are presented the mechanical and chemical properties for the 40CrMnMoS8-6 steel [12].

Mechanical properties Table 2

Tensile Strength, R_m [N/mm^2]	Flow Strength, $R_{0.2}$ [N/mm^2]	Hardness, HRC
1000	880	54

Chemical composition Table 3

Chemical element	Min [%]	Max [%]
C	0.35	0.45
Si	0.3	0.5
Mn	1.4	1.6
P	0.0	0.03
S	0.05	0.1
Cr	1.8	2.0
Mo	0.15	0.25

2.2. Data acquisition, distribution and analysis system

KISTLER data acquisition and distribution system contains the following components:

- Measurement Computing computer board code: PCIM-DAS 1602/16;
- KISTLER Multichannel Charge Amplifier code: 5070A;
- KISTLER Multicomponent Dynamometer code: 9257B;
- DynoWare Software code: 2825A, for data acquisition and analysis.

KISTLER data acquisition and distribution system, together with Victor VCENTER 55 CN Milling, the PC and the Dynoware software, formed the entire research experiment infrastructure, which is presented in Figure 1.

In Figure 2 is presented the acquisition and distribution system, during the hole processing. The component parts of the system are:

- CNC Machine spindle (1);
- The solid carbide drill (2);
- 40CrMnMoS8-6 material (3);
- KISTLER Multicomponent Dynamometer (4);

- The data transmission cable (5), which connect the Multicomponent Dynamometer to the Multichannel Charge Amplifier.

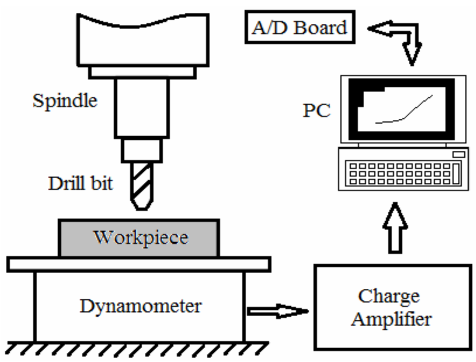

Fig. 1. *Data processing system*

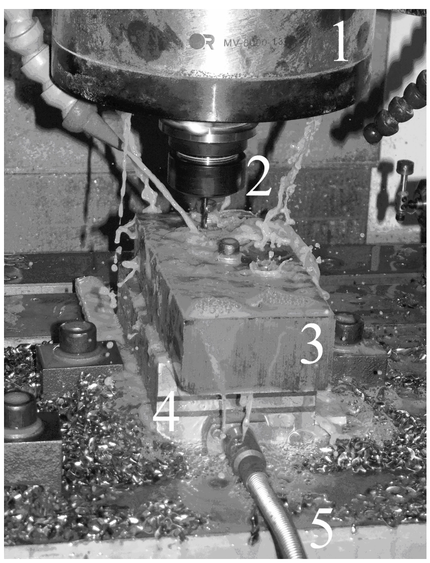

Fig. 2. *Holes processing*

2.3. Data acquisition process

The experiment was divided into sets of records in order to obtain a simply and efficient data acquisition process.

After the sets of records were set, were done the corresponding NC programs. Next step was the holes processing, in order to acquire and record the data from the drilling process. It was established a total of 25 sets of records, each one containing 5 records. The total number of records was 125. In Table 4 are presented the last five sets of records, corresponding to the ø12 mm solid carbide drill.

Table 4 could be considered an extension for Table 1, for the values which correspond to Ø12 mm diameter. In Table 1, for an Ø12 mm diameter, are shown the spindle speeds and feed rates, while in Table 4 are shown the corresponding records from the acquisition process. In each set of records, two of the three independent factors were maintained to a constant value (the drill diameter and the spindle speed), and only the third was changed (the feed rate). In these conditions:

- All the sets of records (which correspond to Ø12 mm drill diameter) have the cutting depth equal to 12;
- The spindle speed factor [rev/min] is constant for a set of records, but its value is changed when a set of records is completed;
- The feed rate factor [mm/min] is changed after every processed hole.

Consequently:

- The cutting depth factor is the same for all the five sets of records;
- The spindle speed factor is constant for a set of records, but it is changing when a set is done;
- The feed rate factor is changing after every hole.

