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INFLUENCE OF CUTTING PARAMETERS ON CUTTING FORCE DURING DRY MACHINING OF HIGH-ALLOY STEEL

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Abstract
In this research, influence of cutting parameters (speed, feed rate and depth of cutting) on the resultant cutting force while dry machining high-alloy steel on a conventional lathe is investigated. A full factorial experiment was conducted with three repetitions in central point in order to determine the mathematical model for prediction of cutting force with respect to cutting parameters input. After analysis of results it can be seen that a linear model can be very accurate in prediction of cutting force, especially after inclusion of the effects of interactions between cutting parameters.
Keywords: Cutting force, cutting parameters, analysis of variance

1. Introduction

It is well known that cutting parameters (speed, feed rate and depth of cutting) and their selection highly influence any process of conventional machining, especially when we talk about conventional turning. Various parameters, such as cutting force, surface roughness and thermodynamics of cutting are influenced directly with these three most important parameters. Accurate prediction of cutting force in conventional turning can be very significant considering its influence on tool life, vibration occurrence and respectively required surface finish of the work piece. Having an accurate mathematical model can be very helpful for achieving correct predictions of cutting force and its optimisation.
In this research forming a mathematical model for prediction of cutting force with the input of cutting parameters for high-alloy steel was attempted, using the theory of DOE and analysis of variance.

2. Experimental set-up

Experimental measurements were conducted on a conventional lathe POTISJE PA 501M, without using any form of additional cooling and lubrication media, so it can be said that the environment of dry machining was used. Experiment was conducted using a carbide turning insert CNMG431-SM produced by Sandvik Coromant, while machining a high-alloy, cylindrical, steel work piece with a diameter of 60 mm. For measuring the cutting force Kistler dynamometer with a mounted tool holder 9441B and a multichannel charge amplifier type 5070 was used. For each experimental point equal length of work piece was machined.

3. Linear model

As already stated, three main influential parameters were considered, cutting speed, feed rate and cutting depth, each on three levels presented in the table 1. For practical reasons cutting speed was determined through spindle speed. Linear model was considered, for the first run, in the form:

$$Fres = b_0 + b_1X_1 + b_2X_2 + b_3X_3 \quad ...(1)$$

Table 1. Levels of parameters

Level	Spindle speed - n (RPM)	Feed rate - s (mm/rev.)	Depth - a (mm)
-1	265	0,098	1
0	400	0,196	1,5
1	500	0,285	2

Parameters were coded by the D-optimality criterion into the coded values. A full factorial experiment with three repetitions in central point was conducted. Therefore, the number of experimental points was 11.

Order of conducting the experiment was random. The experimental procedure with measured results is presented in table 2.

Table 2. Design matrix of the experiment with experimental results

Experimental point - N	Order of conducting the experiment	X_0	X_1	X_2	X_3	Fx (N)	Fy (N)	Fz (N)	Fres (N)
1.	3.	1	1	1	1	1278,3	233,51	1331,7	1860,65
2.	2.	1	-1	1	1	1349,1	225,38	1410,6	1964,86
3.	4.	1	1	-1	1	588,92	107,97	579,57	833,30
4.	1.	1	-1	-1	1	653,86	110,27	649,82	928,42
5.	10.	1	1	1	-1	695,4	163,52	693,42	995,57
6.	11.	1	-1	1	-1	790,45	834,8	756,55	1376,25
7.	8.	1	1	-1	-1	554,53	597,16	515,11	964,08
8.	9.	1	-1	-1	-1	369,69	95,27	341,28	512,07
9.	5.	1	0	0	0	737,55	144,42	740,19	1054,85
10.	6.	1	0	0	0	740,69	146,06	743,24	1059,42
11.	7.	1	0	0	0	739,77	148,31	742,18	1058,34

Calculated parameters of the model are: b_0=1146,165 ; b_1=-16 ; b_2=369,933 ; b_3=217,408

Analysis of variance for the linear model is presented in table 3.

Table 3. Analysis of variance for the linear model

	df	SS	Variance	F_0-value
Regression	k=3	SSreg=1474992,761	491664,254	F_0=8,93
Residuals	N-k-1=7	RSS=385480,679	55068,668	
Total	10	SYY=1860473,44		

Adequacy of the linear model was checked with the F-test. For a confidence level α=0.05% the proposed linear model was adequate. For determining the model adequacy, coefficient of determination was also considered (R^2=0,79). Due to the fact that the experiment is three-factorial and that the coefficient of determination is increased by adding of factors, adjusted coefficient of determination was considered ($\overline{R}^2$=0,7). As can be seen 70% of variability of output variable is described by the three defined influential parameters. Analysis of significance of parameters for linear model is presented in table 4. For determining the significance of parameters F-test was used. For a confidence level α=0.05% it was concluded that all parameters significantly influence the output variable.

