NEURAL NETWORKS APPLIED TO PREDICTION OF AXIAL FORCE AT HELICAL DRILL MACHINING

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Abstract: *The analytical determination of cutting forces components using mathematical equations can be approximate because these equations do not consider all interdependencies between the factors which influence the cutting process. For this reason, when it is necessary to study the drilling forces, experimental methods based on determination of these forces through measuring of elastic deformations, such as twisting angle or elongation, of some components of dynamometers are used. The measurements of axial force at drilling are carried out at the same time with determination of coefficients and exponents from empirical equations which are available in the literature, for materials used in experiment.*

The paper presents experimental results on HSS helical drills with two straight edges with three diameters used for cutting two materials A570 and 16MnCr5. The cutting parameters are: one speed (n) [rpm] and three feeding rates (f).

Neural networks are used in the fields where the predictability of a phenomenon or the answer to a phenomenon cannot be solved using simple mathematical equations. In this case, the artificial neural networks (ANN) are used for optimization of drilling process correlated with experimental tests.

Keywords: drilling, straight edge, cutting forces, Kistler system, ANN

1. Introduction

In the process of machining with drills with straight-edged, the analysis of physical phenomena can be performed using the basic models of the orthogonal cutting, the forces that acts on the drill be deducted, by analogy with the forces acting on the cutting edge of a lathe tool to turning orthogonal [Sahu, 2004], figure 1 [Yang, 2002]. Thus, the forces of the machining cross section which acts on the two main ways of drill shaft can be broken down into several components.

In another form, simplified [Minciu, 1999], the components of the cutting force in drilling are defined as shown in Figure 2:

- main cutting force P_z, in the direction of cutting movement
- advance, P_x, in the direction of the tool axis;
- rejection force, P_y;

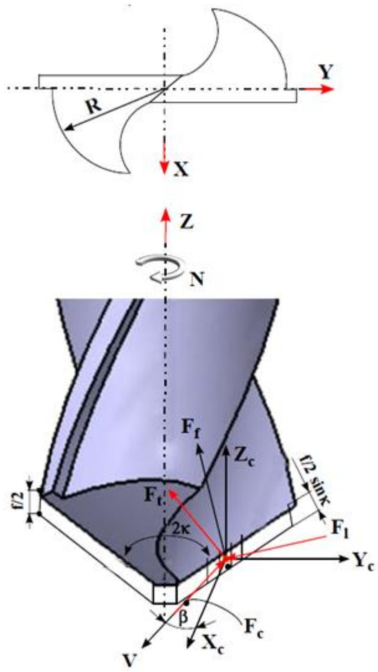

Figure 1: *Correlation between forces in orthogonal cutting and drilling [Yang, 2002]*

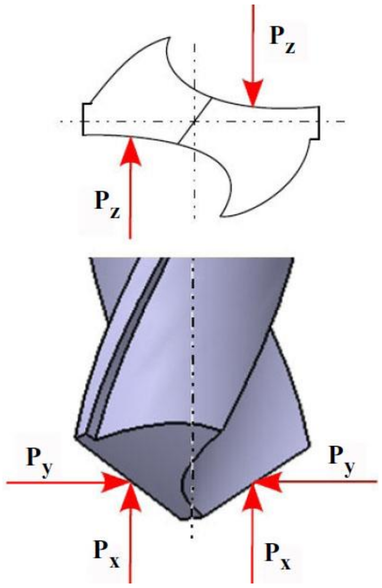

Figure 2: *Components of the cutting forces [Minciu, 1999]*

The manner in which the cutting forces to play an important role in the quality of the product and in the stability of the process of processing, forced to imagine of methods of prediction of its size, which may be grouped into three classes: analytical methods, numeric, experimental methods [Langella, 2005], [Pirtini, 2005].

2. The analytical models, numerical and experimental to the evaluation of the axial force

Analytical models to the evaluation of the axial force

Classic in the literature of the Romanian scientific [Ștețiu, 1994] supports a similarity between the turning and drills and proposes an analytical model for the determination of the axial force arising from cut. In figure 3, is presented the analogy between the forces for turning and the drills.
The radial force acting on the chip, determine the relation with the [Ștețiu, 1994]:

$$F_r = C_r \cdot \frac{s_d^{1-\mu} \cdot z}{2 \cdot \sin^{\mu} \kappa} \cdot (D - D_0) \qquad (1)$$

where C_r there is the unitary resistance [N/m^2].

