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Determination of Mathematical Formulae for the Cutting Force F_C during the Turning of C45 Steel

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This article provides an assessment of the effect of selected processing conditions on the value of the cutting force, F_c, during straight turning. The assessment is based on equations in the form of power polynomials obtained from the results of experimental tests. The tests were conducted while turning C45 carbon steel with the use of cutting fluid applied in ample quantities and without cutting fluid. At the end of the article, an analysis of the obtained mathematical dependencies is provided along with experimental verification.

Keywords: Turning, cutting force, wiper insert

1. Introduction

The determination of the values of forces occurring in machine cutting is one of the fundamental areas of the mechanics of the process. Thanks to the research achievements accomplished to date, the components of the total cutting force, F, can be determined in two ways [1]:

- on the basis of theoretical and experimental dependencies, or
- through experiments.

In practice, the experimental approach to the total cutting force and its components consists of the electrical measurement of mechanical values, a widely–used method in the mechanics of materials. Currently, the methods of measurement of the elastic deformations resulting from the impact of the forces using piezoelectric sensors are considered elementary. A typical programme of the experimental measurements of the components of the cutting force usually includes the influence of cutting parameters, cutting edge geometry, tool material grade, work piece material grade and the effects of the use of cutting fluid. Special computer software is used to develop mathematical models of the influence of process–specific parameters, including the influence of a number of factors analysed simultaneously. The mathematical models provide the basis for simulations making use of a complex set of analysed factors. Statistically processed results of the measurements of the total cutting force constitute an input for the analysis and assessment of the effect of the machine cutting conditions.

In certain methods and variants of machining, e.g. in straight turning, the correlations between the components, F_c, F_f, and F_p, and the total cutting force, F, are already known, therefore it is only necessary to measure the F_c component to evaluate the values of the force.

In this article, an assessment of the influence of selected process conditions (cutting speed, feed rate, corner radius, and method of application of cutting fluid) on the value of F_c during straight turning has been made. The assessment is based on equations in the form of power polynomials obtained from the results of experimental tests.

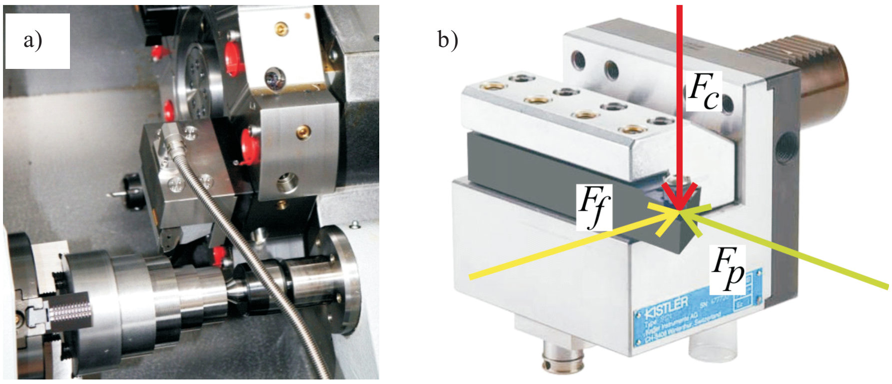

Figure 1 Test stand: a) the workspace of Haas SL 10 turning lathe with the dynamometer, b) the three-component piezoelectric dynamometer, Kistler 9121: F_c – cutting force, F_f – feed force, F_p – back force

2. Test conditions

The objective of the experimental tests was to collect data concerning the conditions in which the processing was performed and the values of cutting forces during straight turning by means of both conventional inserts and wiper inserts. The tests were carried out using the following two methods of cutting fluid application:

- with the fluid applied in ample quantities (WM – Wet Machining), and

- without any cutting fluid (DM – Dry Machining).

The collected data was used to determine a mathematical calculation in the form of power polynomials that enabled the calculation of the cutting forces, F_c.

The test stand for the measurement of the forces consisted of a Haas SL10 CNC turning lathe [2, 3]. Figure 1 shows the workspace of the machine tool equipped with a three–component piezoelectric dynamometer, Kistler 9121, mounted on the tool turret.

During the tests, samples made of C45carbon steel (hardness 230 HB) in a normalised condition were subject to straight turning. The tool used was aSandvik PTGNR 2020 K16 (ISO) turning insert for OD turning. Two types of inserts made of GC4215 sintered carbide, for general turning of steel (P15–P20) were fitted in the tool holder. For both types, the following inserts with different corner radius (r_ε) were used:

1. Conventional geometry inserts:
   - TNMG 160404PF ($r_\varepsilon = 0.4$ mm),
   - TNMG 16 04 08 PF ($r_\varepsilon = 0.8$ mm)
2. Wiper geometry inserts:
   - TNMX 160404WF ($r_\varepsilon = 0.4$ mm),
   - TNMX 16 04 04 WF ($r_\varepsilon = 0.8$ mm).

