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A PREDICTIVE MODEL OF CUTTING FORCE IN TURNING USING TAGUCHI AND RESPONSE SURFACE TECHNIQUES

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Abstract. *This contribution presents the development of a predictive model for cutting force components in longitudinal turning of constructional steel with a coated carbide tool. The model is formulated in terms of the cutting conditions. Taguchi method is used for the plan of experiments and the analysis is performed using response surface methodology. Next, a related comparison is attempted to results obtained using the Kienzle - Victor cutting force model.*

1 INTRODUCTION

The knowledge of cutting forces developing in the various machining processes under given cutting factors is of great importance, being a dominating criterion of material machinability, to both: the designer-manufacturer of machine tools, as well as to user. Furthermore, their prediction helps in the analysis of optimisation problems in machining economics, in adaptive control applications, in the formulation of simulation models used in cutting databases.

In this regard, cutting forces being a substantial dependent variable of the machining system has been investigated by many researchers in various cutting processes through formulation of appropriate models for their estimation.

These models are analytical, semi-empirical and empirical relationships, which connect cutting factors to forces.

The analytical models are based upon the theory of mechanics of cutting, orthogonal or oblique but they are complicated and mostly, they demand the a-priori knowledge of response magnitudes, as shear angle and friction angle [1].

The semi-empirical expressions contain constants that are experimentally predicted and they can be classified as linear, power and exponential functions. The most established cutting force relationship although old is that proposed by Kienzle and Victor, also known as the specific cutting resistance model [2]; it will be considered in the following.

Over the last years, empirical models for the machinability parameters in various machining processes have been developed using data mining techniques, such as statistical design of experiments (Taguchi method, response surface methodology), computational neural networks and genetic algorithms [3-8].

All these techniques are, more or less, ''black box'' approaches but possess the advantage of providing the impact of each individual factor and factor interactions, after an appropriate design of the experiment.

Especially, for the Taguchi and response surface methodology, a minimum amount of experimental trials is combined to a reliable global examination of the variables interconnection, instead of one- factor- at- a –time experimental approach and interpretation [9].

Turning operations are widely used in workshop practice for applications carried out in conventional machine tools, as well as in NC and CNC machine tools, machining centres and related manufacturing systems.

All three cutting force components are of interest because apart from the tangential (main) component that gives the cutting power and its determination is apparently necessary, the radial and in-feed components control dimensional and form errors in case of workpiece and tool deflections and tool wear.

The present paper describes the development of a predictive model for cutting force components in longitudinal turning of St37 steel with a TiN coated carbide tool. The model is formulated in terms of the cutting conditions, namely feed (f), cutting speed (v) and depth of cut (a). Taguchi method is used for the plan of experiments for the three aforementioned factors at four levels and the analysis is performed using response surface methodology. Next, a related comparison is attempted to results obtained using the Kienzle and Victor cutting force model.

2 EXPERIMENTAL

2.1 Materials and Instrumentation

External longitudinal turning was performed in a lathe Colchester 2500 of excellent operational condition.

Bars of St37 steel of 400 mm in length and of 40 mm in diameter were processed by a TiN coated P40 carbide tool, which was kept practically sharp during the experiment.

The tool approach angle was 93º and the clearance angle 0º.

No cutting fluid was used.

The cutting force measurements were undertaken by a three-axis Kistler piezoelectric dynamometer. For signal processing a 100 Hz low pass filter was used for a quasi-static consideration.

The cutting conditions are listed in Table 1 and they correspond to chatter free and semi-finish conditions, as well as to all three chip formation modes: discontinuous, built-up edge and continuous (regular).

To elaborate the plan of experiments the method of Taguchi was used for the 3 factors considered (rotational speed, depth of cut and feed,) at four levels, respectively (Table 1).

The array chosen was L_{16} (4^3) for the main effects of the factors and the interactions (Table 2).

The array has 16 rows corresponding to the number of tests with 3 columns at 4 levels. The factors and the interactions are assigned to the columns.