For the exponent μ are determined the values: μ=0.25, for steel; μ=0.33, for cast iron; κ - attack angle, D_0 - diameter of initial hole.

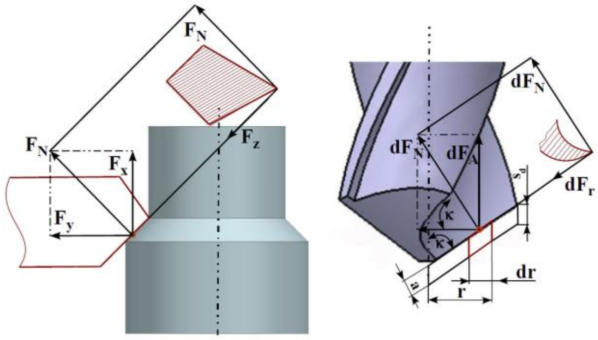

Figure 3: *Analogy turning-drilling. The components of the cutting forces [Ștețiu, 1994]*

May also be define and relations other for the calculation of the axial force of the drill - the main cutting force [Enache, 1983]:

$$F_A = 0{,}91 \cdot C_F \cdot D^{x_F} \cdot s^{y_F} \qquad (2)$$

$$F_Z = 1{,}1 \cdot \frac{K_{s1} \cdot s^{1-\mu}}{2^{1-\mu} \cdot \sin^{\mu} \kappa} \cdot (D - D_0)\,[daN] \qquad (3)$$

Where D is the diameter of the drill [mm]; s - feed [mm/rpm]; C_F - adjustment coefficient of the axial cutting force; x_F and y_F - exponents to the determination of the axial cutting force.

Numerical models to the evaluation of the axial force

For the implementation of the optimization algorithms, the cutting forces must be defined by numerical models. In the line of approaches that has checked the development of numerical patterns with simulation force of the axial drills CAD [Kyratsis, 2011], fuzzy logic (fuzzy logic) [Vimal, 2009], methods of experimental planning Taguchi, Anova etc. [Jindal, 2012].

The finite element method (FEM) can provide a uniform system of virtual approach of the drilling process, soft packages of analysis with the finished items being used frequent [Isbilir, 2011], [Petrariu, 2008], [Roud, 2011].

Experimental models to the evaluation of the axial force

Experimental models which have as their object of study the size of the cutting forces, they pursued the establishment of derive empirical relationships taking account of the factors of influence the most important.

Over the size of the cutting force influence a multitude of factors, most frequently encountered in the experimental determinations being the following: the material, the geometry of the cutting tools, the material of the cutting tools, lubricant, vibrations etc. [Kadam, 2011], [Xia, 2004].

Were made geometries of the drill, [Abrão, 2007], [Ema, 2012], which lead to a decrease in the essential part of axial force.

Experimental research [Ben Salem, 2012], [Kadam, 2011] have determined the influence of the machining parameters on the axial force in the process of drill.

Experimental models [Ștețiu, 1994], [Hamade, 2006] have led to obtaining simplified relations for the calculation of the main cutting force which have recourse to the analytical model determined - see the relationship (1). As a result of the application of the model are obtained relations listed in table 1, for a steel with σ_r=50÷60 daN/mm^2 and cast iron with HB=180÷200.

Table 1: *Equations of advance force [Ștețiu,1994]*

Material	*Force [daN]*
Steel (μ=0.25)	$F_r=104\cdot D\cdot s^{0,75}$
Cast iron (μ=0.35)	$F_r=57\cdot D\cdot s^{0,67}$

Usually, the axial force F_A is being expressed by the means of a relation like:

$$F_A = C_{F_1} \cdot D^{z_F} \cdot s^{y_F} \cdot (HB)^{n_F} \cdot K_F \qquad (4)$$

where n_F is the coefficient determined in an experimental way.

The values calculated with the relationship (4) shall be adjusted by a global coefficient, obtained that the product has more than one, with relationship:

$$K_F = K_{aF} \cdot K_{saF} \cdot K_{\kappa F} \cdot K_{\eta F} \qquad (5)$$

From the analysis of correction coefficients one can observe that, main factors that are non-constructive and that can influence the axial force are: sharpening method (K_{aF}), over sharpening (K_{saF}), mechanic characteristics of material ($K_{\kappa F}$), modality of greasing ($K_{\eta F}$).

3. Equipment and methodology

Equipment

Tests have been carried out in conditions of total dry matter, using the drilling machine with column 6GM-A1, on a table of which is placed the dynamometer and blanks for processing. In order to establish the dependence of axial force-the diameter of the drill, were used 3 HSS helical drills with straight (within the range of diameters of the Ø20mm, Ø18mm and Ø 16mm).

