Simulation of 20MoCr130 steel drilling process and some mathematical models determined

Mihaiela Iliescu, Aurelian Vlase, Doru Bardac

Abstract**—**Very important materials, with lot of application in automotive, aircraft, medical products, large consumer goods, etc industries, are the stainless steels. Machining is often necessary while manufacturing parts made of these steels and drilling is a widely used procedure. This paper presents new mathematical models – of drilling axial force and torque - obtained as result of simulation, experimental research and regression analysis, carried out on 20MoCr130 stainless steel samples. Graphs, as well as further application of the obtained models are, also, shown.

Keywords**—**simulation, drilling, axial force, torque, model.

I. Introduction

IT was in the early of 20th century that, stainless steels were "discovered" and, nowadays, their application fields are various and challenging. Primarily used for their corrosion resistance, all of them have a minimum of 10.5% of chromium. This component (chromium, Cr) has great affinity for oxygen, and forms a very thin film of chromium oxide on the surface of the steel, at molecular level, this layer being passive, tenacious and self-renewing [9].

Some important characteristics of stainless steels can be stated as: high corrosion resistance to various chemical agents, fire, heat resistance, impact resistance, hygiene, impressive good look [7]. Consequently, application fields are that of: automotive, aircraft, naval, oil and gas industries, medical products, large consumer goods, food production

Usually, required shape, dimensions and surface roughness of the stainless steel part can be obtained by machining. These materials are very tough, with low thermal conductivity and thus, while machining, sever wear of the cutting tool appear, as well as, high value cutting forces [6].

Because of their high prices, it is necessary to do researches on stainless steels' machinability, in order to optimize the machining process, meaning, having high productivity and low costs of parts. The values of cutting force and torque are representative machinability parameters, meaning the higher the values, the lower this characteristic is [3].

Manuscript received April 15, 2009: Revised version received ***.

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Specific literature presents some relationships regarding variables of the machining process – involving force and torque but, when experimentally checking them, one can notice high difference (of the modeled ones) from the real obtained values [2], [4].

That is why, it has been considered useful to determine adequate new models of some machinability parameters, for a widely industrial used Romanian stainless steel – 20MoCr130.

When a stainless steel part is designed with holes of same, or various dimensions and precisions, often a machining procedure, like drilling, is necessary. Cutting force, specially axial one, and cutting torque, are important parameters (output variables) of the drilling process that can often be used for its optimization.

Simulation, experiments and regression analysis are presented further by this paper, all of them carried out in order to determine new mathematical models of axial cutting force and torque in drilling 20MoCr130 stainless steel.

II. Research Methodology

In order to experimentally determine a mathematical relationship of variables specific to a machining process, there has to be mentioned, both the independent and the dependent ones [1]. After doing that, the dependence relation type must be settled and, correspondingly, the appropriate experiments design established.

For a more precise and adequate study, simulation of the drilling process is worth to be done. Thus, there could be noticed eventual mistakes – such as used cutting tool, hole's position within the part, whole's depth, etc.

The mathematical relations, regarding axial cutting force, in drilling stainless steel materials, presented by most of the articles and books dealing with this problem, are of the type:

$$F = C_F D^{x_F} a_f^{y_F} \quad [\text{N}] \qquad (1)$$

$$M = C_M D^{x_M} a_f^{y_M} \quad [\text{Nm}] \qquad (2)$$

where: F is the axial component of the cutting force;

M – the drilling torque;

D – the diameter of the drilling tool, [mm];

a_f – cutting feed, of the drilling tool, [mm/rot];

x_F, y_F, x_M, y_M - polytropic exponents;

C_F, C_M - constants.

Once the values of exponents and constants known, experiments were carried out.

It could be noticed that the same values of cutting tool's diameter and cutting feed but, different values of cutting speed resulted in various values of axial force and torque. That it why, it was assumed that the that the parameter not mentioned by relations (1) and (2), meaning cutting speed should play an important role in drilling axial force and torque prediction.

As consequence of the above mentioned, there are experienced other mathematical models of axial cutting force and torque, where one more independent variable appear, that is *cutting speed v* [mm/rot]. So, the new, original proposed mathematical models are:

$$F = C_F D^{x_F} a_f^{y_F} v^{z_v} \quad [\mathrm{N}] \qquad (3)$$

$$M = C_M D^{x_M} a_f^{y_M} v^{z_M} \quad [\mathrm{Nm}] \qquad (4)$$

where: v is peripheral rotational speed of the drilling tool, usually mentioned as cutting speed [m/min];

z_v , z_M - polytropic exponents;

For obtaining the constants and polytropic exponents' values, relations (3) and (4) must be of linear type and, so, by logarithm their linear expressions are:

$$\lg F = \lg C_F + x_F \lg D + y_F \lg a_f + z_F \lg v \qquad (5)$$

$$\lg M = \lg C_M + x_M \lg D + y_M \lg a_f + z_M \lg v \qquad (6)$$

III. SIMULATION OF THE DRILLING PROCESS

When a part is designed so that includes holes, it is important to have good accuracy of their axes' position. So, whenever possible, simulation of the drilling process must be done, in order to avoid errors of involved holes' position, length and diameter.