Table 4. Analysis of significance of parameters for linear model

	df	SS	Variance	Fr-value
b_0	1	14450636,279	14450636,279	F_{r0}=2532977,437
b_1	1	2048	2048	F_{r1}=358,983
b_2	1	1094803,396	1094803,396	F_{r2}=191902,436
b_3	1	378129,908	378129,908	F_{r3}=66280,44
Error	2	11,41	5,705	

Based on the calculated values and after decoding the parameters, linear model for prediction of cutting force is presented in the form of the equation:

$$\mathrm{Fres} = -211{,}642 - 0{,}136 \cdot n + 3956{,}503 \cdot s + 434{,}816 \cdot a \quad ...(2)$$

4. Linear model with included interactions

Since the adjusted coefficient of determination shows that 70% of variability of output value (cutting force) is determined by the influence of the cutting parameters, there is still 30% of the variability which remains unaccounted for with using a simple linear model for prediction. Improvement of the model, in order to reach a higher value of this coefficient, was attempted by introducing the influence of the interactions of the parameters into the model.

Predicted model with included interactions has a form:

$$\mathrm{Fres} = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3 \quad ...(3)$$

Existing design matrix of the experiment was extended with the interaction parameters. Calculated additional interaction parameters of the model are:

$$b_{12}=-105{,}223 \; ; \; b13=-33{,}833 \; ; \; b23=146{,}015 \; ; \; b123=102{,}95 \quad ...(4)$$

Analysis of variance for the linear model with included interactions is presented in table 5.

Adequacy of the linear model with interactions was checked with the F-test and for a confidence level α=0.05% proposed model was found adequate. Coefficient of determination and adjusted coefficient of determination for this model are:

$$R^2 = 0{,}98 \; ; \; \bar{R}^2 = 0{,}93 \quad ...(5)$$

As can be seen in this case, 93% of variability of the output variable is determined by the defined parameters. After conclusion that the predicted model is adequate, significance of parameters was analysed. Analysis of significance of parameters for linear model is presented in table 6. For determining the significance of parameters F-test was used. For a confidence level α=0.05% it was concluded that all parameters significantly influence the output variable. Based on the calculated values and after decoding the parameters, linear model with included interactions for prediction of cutting force is presented in the form of the following equation:

$$\begin{aligned}\mathrm{Fres} &= 1146{,}165 - 16 \cdot \frac{n-382{,}5}{117{,}5} + 369{,}933 \cdot \frac{s-0{,}1915}{0{,}0935} + 217{,}408 \cdot \frac{a-1{,}5}{0{,}5} \\ &- 105{,}223 \cdot \left(\frac{n-382{,}5}{117{,}5}\right) \cdot \left(\frac{s-0{,}1915}{0{,}0935}\right) - 33{,}833 \cdot \left(\frac{n-382{,}5}{117{,}5}\right) \cdot \left(\frac{a-1{,}5}{0{,}5}\right) \\ &+ 146{,}015 \cdot \left(\frac{s-0{,}1915}{0{,}0935}\right) \cdot \left(\frac{a-1{,}5}{0{,}5}\right) + 102{,}95 \cdot \left(\frac{n-382{,}5}{117{,}5}\right) \cdot \left(\frac{s-0{,}1915}{0{,}0935}\right) \cdot \left(\frac{a-1{,}5}{0{,}5}\right) \quad ...(6)\end{aligned}$$

Table 5. Analysis of variance for the linear model with included interactions

	df	SS	Variance	F_0-value
Regression	k=7	SSreg=1828377,82	261196,831	F_0=24,4
Residuals	N-k-1=3	RSS=32095,62	10698,54	
Total	10	SYY=1860473,44		

Table 6. Analysis of significance of parameters for linear model with interactions

	df	SS	Variance	Fr-value
b_0	1	14450636,279	14450636,279	F_{r0}=2532977,437
b_1	1	2048	2048	F_{r1}=358,983
b_2	1	1094803,396	1094803,396	F_{r2}=191902,436
b_3	1	378129,908	378129,908	F_{r3}=66280,44
b_{12}	1	88575,038	88575,038	F_{r12}=15525,861
b_{13}	1	9157,375	9157,375	F_{r13}=1605,149
b_{23}	1	170563,042	170563,042	F_{r23}=29897,115
b_{123}	1	84789,62	84789,62	F_{r123}=14862,335
Error	2	11,41	5,705	

5. Conclusion

Based on the conducted analysis of variance for the linear model with included interactions between parameters it can be seen that with this kind of model 93% of variability of output variable (cutting force) can be predicted using only the cutting parameters, cutting speed (spindle speed), feed rate and cutting depth. Even the simple linear model without interactions gives a good prediction of cutting force, based on these three influential parameters. We can see that in the simple linear model, highest influence on the cutting force has feed rate, while the lowest influence is from the spindle speed. In the model with included interactions highest influence on the cutting force is from the feed rate, depth of cutting and their interaction.

Taking all this into consideration, with the proposed model, calculation of the cutting force, while dry machining high-alloy steel in the described set-up for given input cutting parameters can be accurately made as a mean of better understanding of the process and its optimisation.

6. References

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