Level	**n (rpm)**	**a (mm)**	**s (mm/rev)**
1	100	0.4	0.12
2	300	0.8	0.16
3	500	1.2	0.20
4	700	1.6	0.24

Table 1: Assignment of levels to the factors

L_{16} (4^3) test	**1**	**2**	**3**
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	2
6	2	2	1
7	2	3	4
8	2	4	3
9	3	1	3
10	3	2	4
11	3	3	1
12	3	4	2
13	4	1	4
14	4	2	3
15	4	3	2
16	4	4	1

Table 2 : Orthogonal array of Taguchi L_{16} (4^3)

n	**a**	**s**
X_1	**X_2**	**X_3**
-1	-1	-1
-0,5	-0,5	-0,5
0,5	0,5	0,5
1	1	1

Table 3 : Coding of experimental factors

The coding of the cutting conditions (independent variables) and the results of the experiment are tabulated in Tables 3 and 4, accordingly.

n (rpm)	**a (mm)**	**s (mm/rev)**	**F_f**	**F_r**	**F_c_**
100	0.4	0.12	29	57	115
100	0.8	0.16	60	97	193
100	1.2	0.2	276	345	624
100	1.6	0.24	379	353	786
300	0.4	0.16	45	92	153
300	0.8	0.12	87	151	241
300	1.2	0.24	248	368	562
300	1.6	0.2	296	281	580
500	0.4	0.2	31	84	131
500	0.8	0.24	127	265	380
500	1.2	0.12	148	165	307
500	1.6	0.16	249	189	461
700	0.4	0.24	47	143	203
700	0.8	0.2	114	209	317
700	1.2	0.16	168	202	354
700	1.6	0.12	200	146	360

Table 4 : Measured data of the cutting force components

The statistical analysis of the data was carried out into two steps: firstly, analysis of variance (ANOVA) to study the contribution of the factors and the interactions and secondly, development of multiple correlation models for the cutting force components of second-order polynomial form. Also, response surface methodology was used to quantify relationships among one or more measured response variables (the cutting force components) and the vital input factors i.e. the cutting conditions.

3 FORMULATION OF THE MODEL

After the analysis of variance carried out on the cutting force data to investigate into the influence of the factors, main and interactions, on the total variance of the results, the Tables 5 to 7 were formed.

One can observe from Table 5 that regarding the main effects, the greatest influence on the main component F_c is exhibited by the depth of cut, followed by feed and cutting speed. The squared main factors and the interactions are significant as cutting speed with a*s showing the greatest contribution.

Source of variance	DF	SS	MS	F	P
n	1	37516	1118	0,36	0,572
a	1	377525	75085	23,98	0,003
s	1	133056	17163	5,48	0,058
n*n	1	1173	1173	0,37	0,563
a*a	1	2233	2233	0,71	0,431
s*s	1	1243	1243	0,40	0,552
n*a	1	1893	1893	0,60	0,466
n*s	1	170	170	0,05	0,824
a*s	1	4084	4084	1,30	0,297
Error	6	18790	3132		
Total	15	577682			

Note: DF, degrees of freedom; SS, sum of squares; MS, mean squares; F, F-test; P, P-test.

Table 5 : ANOVA table for the F_c cutting force component

Considering the axial force component Ff, as most influential factors feed, depth of cut and depth of cut squared are obtained (Table 6). The interactions appear similar to the previous case.

Source of variance	DF	SS	MS	F	P
n	1	6076	6	0,01	0,944
a	1	59598	11025	10,27	0,019
s	1	60762	13814	12,86	0,012
n*n	1	116	116	0,11	0,754
a*a	1	13053	13053	12,15	0,013
s*s	1	1388	1388	1,29	0,299
n*a	1	11	11	0,01	0,922
n*s	1	91	91	0,08	0,780
a*s	1	1904	1904	1,77	0,231
Error	6	6444	1074		
Total	15	149443			

Note: DF, degrees of freedom; SS, sum of squares; MS, mean squares; F, F-test; P, P-test.

Table 6 : ANOVA table for the Ff cutting force component

Source of variance	DF	SS	MS	F	P
n	1	37516	1118	0,36	0,572
a	1	377525	75085	23,98	0,003
s	1	133056	17163	5,48	0,058
n*n	1	1173	1173	0,37	0,563
a*a	1	2233	2233	0,71	0,431
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n*a	1	1893	1893	0,60	0,466
n*s	1	170	170	0,05	0,824
a*s	1	4084	4084	1,30	0,297
Error	6	18790	3132		
Total	15	577682			

Note: DF, degrees of freedom; SS, sum of squares; MS, mean squares; F, F-test; P, P-test.