The tests were carried out for the parameters shown in Tab. 1. The parameters were selected on the basis of the manufacturer's specifications [4].

Table 1 Cutting parameters

cutting speed: $v_{c1} = 550$ m/min; $v_{c2} = 475$ m/min; $v_{c3} = 415$ m/min
feed: $f_1 = 0{,}1$ mm/rev; $f_2 = 0{,}2$ mm/rev; $f_3 = 0{,}3$ mm/rev
depth of cut: $a_p = 1$ mm
corner radius: $r_\varepsilon = 0{,}4$ mm; $r_\varepsilon = 0{,}8$ mm

The cutting fluid was a conventional BlaserSwisslubeBlasocut fluid supplied to the machining zone at a delivery rate of 5 l/min.

3. Determination of the mathematical relationships

The determination of the mathematical relationships used to calculate the cutting forces was achieved by means of SKZ – a software application developed at the Institute of Machine Tools and Production Engineering of the Lodz University of

Technology [5]. The computer program enables the identification of regression equation coefficients. The regression analysis procedure was developed on the basis of an algorithm of the "acceptance and rejection" method, presented in the references [7].

First, the above–mentioned software was fed with input data (v_c, f, r_ε) from a text file prepared beforehand and the form of the regression function was selected (Y1 = B0 + Sum (Bi * Xi)).

The critical values (F_{kr}) are selected for a significance level of 0.4 and after determination of the regression function it is changed to 0.1. Calculations begin with the simplest regression function and then new elements are added in a sequence. When a newly–added element reduces the significance of an element that has already been introduced, the insignificant element is eliminated from the regression function. Having introduced all significant elements a panel is displayed on the screen, showing a preview of the results. Then, the significance level is decreased and the procedure ends with printing of the results.

The final function of the object of our analysis took the following form:

$$F_c = C_F \cdot f^{f_f} \cdot r_\varepsilon^{f_r} \cdot v_c^{f_v} \ [N] \tag{1}$$

where: f – [mm/rev], r_ε – [mm], v_c – [m/min].

The values of the function constants and coefficients, determined through calculation, have been collected in Tab. 2.

The values of multiple correlation coefficients should be considered as very good, taking into account the broad range of variability of the input values.

Table 2 Values of constants and coefficients for the experimental function

Constants and coefficients			
WM (Wet Machining)		DM (Dry Machining)	
TNMG	TNMX	TNMG	TNMX
C_F = 134054 f_f = 0.723 f_v = -0.786	C_F = 2034987 f_f = 0.676 f_r = -0.633 f_v = -1.318	C_F = 244996 f_f = 0.677 f_r = -0.363 f_v = -0.919	C_F = 960 f_f = 0.759 f_r = -0.845
Coefficient of multiple correlationR			
0.86	0.97	0.89	0.97

When applying the numerical values from Table 2 to the function of the experiments (1) the following results were obtained:

- In WM:

$$TNMGF_c = 134054 \frac{f^{0.723}}{v_c^{0.786}} \ [N] \tag{2}$$

$$TNMXF_c = 2034987 \frac{f^{0.676}}{r_\varepsilon^{0.633} \, v_c^{1.318}} \ [N] \tag{3}$$

- In DM:

$$TNMGF_c = 244996 \frac{f^{0.677}}{r_\varepsilon^{0.363}\, v_c^{0.919}}\ [N] \tag{4}$$

$$TNMXF_c = 960 \frac{f^{0.759}}{r_\varepsilon^{0.845}}\ [N] \tag{5}$$

4. Analysis of the correlations

An analysis of the coefficients shown in Tab. 2 has demonstrated that the values differ depending on the method of application of the cutting fluid and the type of cutting inserts used. This is true for both the constant values, C_0, generally defining the level of cutting forces, and the exponents which determine the influence of individual processing conditions on the level of these forces.

The f_f coefficients, determined for all analysed cases, have similar values, which suggests a similar degree of effect of the feed rate on the cutting forces.

The values of f_r and f_v are clearly different, which indicates a major impact of the method of application of the machining fluid and the type of insert on the level of the cutting forces. However, it was observed that the lower the value of the coefficient, the smaller the influence of the parameter on the cutting force. In the WM method, where TNMG inserts were used, the f_r coefficient was rejected as a result of calculation, which means that in that case the corner radius did not affect the cutting force. Similarly, in the DM method of turning with TNMX inserts the f_v coefficient determining the influence of the cutting speed was also insignificant.