For the studied material and process, there has been carried out simulation, considering rectangular shape samples, each of them with four holes, all of them being, in fact, used in experiments.

The software used for simulation was isy-CAM, which is specific to Isel-automation manufacturing systems [8]. It operates under Windows and is made of two parts:

- Isy-CAM CAD part (for designing and modeling parts 2D or, 3D)
- Isy-CAM CAM part (for machining on CNC machine-tools with 3, 3.5 or 5 axes);

So, some images of the drilling process simulation can be seen in:

- figure 1 – for selecting cutting tool type,
- figure 2 – for hole axis position,
- figure 3 – for phases of the simulated drilling
  - a. → sample before drilling
  - b. → sample while drilling the second whole
  - c. → sample after drilling.

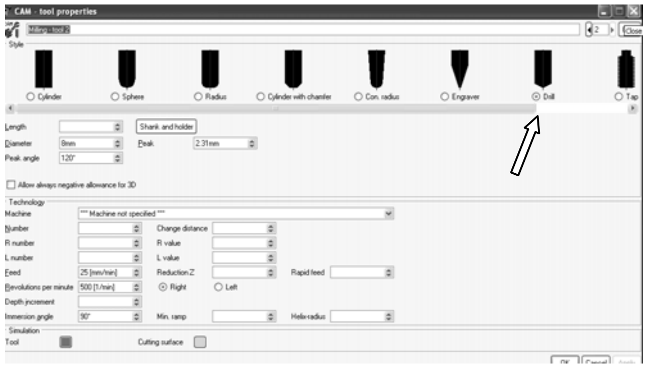


Fig. 1 Isy-CAM – selecting cutting tool

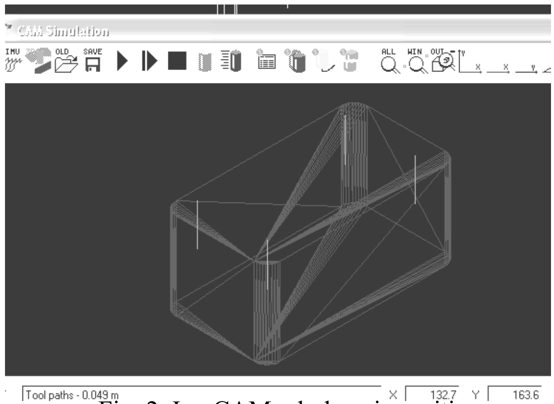


Fig. 2 Isy-CAM – hole axis position

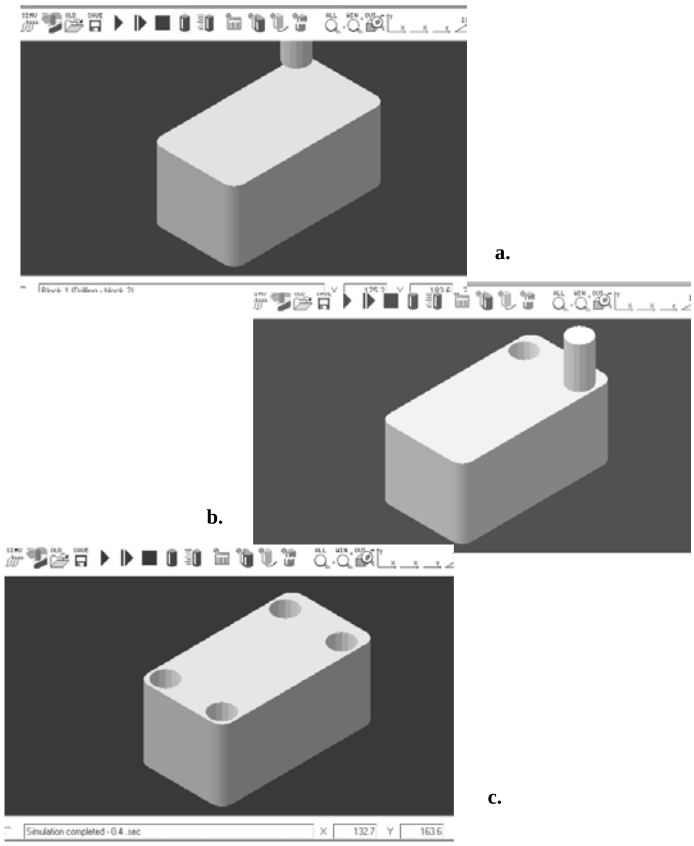


Fig. 3 Isy-CAM – drilling simulation

IV. MATHEMATICAL MODELS

Obtaining the new mathematical models proposed implies, first, experiments and, after that, constants and polytropic exponents determination, as well as regression analysis.