Table 7 : ANOVA table for the Fr cutting force component

According to Table 7 the radial force component Fr is influenced by similar factors as Fc.
The second-order relevant models for the cutting force components along with their coefficients of determination are, as follows:

$$\mathbf{F_c = 351.17 - 22.75X_1 + 186.44X_2 + 89.14X_3 - 37.44X_1X_2 - 11.22X_1X_3 + 55X_2X_3 + 22.83X_1^2 - 31.5X_2^2 + 23.5X_3^2} \tag{1}$$

$$\mathbf{R^2 = 0.968}$$

$$\mathbf{F_f = 144.417 - 5.694X_1 + 115.833X_2 + 30.306X_3 - 18.778X_1X_2 - 5.667X_1X_3 + 31.222X_2X_3 + 7X_1^2 + 8X_2^2 + 4.333X_3^2} \tag{2}$$

$$\mathbf{R^2 = 0.981}$$

$$\mathbf{F_r = 233.250 + 1.639X_1 + 71.444X_2 + 79.972X_3 + 2.889X_1X_2 - 8.222X_1X_3 + 37.556X_2X_3 - 7.167X_1^2 - 76.167X_2^2 + 24.833X_3^2} \tag{3}$$

$$\mathbf{R^2 = 0.957}$$

It is obvious that the models are characterized by very high correlation taking into account that they have as inputs cutting conditions that produce all three types of chip controlled by the variation in cutting speed, as aforementioned.

The estimated response surfaces for the cutting force components are illustrated in Figures 1 to 3.

For all three components it is apparent that they seriously increase when the depth of cut and feed increase, whilst the rotational speed has a rather negligible influence.