Blanks to processing have been made of 16MnCr5, sizes Ø50x70 mm, respectively of A570, size 90x50x50 mm (SR EN ISO 10084:2002).

Data acquisition

The data acquisition comprises: Earth Kistler tensometric - Model 9272, an amplifier electronic commerce - Kistler model 5070Ax01xx, connection cables (1677Kistler A5 and 1678A5) and the computer with the data acquisition. Block diagram with parts of the installation of the experimental is shown in Figure 4 [Baroiu,2013]. In order to measure the axial force to drills, acquisition and data processing has been used in a product special software, DynoWare, the Kistler Company.

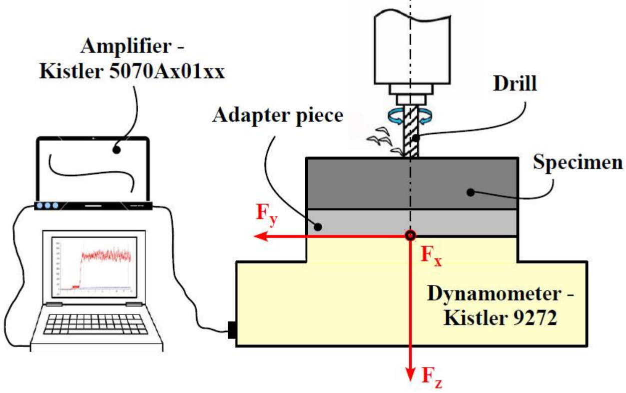

Figure 4: *Block diagram of the experimental installation [Baroiu,2013]*

The research methods

Through the channels amplifier, the conversion of signals from charging from the dynamometer voltages to the output. The output voltage is proportional with the size of the axial forces that occur at drills.

In blanks of parallelepiped shape of the A570 and cylindrical shape of 16MnCr5, were made in advance, two threaded bores M10 to be caught on the part-adapter which in its turn, was reinforced on the dynamometer Kistler 9272 by means of four screws. The tightness of each bolt was carried out with a torque wrench (TORCOFIX model-K Rahsol), to a torque of 20 N·m.

Given the possibility of the dynamometer to measure the force components on three directions, in the present case, have suppressed force components in tangential direction (F_x) and of the press (F_y), leaving only opened the channel to purchase data for F_z component of the cutting force.

During the process of retrieval of the data values entered are rendered in real time, with the computer monitor, by the soft DynoWare. This allows, in addition to a real-time view of the measured curves, the calculation of the other sizes what encountered in the cutting process, configuration and data storage to be measured.

In parallel with the definition of the parameters of the specific input of the dynamometer, specify machining parameters for each case in part: cutting speed (v_c), the advance (f), the speed (n), the feed rate (v_f), the depth of cut (a_p).

In Table 2 shall be specified in the measurement range and frequencies of work for the elements of the measured force, F_z.

Table 2: *Intervals for measurement, frequency for Fz*

Measurement Interval	F_x *[kN]*	F_x *[kN]*	F_x *[kN]*
	-5÷5	-5÷5	-5÷20
Frequency	$f_n(x)$ *[Hz]*	$f_n(y)$ *[Hz]*	$f_n(y)$ *[Hz]*
	-	-	500
Sensitivity	F_x *[pC/N]*	F_y *[pC/N]*	F_z *[pC/N]*
	-7.9	-7,9	-3.6

Parameters of the work regime are the ones specified in Table 3.

Table 3: *Machining parameters*

(D) *mm*	*(v_c)* *m/min*	*(v_f)* *mm/min*	*(n)* *rot/min*	*(f)* *mm/rot*
Ø20	17.6	44.8	280	0.16
Ø18	15.8	70	280	0.25
Ø16	14.1	115	280	0.4

In order to avoid the influence of the depth of the machining hole over the size of the axial force, measurements were made only for the depths of the hole of not more than *1,5·D*, where *D* is the diameter of the drill.

The values of the depth of the holes are correlated with the time of purchase (chosen by 10 or 7 seconds) and are listed in Table 4. The processing time was measured continuously with the aid of a stopwatch.