A. Experiments

There were carried out experiments under specially designed conditions, meaning: drilling process simulation, experimental stand components; established variation fields and values of studied variables; certain experiments designs; regression analysis techniques.

So, the machine tool was a drilling machine, coded GC_032DM_3. whose electric motor had 3,5 kW power. Its table dimensions were 420 × 480 (mm) and the main spindle had a no. 4 Morse cone. Possible rotational speed range values of the drilling tool were 70 ÷ 1400 [rot/min], with 12 geometrical ratio levels variation and possible cutting feed values were 0.12; 0.20; 0.32; 0.50 [mm/rot].

There has been used a cooling/lubricating fluid, 20% P emulsion.

Cutting tools were helix drilling ones, made of Rp5 material and having Rockwell hardness no. 62. The edge angle was $2\chi = 140^\circ$ and the diameter' values considered were:

$$\Phi_1 = 8; \quad \Phi_2 = 12; \quad \Phi_3 = 14 \quad [\text{mm}]$$

As for the drilling experimental conditions, they were according to R1370/2-69 Standard, type A.

Adequate measuring of axial cutting forces and torques, in drilling, involved the design and manufacture of a special rotational device, acting as a dynamometer. Its most important element is represented by an elastic sleeve, on which there were attached four resistive transducers, each inclined by 45° with respect to horizontal and vertical axes.

The "exit" cables of this device were connected to an IEMI type electronic bridge which, was coupled to a data acquisition system, using the graphical programming LabVIEW software. – see Figure 4.

The studied material was 20MoCr130, its chemical structure being presented in Table 1, while its mechanical characteristics are mentioned by Table 2

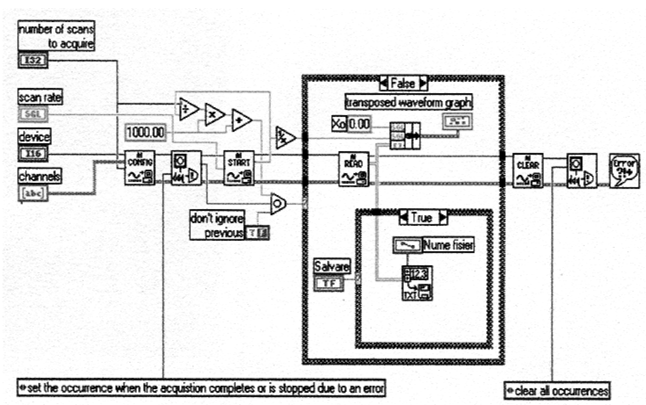


Fig.4 LabVIEW graphical program

Table 1 Chemical Structure

C [%]	Mo [%]	Ni [%]	Cr [%]	Mn [%]
0.20	3.82	0.24	13.2	0.68
Si [%]	S [%]	P [%]		
0.30	0.017	0.035		

Table 2 Mechanical Characteristics

Tensile Strength, R_m [N/mm^2]	Flow Strength, R_{02} [N/mm^2]	Relative Elongation δ [%]	Hardness, HB
920	670	10.7	240

Images of the designed stand, taken while experimenting are

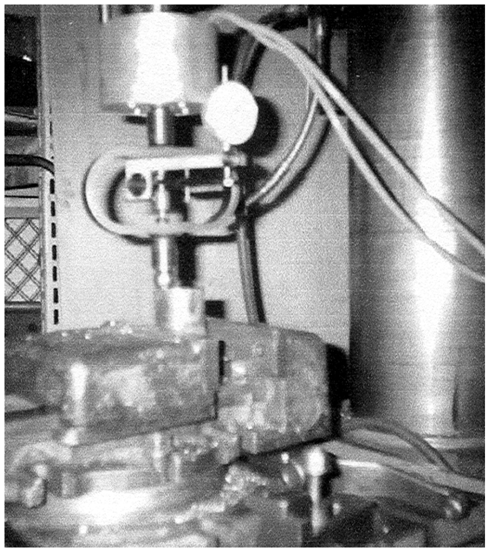


Fig.3 Drilling experiments

shown in figure 5.

An example of the obtained graphic, for all drilling force's components, as well as for the power involved by the process is presented in Figure 6.