Another reason why the feed rate factor [mm/min] was chosen instead of feed factor [mm/rev] is the fact that with the obtained data can be studied easily:

- The influence of the feed rate, according to a constant cutting depth and spindle speed;
- The influence of the spindle speed, according to a constant cutting depth and feed rate.

In Table 4, were marked up with bold, the three parameters which have been used as independent factors. In the F_z-exp. column are presented the resulted data

The experiment results, for Ø12 mm diameter Table 4

d [mm]	**n [rev/min]**	**v [m/min]**	**f_n [mm/rev]**	**v_f [mm/min]**	**F_z-exp. [N]**	**F_z-model [N]**	
12	**1040**	39.2	0.30	**312**	2939	2807	1st Set
12	**1040**	39.2	0.34	**351**	3201	3080	
12	**1040**	39.2	0.38	**390**	3492	3346	
12	**1040**	39.2	0.41	**429**	3745	3606	
12	**1040**	39.2	0.45	**468**	4058	3862	
12	**1170**	44.1	0.27	**312**	2685	2616	2nd Set
12	**1170**	44.1	0.30	**351**	2841	2870	
12	**1170**	44.1	0.33	**390**	3043	3117	
12	**1170**	44.1	0.37	**429**	3300	3360	
12	**1170**	44.1	0.40	**468**	3511	3598	
12	**1300**	49.0	0.24	**312**	2546	2456	3rd Set
12	**1300**	49.0	0.27	**351**	2692	2694	
12	**1300**	49.0	0.30	**390**	2862	2926	
12	**1300**	49.0	0.33	**429**	3063	3154	
12	**1300**	49.0	0.36	**468**	3249	3378	
12	**1430**	53.9	0.22	**312**	2417	2320	4th Set
12	**1430**	53.9	0.25	**351**	2556	2545	
12	**1430**	53.9	0.27	**390**	2733	2764	
12	**1430**	53.9	0.30	**429**	2873	2979	
12	**1430**	53.9	0.33	**468**	3038	3190	
12	**1560**	58.8	0.20	**312**	2324	2201	5th Set
12	**1560**	58.8	0.23	**351**	2461	2415	
12	**1560**	58.8	0.25	**390**	2576	2623	
12	**1560**	58.8	0.28	**429**	2726	2827	
12	**1560**	58.8	0.30	**468**	2858	3028	

from the acquisition process, and in the F_z-model column are presented the corresponding data, obtained with the mathematical model.

In Figure 3 is shown first cutting force-time diagram obtained with DynoWare software, corresponding to the first set of records. It presents the recorded signals transmitted from the piezoelectric sensors to the computer board. Each of the four sensors corresponds to one of the four F_z forces: F_{z1}, F_{z2}, F_{z3} and F_{z4}, F_z being the total F_z force:

$$Fz = Fz_1 + Fz_2 + Fz_3 + Fz_4 \text{ [N]}, \qquad (2)$$

F_{zi} force variations, where $i \in \{1, 2, 3, 4\}$, are dependent on the distances between the processed hole and the four sensors. The sensor which is the closest to the processed hole generates the biggest value for its corresponding F_z force. The negative signals recorded by some sensors are justified by the fact that the holes position (consequently sensors position) is diametrically opposed relative to dynamometer gravity centre. In this case, the top plate tends to rise up (increases distance between itself and base plate) in this area.

3. Obtaining the Mathematical Model

In order to obtain a mathematical model for calculating the drilling thrust force, dependent on the three factors above discussed, the following steps were covered:

- Filtering the recorded data and determining the maximum F_z force;