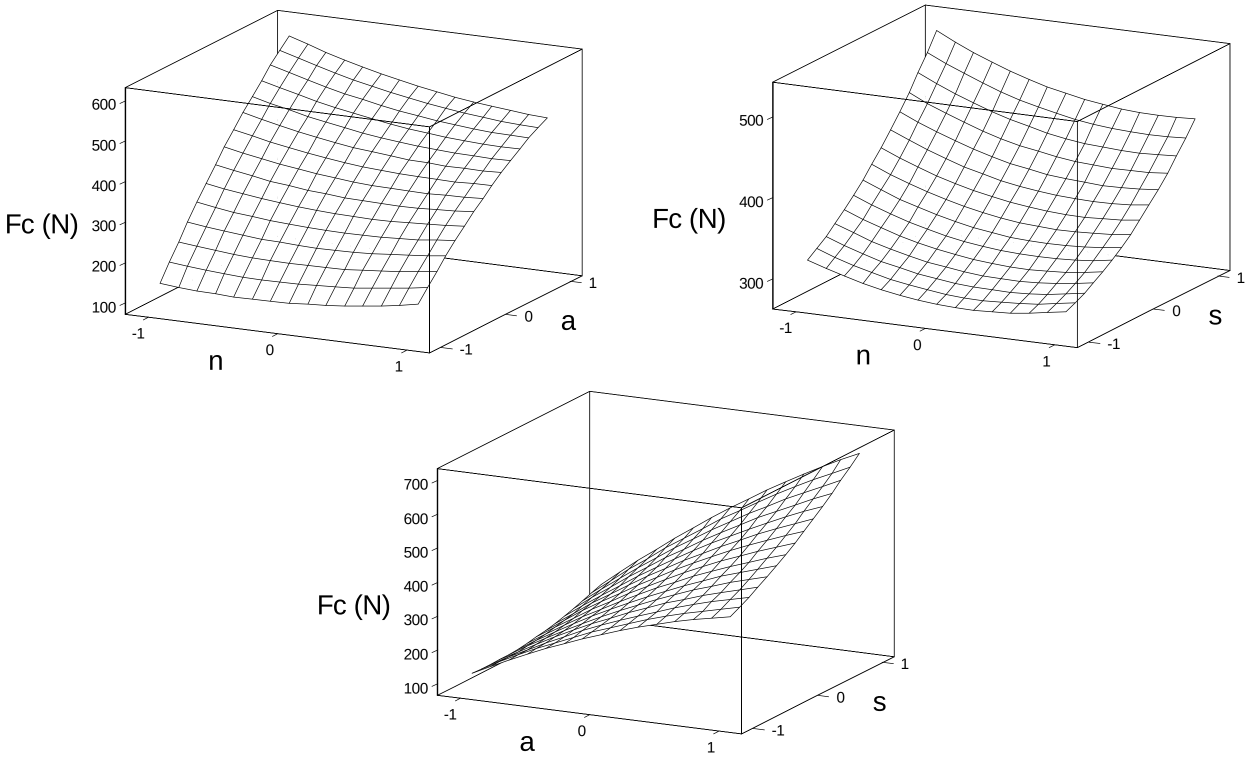

Figure 1. Estimated response surface of Fc against the cutting conditions

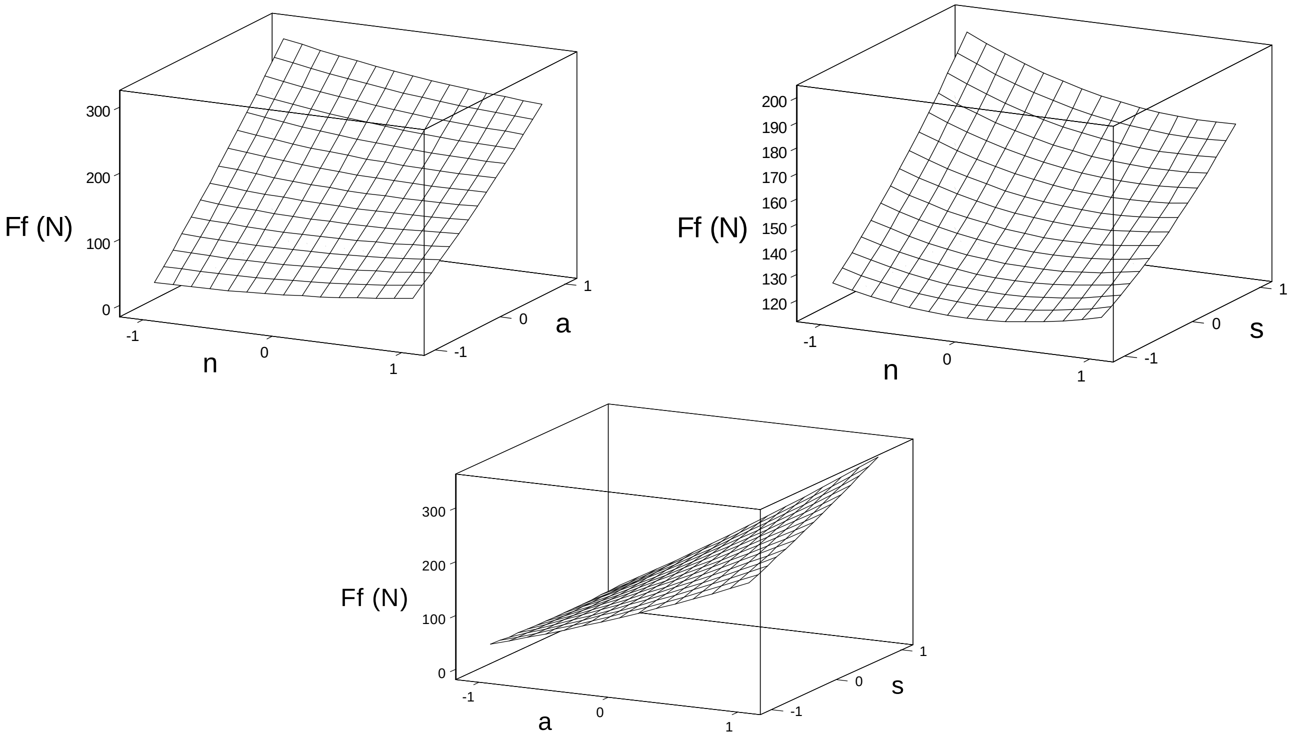

Figure 2. Estimated response surface of Ff against the cutting conditions

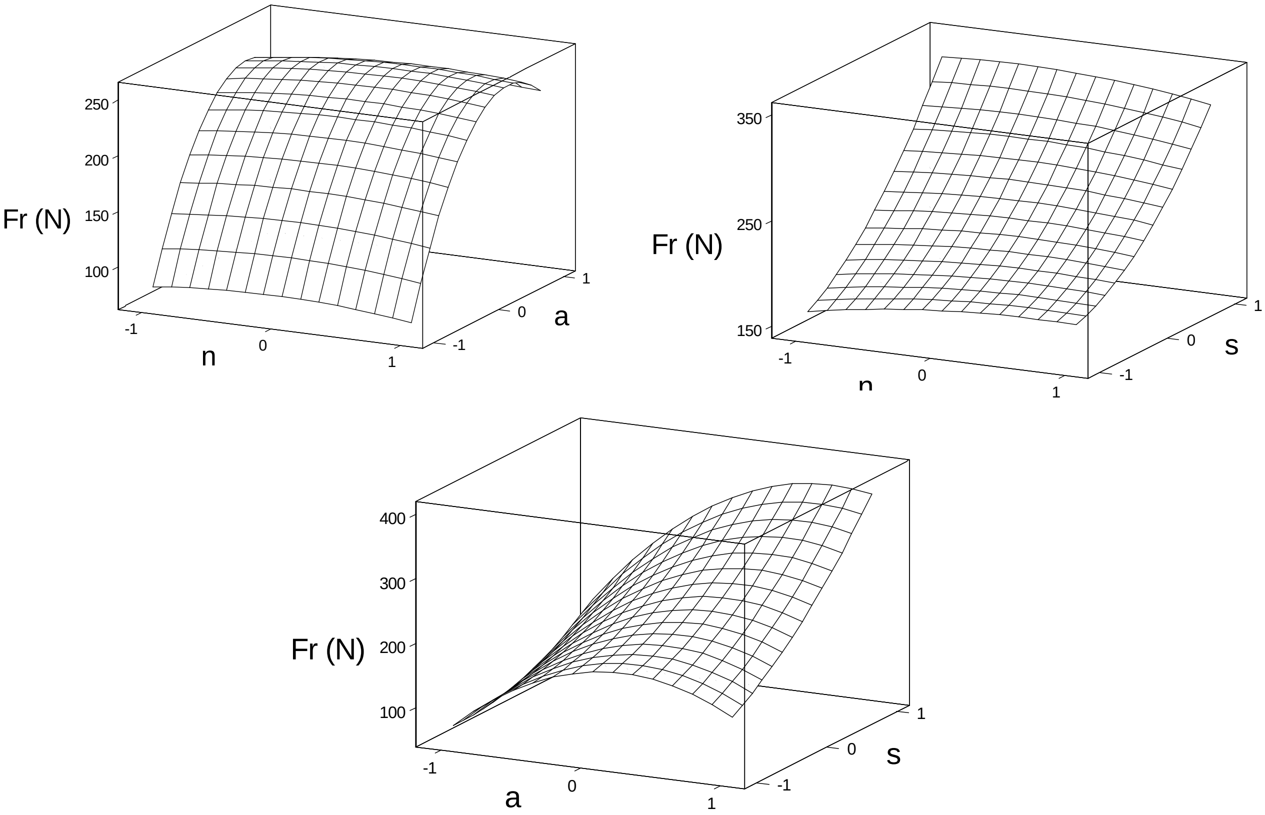

Figure 3. Estimated response surface of Fr against the cutting conditions

4 COMPARISON OF THE POSTULATED CUTTING FORCE MODEL TO KIENZLE-VICTOR MODEL

The Kienzle–Victor model as mentioned in the Introduction is well established and introduces the specific cutting resistance to assess the main cutting force component [2]:

$$F_c = k_s A \, , \tag{4}$$

where k_s is the specific cutting resistance and A is the undeformed chip area given by:

$$A = a\,s \, . \tag{5}$$

It was found that k_s reduces when the undeformed chip thickness h increases following a negative power law and the main force component is finally:

$$F_c = k_{s1} b h^{(1-m)} \quad , \tag{6}$$

where b is the width of cut and k_{s1} (equal to k_s if A = 1 mm^2) and m are constants mostly dependent on the workpiece material..