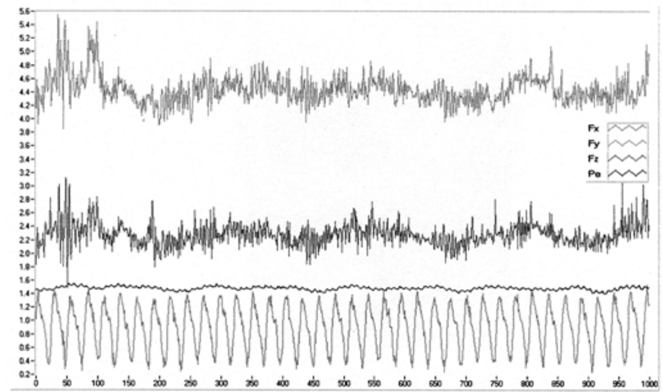


Fig.6 LabVIEW data acquisition – drilling force's components

Table 3 Experimental results

Exp. No.	Cutting Tool Diameter, D [mm]	Cutting Feed a_f [mm/rot]	Rotational Speed n [rot/min]	Cutting Speed v [m/min]	Axial Cutting Force, F [N]	Drilling Torque M [Nm]
1	8	0.12	560	14.07	2282	4.97
2	8	0.20	560	14.07	2976	6.68
3	8	0.12	900	22.61	1998	4.43
4	12	0.12	560	21.10	3522	9.54
5	12	0.20	560	21.10	4502	12.58
6	14	0.12	900	39.56	3565	10.71

where: n is the rotational speed of the machine tool's main spindle

$$n = \frac{1000v}{\pi D} \quad \text{[rot/min]}$$

Experimental values obtained for the axial force and torque, in drilling 20MoCr130 stainless steel are shown in Table 3.

B. Obtaining First Mathematical Models

Based on the experimental results, and on research methodology mentioned, the equation systems necessary for models' determination are as follows:

$$\begin{cases} \lg 2282 = \lg C_F + x_F \lg 8 + y_F \lg 0.12 + z_v \lg 14.07 \\ \lg 2976 = \lg C_F + x_F \lg 8 + y_F \lg 0.20 + z_v \lg 14.07 \\ \lg 1998 = \lg C_F + x_F \lg 8 + y_F \lg 0.12 + z_v \lg 22.61 \\ \lg 3522 = \lg C_F + x_F \lg 12 + y_F \lg 0.12 + z_v \lg 21.10 \end{cases} \quad (7)$$

$$\begin{cases} \lg 4.97 = \lg C_M + x_M \lg 8 + y_M \lg 0.12 + z_M \lg 14.07 \\ \lg 6.68 = \lg C_M + x_M \lg 8 + y_M \lg 0.20 + z_M \lg 14.07 \\ \lg 4.43 = \lg C_M + x_M \lg 8 + y_M \lg 0.12 + z_M \lg 22.61 \\ \lg 9.54 = \lg C_M + x_M \lg 12 + y_M \lg 0.12 + z_M \lg 21.10 \end{cases} \quad (8)$$

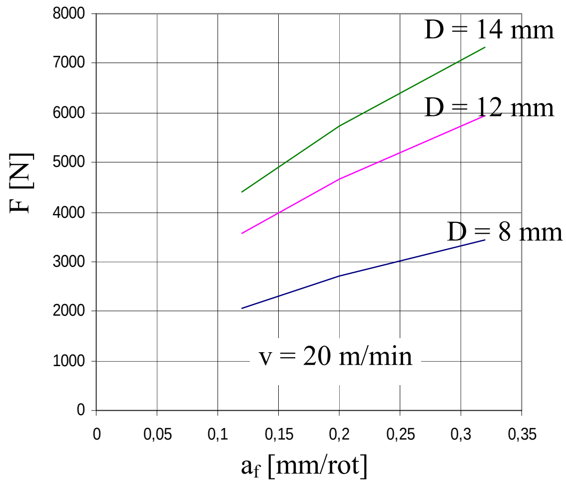
By solving the equations systems, the values of constants, C_F, C_M and polytropic exponents, x_F, y_F, x_M, y_M are obtained [7].

Knowing that the initial dependence relationships were exponential ones, and the ones used in solving are obtained from the first ones, by logarithm, the final mathematical models of the axial cutting force and torque, in drilling 20MoCr130 stainless steel are:

$$F = 870 D^{1.35} a_f^{0,52} v^{-0.28} \quad \text{[N]} \qquad (9)$$

$$M = 0.684 D^{1.85} a_f^{0,58} v^{-0.24} \quad \text{[Nm]} \qquad (10)$$

Graphs of the axial force and torque variances, on some of the considered variables (cutting feed, af, and cutting tool diameter, D) are shown in Figure 7 and, respectively, Figure 8.