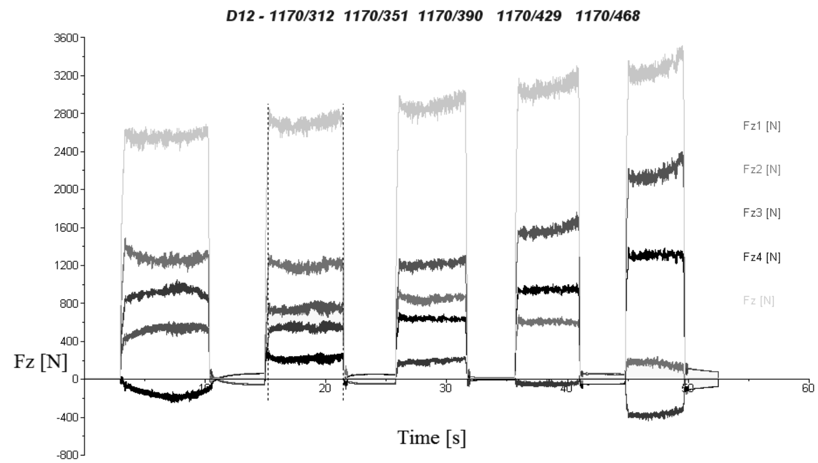

Fig. 3. *First set of records, corresponding to ϕ12 mm solid carbide drill*

- Transferring the filtered data into a transferring file format;
- Loading the transferring file into the *Regression Modelling* software application [8];
- Obtaining the mathematical models and the different correlation coefficients;
- Selecting the mathematical model which contains the optimum correlation coefficient.

In Figure 4 is shown the regression algorithm used in order to obtain the mathematical model. The algorithm steps are described below:

- First, a ".txt" file was created, in which were placed in columns the independent and dependent factors;
- The ".txt" file was loaded in the *H* matrix (according to Figure 4);
- For each column (factor) was assigned one vector: *x*-for the cutting depth, *y*-for the cutting speed, *z*-for the feed rate and *w*-for the thrust force (the thrust force is the dependent factor);
- Have been initialized a set of variables which will record the coefficients of the mathematical model;
- Onto the four vectors is applied the principle of the least squares, in order to obtain the optimum coefficients for the mathematical model;
- Thus result the coefficients of the mathematical model;
- Is calculated the correlation factor for the obtained data.

It is important to say that the regression algorithm generates four types of functions:

H =

	0	1	2	3
120	12	58.81	312	$2.324\cdot10^3$
121	12	58.81	351	$2.461\cdot10^3$
122	12	58.81	390	$2.576\cdot10^3$
123	12	58.81	429	$2.726\cdot10^3$
124	12	58.81	468	...

$$x := H^{\langle 0\rangle} \quad y := H^{\langle 1\rangle} \quad z := H^{\langle 2\rangle} \quad w := H^{\langle 3\rangle}$$

$$a := 1 \quad b := 1 \quad c := 1 \quad d := 1 \quad f := 1 \quad n = 125$$

$$S1(a,b,c,d,f) := \sum_{i=0}^{n-1}\left[w_i - a\cdot(x_i)^b\cdot(y_i)^c\cdot(z_i)^d - f\right]^2$$

$$\begin{pmatrix} a1 \\ b1 \\ c1 \\ d1 \\ f1 \end{pmatrix} := \mathrm{Minimize}(S1, a, b, c, d, f) \implies \begin{pmatrix} a1 \\ b1 \\ c1 \\ d1 \\ f1 \end{pmatrix} = \begin{pmatrix} 1.60192 \\ 2.07234 \\ -0.59926 \\ 0.78661 \\ 0.25814 \end{pmatrix}$$

$$F1(x,y,z) := a1\cdot x^{b1}\cdot y^{c1}\cdot z^{d1} + f1$$

$$Rc_0 := \sqrt{1 - \frac{\sum_{j=0}^{n-1}\left(w_j - F1(x_j, y_j, z_j)\right)^2}{\sum_{j=0}^{n-1}\left(w_j - \mathrm{mean}(w)\right)^2}} \implies Rc_0 = 0.9944508609$$

Fig. 4. *The regression modeling software application*

- power function;
- exponential function;
- polynomial quadratic equation function;

polynomial equation of 3rd degree function.

After going through the above steps, the mathematical model was chosen. It is a power type one, with the biggest correlation coefficient: C_c = 0.994. The mathematical model is presented in Equation (3):

$$Fz = 1.602 \cdot d^{2.072} \cdot v^{-0.599} \cdot v_f^{0.787} \text{ [N]}, \quad (3)$$

where: d - drill diameter [mm]; v - cutting speed [m/min]; v_f - feed rate [mm/min]; F_z - drilling thrust force [N].

The correlation coefficient C_c = 0.994 guaranties that the mathematical model accurately reflects the obtained data from the research experiment.