Table 4: *Value of hole depth*

(f) *mm/rot*	*(n)* *rot/min*	*(t)* *s*	*(d)* *[mm]*
0.16	280	10	7.5
0.25	280	10	11.7
0.4	280	10	18.7
0.16	280	7	5.2
0.25	280	7	8.2
0.4	280	7	13

4. The results obtained and interpretation of measurements

For each test, having acquired the signals of axial force, generated in the process of drill via piezoelectric dynamometer type 9272 Kistler. In accordance with the reference number of the dynamometer shall be measured cutting force in the direction of the *Z* axis. In Figure 5, shall be submitted to the areas of interest of the recorded trace to measure axial force: 1 - drill input; 2 - the beginning cutting; 3 - the complete entry of the drill in the task; 4 - area of a cut-off of the advance and the output of the drill. Of each experiment I would have been associated with the recordings and graphic representations of which may be observed in details on the regime of the machining and the variations in the magnitudes of the axial force, F_z.

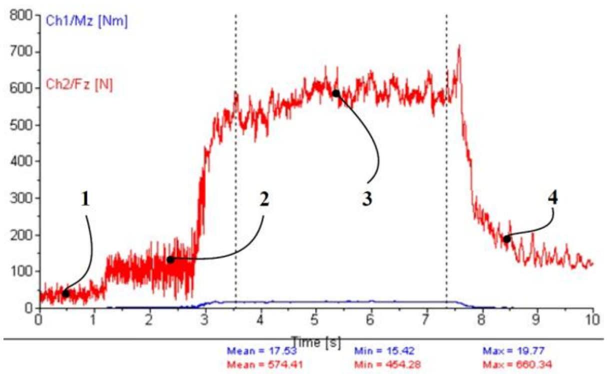

Figure 5: *Areas of interest of signal for Fz*

In tables 5÷6, the average values of the size of the axial force, calculated by the soft DynoWare, selection range for the calculation considered the area where the helical drills working at full load, within a period of time which ensure the stability of the process of measurement.

Table 5: *Values of axial force Fz [N] for the machining of the material A570*

A570	*D = Ø20 mm*		
f mm/rot	0.16	0.25	0.4
F_z *[N]*	922.63	1108.16	1468.44
A570	*D = Ø18 mm*		
f. mm/rot	0.16	0.25	0.4
F_z *[N]*	844.73	915.54	1303.43
A570	*D = Ø16 mm*		
f mm/rot	0.16	0.25	0.4
F_z *[N]*	747.13	874.41	1198.01

Table 6: *Values of axial force Fz [N] for the machining of the material 16MnCr5*

16MnCr5	*D = Ø20 mm*		
f [mm/rot]	0.16	0.25	0.4
F_z *[N]*	679.07	925.25	1244.4
16MnCr5	*D = Ø18 mm*		
f [mm/rot]	0.16	0.25	0.4
F_z *[N]*	653.04	882.62	1107.37
16MnCr5	*D = Ø16 mm*		
f [mm/rot]	0.16	0.25	0.4
F_z *[N]*	567.7	729.85	998.02

Equations that are obtained by linear regression for axial force, are like:

$$F_Z = -428{,}963 + 2025{,}33 \cdot s + 51{,}3679 \cdot D \qquad (6)$$

As shown in Figure 6, shall be submitted to the diagram of the likelihood of residues at a confidence interval of 95 %, for the variable output F_z, that the difference between the feedback signal to be measured and the theoretical response of each experiment.

In the plot, it may be noticed that the force F_z, obtained from the measurements can be found in the confidence interval specified.

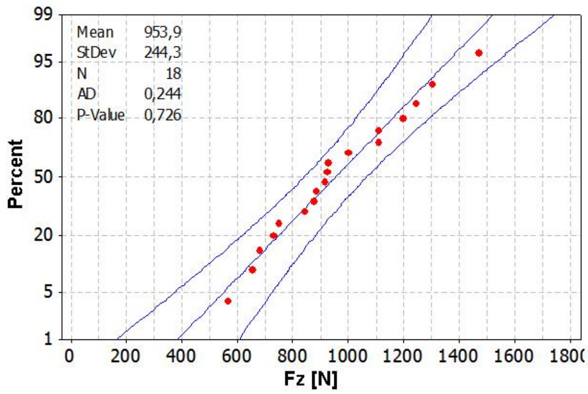

Figure 6: *Fault of probability of residues for force Fz*

When account is taken of the conduct of the tests, it follows that for the trials to which the advance shall be deemed to be constant, relationship (4), the form:

$$F_Z = C'_{F_Z} \cdot D^{x_{F_Z}} \ \text{[N]}; \qquad (7)$$

or, for the diameter of the drill constant, the relationship will be of the form:

$$F_Z = C''_{F_Z} \cdot s^{y_{F_Z}} \ \text{[N]}; \qquad (8)$$

By logarithms, relations above may be written in the form of:

$$\log F_Z = \log C'_{F_Z} + x_{F_Z} \cdot \log D; \\ \log F_Z = \log C''_{F_Z} + x_{F_Z} \cdot \log D, \qquad (9)$$