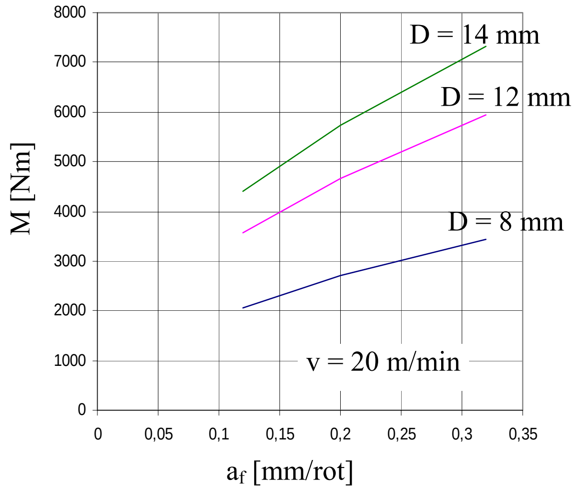
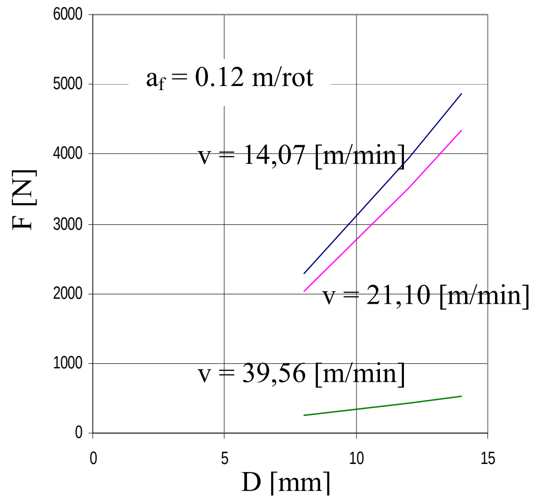


Fig.7 Axial force, F, and torque variation, M, on cutting feed, a_f



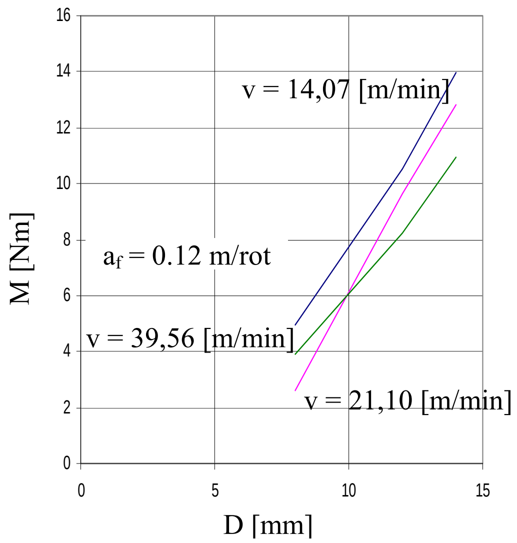


Fig.8 Axial force, F, and torque variation, M, on cutting tool diameter, D

As relations (9) and (10) were obtained by solving classical equation systems – four unknown parameters and four equations, one can think of trying to improve the obtained mathematical models. That is if, changing one of the equations – in systems (7) and, respectively, (8), by considering another experimental results from Table 3 – experiment number 5 or, 6, different values for the constants and polytropic exponents should be obtained.

C. Obtaining Second Mathematical Models

Regression analysis represents a more adequate tool for determining mathematical models representing relationship of the studied variables.

So, the dependent variable (output) is considered to be axial cutting for or torque, while independent variables (inputs) are cutting tool diameter, cutting speed and cutting feed.

In each case, there have been established (based on previous experiments) variation intervals and number of experimental values.

For a more efficient and precise analysis, there has been used a special software – DOE KISS, student version [4].

Considering the number of independent variables studied (3) and the software version available, there have been done experiments, according to a Full Factorial Design, each variable with two variation levels.

As needed [5], [6], coded variable values had to be considered so, relationship of natural, z_j, to coded, x_j, is given by relation:

$$x_j = \frac{z_j - \frac{z_{min} + z_{max}}{2}}{\frac{z_{max} - z_{min}}{2}}, \quad j = 1,2,3 \qquad (11)$$

Real and coded values of inputs are presented in table 4 while, the applied experiment design is shown in table 5.

As result of all the above mentioned, relation (1) can be customized for each of the independent variables considered, thus obtaining:

$$x_1 = \frac{z_1 - 11}{3}; \quad x_2 = \frac{z_2 - 0.16}{0.04};$$

$$x_3 = \frac{z_3 - 26.815}{12.745} \qquad (12)$$

Table 4 Independent variables values

	Real, z_j		Coded, x_j	
Cutting tool diameter, D [mm]	8	14	-1	+1
Cutting feed, a_f [mm/rot]	0.12	0.20	-1	+1
Cutting speed, v [m/min]	14.07	39.56	-1	+1

Table 5 Full factorial experiment design

Experience number	x_1	x_2	x_3
1	-1	-1	-1
2	-1	-1	+1
3	-1	+1	-1
4	-1	+1	+1
5	+1	-1	-1
6	+1	-1	+1
7	+1	+1	-1
8	+1	+1	+1

Experimental results, for cutting force and torque values, are presented in table 6. It should be mentioned that each experience has been repeated five times, these involving that replicates number equals five.