In Table 5 are shown the limits of the independent factors, for which the mathematical model has applicability.

Limits of independent factors Table 5

Drill diameter [mm]	Spindle speed [rev/min]	Feed rate [mm/min]
4-12	1040-4800	312-588

The deviation between the values obtained with the mathematical model, and the values obtained form the experimental researches are presented in Table 6.

The deviation grade Table 6

Upper deviation [%]	Lower deviation [%]	Relative deviation [%]
5.95	–5.29	–0.01

It is important to consider all the three decimals of the mathematical model coefficients not for mathematical reasons, but for technical reasons. If the mathematical model is simplified, by reducing the number of decimals to two decimals or one, instead of three, the correlation coefficient of the mathematical model substantially decreases.

4. Conclusions

This paper presented the methodology applied to obtain a mathematical model for drilling thrust force. The mathematical model resulted is a power type one, dedicated to 40CrMnMoS8-6 steel and its processing with solid carbide drills. It is dependent on three drilling parameters: cutting depth [mm], cutting speed [m/min] and feed, which is represented, in the mathematical model, by feed rate [mm/min].

The mathematical model will be used to develop a software module capable to calculate the cutting parameters and power in drilling and verify the thrust force. This software module will be a part of an integrated software system for designing and manufacturing the industrial products with holes, developed according to intelligent object principles [3].

Acknowledgements

This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), ID59321 financed from the European Social Fund and by the Romanian Government.

References

1. Badan, I., Oancea, Gh.: *Software Tool Used for Holes Modelling in AutoCAD Environment*. In: The 3rd WSEAS International Conference Engineering Mechanics Structures, Engineering. Geology, Corfu Island, Greece, July 22-2, 2010, p. 152-156.
2. Chandramohan, D., et al.: *Thrust Force and Torque in Drilling the Natural Fiber Reinforced Polymer Composite Materials and Evaluation of Delamination*

Factor for Bone Graft Substitutes - A Work of Fiction Approach. In: International Journal of Engineering Science and Technology **2** (2010) No. 10, p. 6437-6451.

3. Chicoş, L.A.: *Utilizarea conceptului de inginerie simultata in dezvoltarea de produse* (*Using the Simultaneous Engineering Concept in Product Development*). In: PhD. Thesis, *Transilvania* University of Braşov, Romania, 2007.
4. Erkki, J.: *A Summary of Methods Applied to Tool Condition Monitoring in Drilling*. In: International Journal of Machine Tools & Manufacture **42** (2002), p. 997-1010.
5. Ertunc, H.M., Oysu, C.: *Drill Wear Monitoring Using Cutting Force Signals.* In: Mechatronics **14** (2004), p. 533-548.
6. Gopal Krishna, P.V., et al.: *Some Investigations in Friction Drilling AA6351 Using High Speed Steel Tolls*. In: ARPN Journal of Engineering and Applied Sciences **5** (2010) No. 3, p. 11-15.
7. Iliescu, M., Vlase, A.: *New Mathematical Models of Axial Cutting Force and Torque in Drilling 20MoCr130 Stainless Steel.* In: WSEAS, MACMESE (2008), p. 210-215.
8. Jayabal, S., Natarajan, S.: *Influence of Cutting Parameters on Thrust Force and Torque in Drilling of E-Glass/Polyester Composites.* In: Indian Journal of Engineering & Materials Science **17** (2010), p. 463-470.
9. Oancea, G., et al.: *Estimarea costurilor de prelucrare a produselor industriale* (*Costs Estimating of Industrial Products Manufacturing*). Braşov. *Transilvania* University Press, 2008.
10. Rubenstein, C.: *The Torque and Thrust Force in Twist Drilling. I. Theory*. In: International Journal of Machine Tools and Manufacture **31** (1991) No. 4, p. 481-489.
11. Udiljak, T., Ciglar, D., Scorik, S.: *Investigation into Bone Drilling and Thermal Bone Necrosis.* In: Advances in Production Engineering & Management **2** (2007) No. 3, p. 103-112.
12. *** Chemical *and Mechanical Properties and Material Code for 40CrMnMoS8-6 Alloyed Steel*. Available at: http://www.ozct.com.tr/en/pdf/1.2312%2040CrMnMoS8-6.pdf. Accessed: 06.12.2011.