Expressions which can be written in logarithmic coordinate, in the form of the right:

$$y - \bar{y} = m\left(x - \bar{x}\right). \qquad (10)$$

The slope of rights of type (10) can be determined by the method of some small squares being defined by

$$m = \frac{\overline{xy} - \overline{x} \cdot \overline{y}}{\overline{x^2} - (\overline{x})^2} \qquad (11)$$

where

$$\overline{x} = \frac{1}{N}\sum_{k=1}^{N} x_k; \quad \overline{y} = \frac{1}{N}\sum_{k=1}^{N} y_k;$$
$$\overline{x^2} = \frac{1}{N}\sum_{k=1}^{N} x_k^2; \quad \overline{xy} = \frac{1}{N}\sum_{k=1}^{N} x_k y_k, \qquad (12)$$

N - representing the number of determinations

In relations (11) and (12), through the variable x is understood $\log D$ or $\log s$, as the case may be, and by the variable y means $\log F_z$.

In tables 7÷9, one explicatory presents, the values of exponents y_{F_z}, respectively the value of coefficients C'_{F_z} and C''_{F_z}, for the transformed material, A570.

Table 7: *The calculation of the exponent* x_{F_z}, *for f = 0, 16 mm/rot, at the machining A570*

D mm	f. [mm/rot]	F_z [N]	x = log s	y = log F_z
20	0.16	922.63	-0.7958	2.965
	0.25	1108.16	-0.6020	3.044
	0.4	1468.44	-0.3979	3.166
	Σx	Σy	Σxy	Σx²
	-1.79588	9.1764	-5.4530	1.154
D mm	f. [mm/rot]	xy	x^2	y^2
20	0.16	-2.3598	0.6334	8.791
	0.25	-1,8330	0,3624	9,269
	0.4	-1.2602	0.1583	10.02
	Σy²	(Σx²)/N	(Σxy)/N	y_{F_z}
	28.0899	0.3847	-1.8176	0.507

Table 8: *Calculation of the exponent* C'_{F_z} *for f=0,16 mm/rot, at the machining A570*

D [mm]	f. [mm/rot]	F_z [N]
20	0.16	903.63
18		844.73
16		747.13
x_{F_z}	y_{F_z}	C'_{F_z}
0.8560	0.5079	177.8502

Table 9: *Calculation of the exponent* C''_{F_z} *for s=20 mm/rot, at the machining A570*

D [mm]	f. [mm/rot]	F_z [N]
20	0.16	922.63
	0.25	1108.16
	0.4	1468.44
x_{F_z}	y_{F_z}	C''_{F_z}
0.8560	0.5079	177.5559

Experimental results, interpreted have led to the following equations of the axial force, for the two transformed materials. For drills with straight edge, in the field of diameters Ø16÷Ø20 mm and advances 0.16, 0.25 and 0.4 mm/rot for the machining A570 and 16MnCr5, it results the following equations:

$$F_Z = 156{,}96 \cdot D^{0{,}89} \cdot s^{0{,}50} \text{ [N]}; \qquad (13)$$

$$F_Z = 133{,}78 \cdot D^{0{,}96} \cdot s^{0{,}62} \text{ [N]}; \qquad (14)$$

The size of the axial force due to the action of the chisel edge, it can be considered approximately equal to half the size of the axial force of ownership.

5. Neural artificial networks

Artificial neural networks are very flexible tools used in the prediction of process parameters aiming the optimization of manufacturing process [Susac,2016]. Their use is possible if the input and output parameters is related.

The scheme of the neural model proposed for axial force prediction is presented in Figure 7. Based on this model, the values of the axial force is calculated. The results are in very good agreement with experimental values; the average error is 2.09%. On the basis of the relationship (6), which defines the values of the axial force, F_z, and relationships (13)÷(14) which define the values of the axial force, F_z, calculated on the basis of coefficients and polytrophic exponents, and one has achieved a comparative analysis with values measured of the axial force.