Results of regression analysis, carried out with DOE KISS software, are shown in figure 9:

a. → for axial cutting force,

b. → for torque.

It must be mentioned that regression coefficients whose P (2 Tail) values are higher than 0.05, are considered to have no significant influence on the output variable.

Table 6 Experimental results values

Experience number	Axial force, F [N]	Torque, M [N m]
1	2280	4.97
2	1921	4.19
3	2976	6.49
4	2892	6.30
5	3607	7.86
6	3565	7.77
7	3674	8.01
8	3916	8.54

Y-hat Model

Factor	Name	Coeff	P(2 Tail)	Tol	Active
Const		3103,9	0,0000		
A	diameter	586,625	0,0000	1	X
B	feed	260,625	0,0000	1	X
C	speed	-30,375	0,0000	1	X
AB		-156,125	0,0000	1	X
AC		80,375	0,0000	1	X
BC		69,875	0,0000	1	X
ABC		1,12500	0,6968	1	X

Rsq	0,9994
Adj Rsq	0,9993
Std Error	18,0987
F	7827,4416
Sig F	0,0000

Source	SS	df	MS
Regression	1,79E+07	7	2,56E+06
Error	10482,0	32	327,6
Total	1,80E+07	39	

Factor	Name	Low	High	Exper
A	diameter	8	14	11
B	feed	0,12	0,2	0,16
C	speed	14,07	39,56	26,815

Prediction

Y-hat	3103,875
S-hat	13,4011626

99% Prediction Interval

Lower Bound	3063,67151
Upper Bound	3144,07849

a. – for axial cutting force

Y-hat Model

Factor	Name	Coeff	P(2 Tail)	Tol	Active
Const		6,76625	0,0000		
A	diameter	1,27875	0,0000	1	X
B	feed	0,56875	0,0000	1	X
C	speed	-0,06625	0,0002	1	X
AB		-0,33875	0,0000	1	X
AC		0,17625	0,0000	1	X
BC		0,15125	0,0000	1	X
ABC		0,00375	0,8167	1	X

Rsq	0,9962
Adj Rsq	0,9953
Std Error	0,1015
F	1183,3940
Sig F	0,0000

Source	SS	df	MS
Regression	85,3	7	12,2
Error	0,3	32	0,0
Total	85,6	39	

Factor	Name	Low	High	Exper
A	diameter	8	14	11
B	feed	0,12	0,2	0,16
C	speed	14,07	39,56	26,815

Prediction

Y-hat	6,76625
S-hat	0,09439191

99% Prediction Interval

Lower Bound	6,48307426
Upper Bound	7,04942574

b. – for torque

Fig.9 DOE KISS software – Regression analysis results

Based on regression analysis results there were obtained second mathematical models, for axial cutting force and torque, as shown by relations (13) and, respectively, (14).

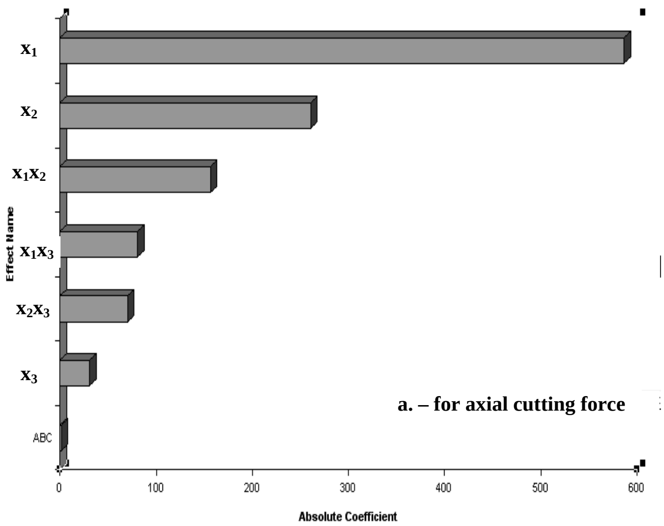
$$F = 3103.9 + 586.625x_1 + 260.625x_2 - 30.375x_3 - 156.125x_1 \cdot x_2 + 80.375x_1 \cdot x_3 + 69.87x_2 \cdot x_3 \qquad (13)$$

$$M = 6.76625 + 1.27875x_1 + 0.56875x_2 - 0.06625x_3 - 0.33875x_1 \cdot x_2 + 0.17625x_1 \cdot x_3 + 0.15125x_2 \cdot x_3 \qquad (14)$$

Pareto chart of coefficients, meaning the graph that points out how strong the influence of each independent variables, as well as their interactions, on the dependent variable is, can be noticed in figure 10,

a. → for axial cutting force,

b. → for torque.