This model is semi-empirical as it is based on the hypothesis of higher cutting pressure to deform plastically smaller volume of material due to size effects (the lesser is the probability for meeting dislocations that assist plastic deformation, for instance).

As the specific cutting resistance is also a function of cutting speed, tool material, rake angle, wear and cutting fluid corresponding correction factors have been used; correction for the influence of the cutting speed is the most usual in practice.

For a more direct relative comparison of the two models the technological constants k_{s1} and m are firstly experimentally determined. This can be done by estimating the abscissa at h =1 mm and the inclination of the linear log(Fc/b) – logh relationship.

Next, the variation of the two constants versus the rotational speed is estimated and they are introduced in (6) as functions of the rotational speed.

The results of both models for the main cutting force component Fc, the proposed in this paper and the Kienzle-

Victor in association with the experimental values are illustrated in Figures 4 and 5.

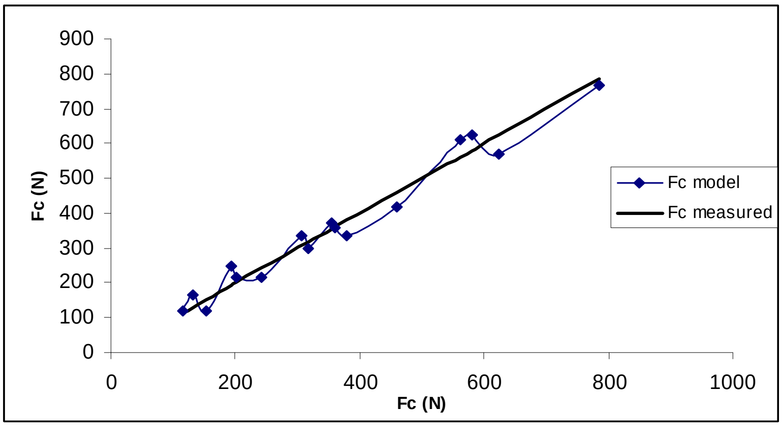

Figure 4. Comparison of the Fc calculated values through the postulated model to the measured ones

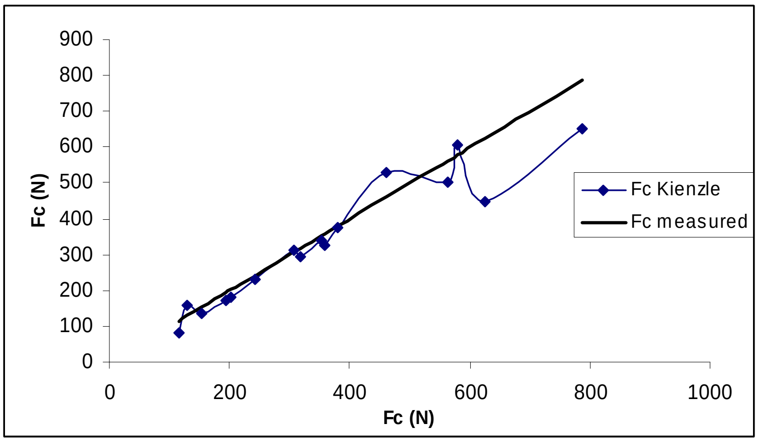

Figure 5. Comparison of the Fc calculated values via the Kienzle-Victor model to the measured ones

The other two force components can also be expressed by Kienzle-Victor equations but it is omitted in this study for the shake of space.

5 CONCLUSIONS

The main conclusions arrived at are:

- The highest influence on cutting forces is exerted by the depth of cut and the feed of varying order of contribution for every force component, whilst the cutting speed has a less significant negative effect. Apart from these main effects, important interactions are revealed between the parameters, especially a*s.
- Owing to this fact, a comparison is attempted to the well established semi-empirical, cutting resistance based, Kienzle-Victor model. The results obtained prove that the present model is in better agreement with the experimental findings than the former model for a wider range of cutting speed and can be applied alternatively, when high demands of prediction exist.

A further extension of the proposed model with other cutting factors, as tool geometry and wear, will increase its accuracy and reliability.

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