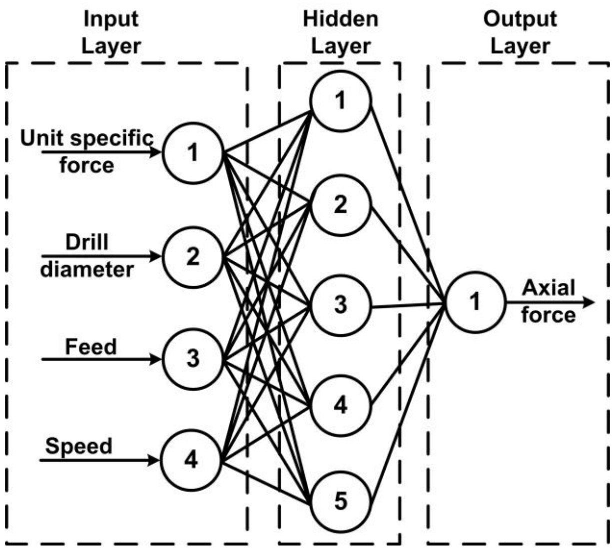

Figure 7: *Neural model for axial force prediction*

Thus, in tables 10÷11 and figures 8÷9 one presents the values obtained for F_z, appeared between measurements, analytical methods, and the ones obtained by the prediction of neuronal networks.

Table 10: *Comparative values of Fz force, at the machining A570*

D [mm]	*f. [mm/rot]*	*F_z meas. [N]*	*F_z, regres. [N]*	*F_z, neur. network [N]*
20	0.16	922.63	922.4	915.1
20	0.25	1108.1	1104.7	1110.9
20	0.4	1468.4	1408.5	1444.5
18	0.16	844.73	819.71	819.3
18	0.25	915.54	1001.9	981.9
18	0.4	1303.4	1305.7	1304.0
16	0.16	747.13	716.9	747.9
16	0.25	874.41	899.2	880.0
16	0.4	1198.0	1203.0	1156.2

Table 11: *Comparative values of F_z force, at the machining 16MnCr5*

D [mm]	*f. [mm/rot]*	*F_z meas. [N]*	*F_z, regres. [N]*	*F_z, neur. network [N]*
20	0.16	679.0	682.4	695.3
20	0.25	925.2	934.7	921.1
20	0.4	1244.4	1258.5	1261.8
18	0.16	653.0	619.7	624.8
18	0.25	882.6	821.9	822.2
18	0.4	1107.3	1305.7	1115.2
16	0.16	567.7	566.9	571.9
16	0.25	729.8	759.2	748.3
16	0.4	998	973.6	987.2

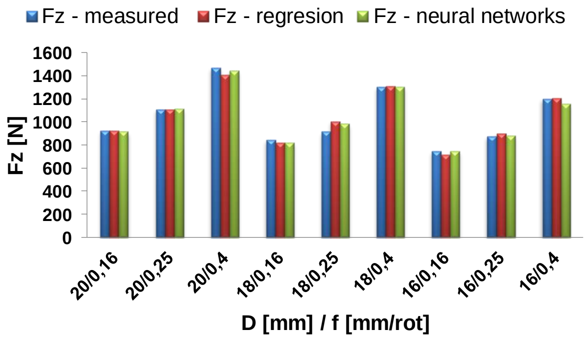

Figure 8: *F_z force at the machining A570*

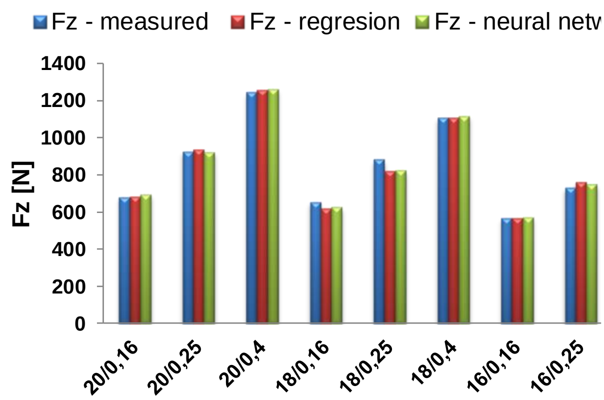

Figure 9: *F_z force at the machining 16MnCr5*

6. Conclusions

- one can observe the diameter of the influence of processing, and the advance of work on the machining cross section in the sense that it increases with the increase of the advance of work, i.e. with the diameter of the drill the helical pattern.

- the values of the forces calculated by the relations of the linear regression lead, in some cases, errors relatively higher, in relation with the force of the measured or estimated with the neuronal networks.

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