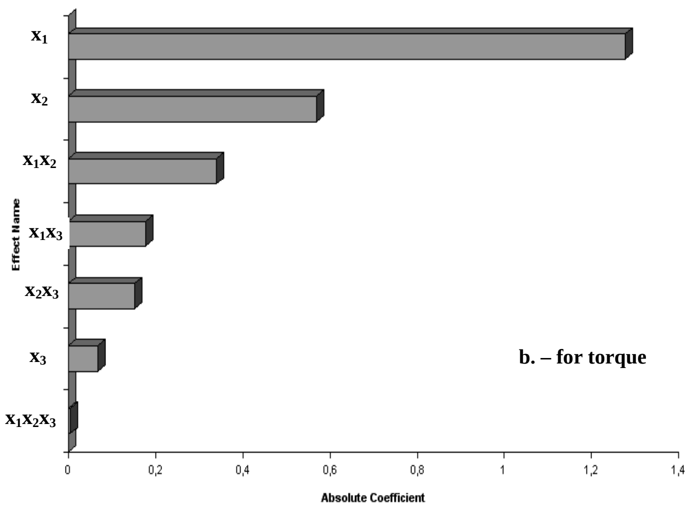
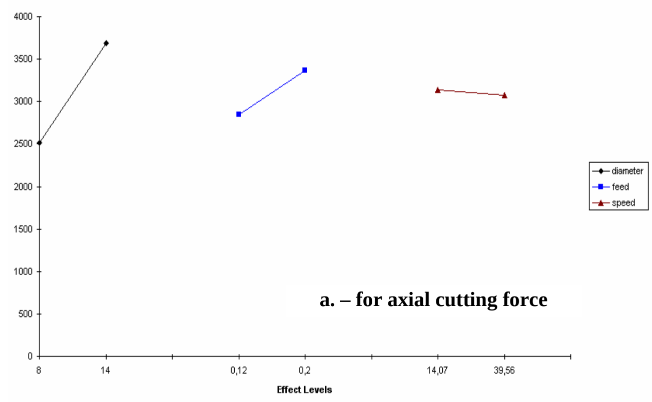


Fig.10 DOE KISS software – Pareto charts of coefficients



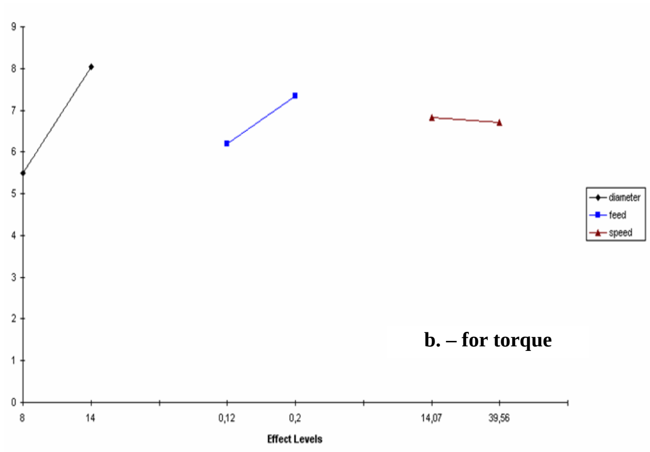


Fig.11 DOE KISS software - Marginal means

There are also presented graphs that evidence the level of output variation, for each input variables extreme values (minimum and maximum) considered. These graphs are called Marginal Means – see figure 11,

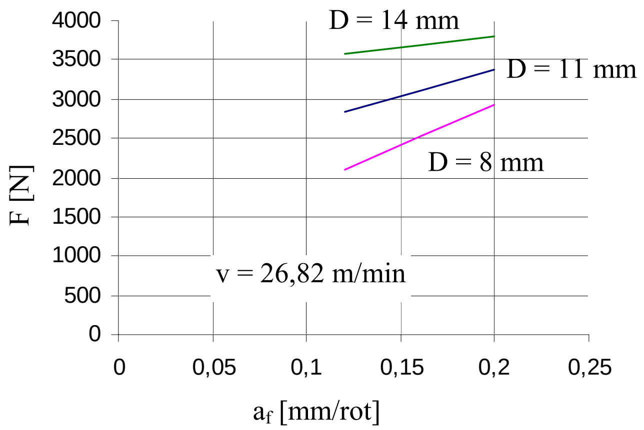
a. → for axial cutting force,

b. → for torque.