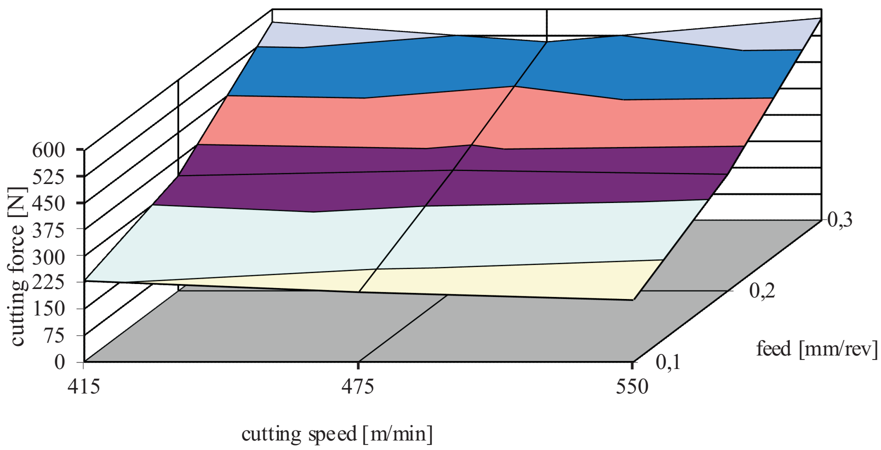

Figure 2 Influence of cutting parameters (f, v_c) on the cutting force

Fig. 2 shows the influence of cutting parameters (f, v_c) on the value of the cutting force F_c.The presentation has been limited to the TNMX 16 04 04 WF wiper insert used in the Wet Machining (WM).Three values of feed rate (0.1, 0.2, and 0.3

mm/rev)and three values of cutting speed (415, 475,and 550 m/min) were used in the experiment.

As shown in Fig. 2 and the correlation (3), the cutting force F_c increases with the feed rate f at all cutting speeds. The discussed cutting parameters, according to the correlation (3), influence the values of the forces in an exponential manner. The surfaces in the graph represent the level of forces that can be expected depending on the variable conditions of processing. Similar graphs were produced for other tests.

5. Verification of the mathematical model

In spite of the high values of multiple correlation coefficients in the developed mathematical model, it has also been verified by comparing the cutting forces, F_c, measured on the test stand with the forces calculated on the basis of this model.

Fig. 3 below shows a comparison of the calculated and measured values of $F_c$during straight turning using the Wet Machining (WM) method (with ample quantities of the cutting fluid) and a TNMX 16 04 04 WF insert. The graph shows the values for three feed rates (0.1, 0.2 and 0.3 mm/rev) and one cutting speed of 415 m/min.

The differences between measured and calculated values of the cutting force are small and fall within the range of 0 to 20 N (or 3 to 7%). Similar differences were observed in other tests, which corroborates the validity of the developed model.

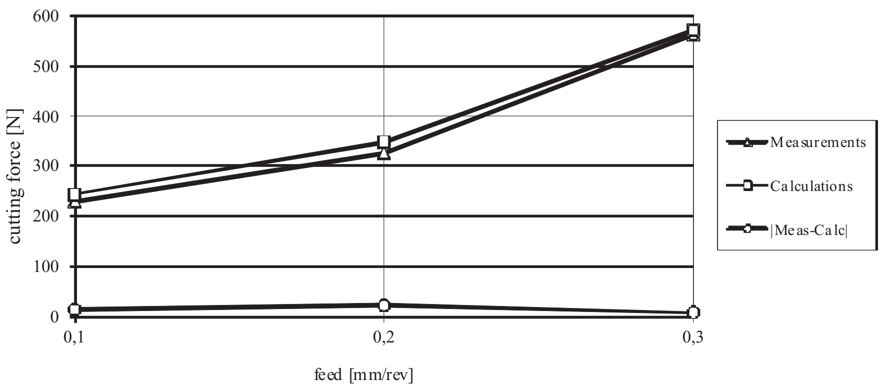

Figure 3 Comparison of calculated vs. measured values of the cutting force

6. Conclusion

On the basis of a theoretical analysis and experimental tests, the functional correlations have been determined, allowing the calculation of the cutting force $F_c$during straight turning of C45 grade carbon steel. An analysis of the exponents defining the influence of individual conditions of the cutting process on the level of forces demonstrated that the cutting speed, v_c, and the corner radius, r_ε, are the most sensitive to the method of application of the cutting fluid (WM, DM) and the type of cutting insert used. The values of the coefficients are considerably varied or, in certain cases, they are insignificant. The influence of the feed rate, f, on the value of the cutting forces has been found to be practically independent of the method of application of the cutting fluid or the type of insert, as regards the tested parameters.

The developed model enables the calculation of the cutting force and provides a good basis for an analysis of the straight turning process. Thanks to the developed mathematical relationships it is possible to avoid labour and time–consuming experiments, as far as the tested cutting conditions are concerned.

Future studies are planned to include experiments in a broader range of cutting parameters and worked materials, as well as other methods of application of machining fluids for cooling and lubrication.

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