Further processing of relations (13) and (14), when considering relation (12), results in mathematical relationships where real variables values are considered and, not coded ones as presented below. So, there were obtained the models expressed by relations (15) and (16):

$$F = -1107.371 + 171.352D + 17151.724a_f - 47.437v - 1301.042D \cdot a_f + 2.102D \cdot v + 137.064a_f \cdot v \quad [N] \qquad (15)$$

$$M = -2.394 + 0.754D + 37.315a_f - 0.103v - 2.823D \cdot a_f + 0.005D \cdot v + 0.297a_f \cdot v \quad [Nm] \qquad (16)$$



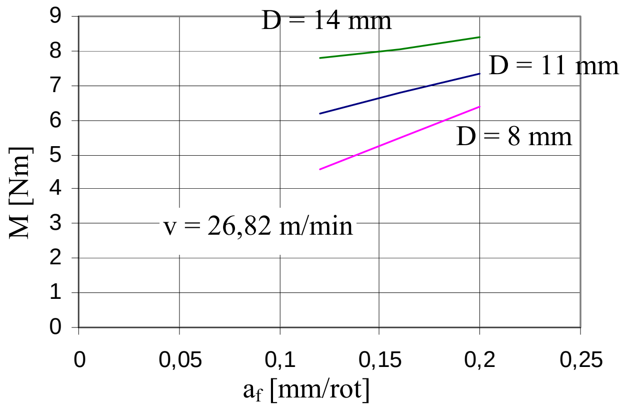


Fig.12 Graphs of axial force, F, and torque, M, variation on cutting feed, a_f

Based on the above obtained models, there have been plotted out graphs of axial cutting force and torque variation, on cutting feed – see figure 12.

V CONCLUSION

Stainless steels represent important materials, whose application fields has known a high extend, specially because of special characteristics, such as: high corrosion resistance to various chemical agents, fire, heat resistance, impact resistance, hygiene, impressive good look

As consequence, they are expensive materials and research on their machinability is worth to be done, in order to optimize the machining process, meaning, having high productivity and high precision with low costs of parts.

Representative element of any material's machinability can be considered to be the cutting force and torque, specially when drilling process is involved. [2] [10]

Study on machinability aspects of a frequently used stainless steel, 20MoCr130, is presented by the article. The dependent variables (outputs) considered are the axial cutting force and the torque, the process being drilling.

There were carried out experiments under specially designed conditions, meaning: drilling process simulation, experimental stand components; established variation fields and values of studied variables; certain experiments designs; regression analysis techniques.

All mathematical models determined, have proved to be adequate, and evidenced similar influence of independent variables (inputs) on the output. Better modeling of axial force and torque is considered to be obtained by regression the analysis, as it allows evidencing both the influence of each input, as well as the influence of their interactions.

Once determined, the considered models were further checked, by more experiments – for different values of the parameters. All the experimentally obtained results were in good concordance with the mathematically predicted values.

Further research should be developed so as, to implement the obtained mathematical models, into an automated optimization system .of the manufacturing process.

Also, some other inputs of the drilling process could be considered and, even, more process characteristics (cutting tool wear, power consumption, surface roughness) models determined.

REFERENCES

[1] Iliescu M., Vlădăreanu L, *Statistic Models of Surface Roughness MET 4 Metallized Coating in Grinding Manufacturing System*, 12th *WSEAS International Conference on Systems*, pag. 777-782, ISSN 1790-2769, Greece, July, 2008

[2] Hsu-Hwa Chang, Chih-Hsien Chen, *Use of Response Surface Methodology and Exponential Desirability Functions to Paper Feeder Design*, WSEAS TRANSACTIONS on APPLIED and THEORETICAL MECHANICS Issue 9, Volume 2, September 2007, ISSN: 1991-8747

[3] Ghionea A., Vlase A, Ghionea I, Wear Evaluation of Cutting Edge and Cutting Speed in Drilling Process of Some Manganese Steel, Proceedings of 18th International DAAAM Symposium ISSN 1726-9679, Austria, 2007

[4] Premrov M, Dobrila P, Bedenik B., Ŝpacapan I., *Slip Modeling in Timber-Framed Walls with Wood-Based or Fiber-Plaster Sheathing Board,* WSEAS TRANSACTIONS on APPLIED and THEORETICAL MECHANICS Issue 9, Volume 2, September 2007, ISSN: 1991-8747

[5] Montgomery D, Runger G, *Applied Statistics and Probability for Engineers*, John Wiley & Sons, Inc., 2003

[6] Stephen S., Schmidt, Robert G, Laungy, Understanding Industrial Design Experiments, Air Academy Press* Associates, USA, 2005

[7] Vlase I, Contribution to Determining of Some Indexes for Quantifying the Stainless Refractory Steels Machinability, Doctoral Thesis, 2002.

[8] Isel-automation Catalogue, 2007

[9] www. stainless-steel-world.net, accessed april, 2009