Development of a parametric model for calculating cutting forces for external cylindrical turning of steel 20CrMNTi

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Abstract. The paper presents a mathematical model for calculating the cutting force when processing 20crmnti steel with the Sandvik CNMG 120408 16P25T tool. The stand based on the 16d25 machine is presented. It allows measuring the actual values of the spindle speed, longitudinal feed, cutting depth, and cutting force. The results are transmitted to the computer via the LTR-EU-8 workstation with galvanically isolated LTE modules and a synchronization interface. According to the test results, the obtained theoretical model has a deviation from the actual measurements of no more than 0.12%. It is shown that the calculation results provided by the leading tool manufacturers are expected to be overstated. The difference in cutting forces can be more than 1.5 times.

1. Introduction

The cutting force is a key parameter which is necessary for predicting the required cutting power, the temperature in the cutting zone and the cutting tool, and the quality of the formed surface [1]. At the same time, the models for predicting cutting forces themselves have recently been significantly simplified [2] or tool manufacturers are carefully bypassing this concept by replacing them with their derivatives, for example, power consumption or tool life [3]. For example, the well-known tool manufacturer Walter (https://www.walter-tools.com) recommends calculating the cutting forces by means of the formula (1) [4]

\[ F_c = A \times k_c \times h^{-mc} \quad (N) \]

where \( A \) – chip cross section (mm²);
\( h \) – chip thickness (mm);
\( k_c \) – specific cutting force (H/mm²);
\( mc \) – correction facto.

But the cutting force depends on many additional parameters, for example, on the hardness of the material or the presence of a crust on the surface of the workpiece. The coefficients \( k_c \) and \( mc \) themselves are approximate, obtained on some “similar” material and instrument. It can be concluded that the presented model is most likely inaccurate and can only be used for superficial estimates of the probability value of the parameter.

In recent years, we have become more and more interested in modeling [5]. Modeling allows you to analyze existing solutions without significant costs. But approximate models give a very conditional
result, which is unacceptable in the modern development of computer-aided design systems [6,7,8,9]. Therefore, there is an urgent need for adequate models to predict cutting forces.

The most complete and simple enough to implement model for calculating the cutting force is the empirical Taylor equations (2) [1], [2] allowing you to take into account any processing conditions. At the same time any special processing conditions can be included in the K coefficients.

\[
P = 10 \times C_p \times t^v \times s^f \times V^n \times K
\]

where \(t, S, V\) – the parameters of the cutting conditions; 
\(K\) – correction factor that allows you to take into account cutting conditions; 
\(C_p, x, y, n\) – empirical coefficients and degree indicators.

Based on the above, the aim of the work is to develop an empirical cutting model based on the Taylor equation for processing 20crmnti steel with a specific cutting tool. The final goal of the work can be stated as the development of a method for quickly obtaining a model for determining the cutting force for a specific material and cutting tool [9,10,11,12,13]. In the future, these models can be used to accurately simulate computer processing.

2. Methods

The standard universal lathe 16D20 was used as a stand for conducting experiments. To fix the actual cutting speed, a non-contact induction speed meter was installed directly on the spindle. To account for real movements, displacement meters were installed with brackets up to 1000 mm for longitudinal movement, and up to 100 mm for transverse movement relative to the spindle rotation axis. A three-dimensional force meter was used with a DCLNR 2525 M12 holder. The force meter has been calibrated. Sandvik CNMG 120408 16P25T cutting insert is new. The devices and the sensor are connected to the LTR-EU-8 workstation with galvanically isolated LTR modules and a synchronization interface. The force meter is connected to the TR212M with an 24-bit / 7.6 kHz ADC designed to connect up to eight load cells with resistance from 100 Ohms to 1 kOhm. The remaining sensors were connected to LTR24 (4 strictly parallel ADC channels 24 bit / 117 kHz) and LTR11 supporting multi-channel data acquisition mode: up to 32 single-phase signal acquisition channels (ADC 14 bit / 400 kHz).

To obtain the coefficients of the empirical model of cutting, it is proposed to use the search for the optimal solution by exhaustive search method taking into account the limitations [14,15,16,17,18]. This method is quite accurate [5] and is quickly solved by specialized software. In our case, we will use the “solution search” function of the MS EXCEL application.

To calculate the coefficients of the empirical cutting model, the cutting forces were measured at various cutting speed, longitudinal feed and the size of the removed allowance. The range of cutting speeds was 150-370 m / min. The average increment of the speed is 50 m / min. The machine has a stepped, mechanical system for changing the spindle speed. The cutting speed depends on the diameter being machined (2). During the experiment, the actual spindle speeds were taken into account.

\[
V = \frac{\pi \times d \times n}{1000} \text{ (m/min)}
\]

where \(d\) – machined diameter (mm); \(n\) – rotations (rpm).

The size of the removed allowance varied from 0.5-2.5 mm with a measurement step of about 0.5. The measurement step depends on the gearbox. In order to eliminate the error of the longitudinal feed due to the error in the manufacture of the machine and wear during the operation period, the actual feed was measured based on the displacement meter. The feed values were 0.11-0.13-0.22-0.25 mm / rev. Workpieces were processed from one batch. The hardness of each preform was previously measured, it was at 156 HB. Processing without coolant.

3. Results
Table 1 presents sample V-s-t-P dependency measurement data. The software interface for calculating the coefficients of the empirical cutting model based on the search for the optimal solution by enumeration taking into account the limitations [19] by the built-in MS EXCEL tools is shown in Figure 1.

| V (mm/min) | S (mm⁻¹) | T (mm) | P (H) |
|------------|-----------|--------|-------|
| 1          | 306       | 0.11   | 1.53  | 263.7 |
| 2          | 178       | 0.22   | 1.54  | 451.5 |
| 3          | 369       | 0.22   | 0.5   | 121.4 |
| 4          | 367       | 0.13   | 2.5   | 433.1 |
| 5          | 375       | 0.13   | 3     | 512   |
| 6          | 217       | 0.25   | 0.5   | 154   |

Figure 1 in cells C12-C17 presents data obtained during the experiment. In cells B5-F5, selected by the “search for a solution” function in the MS EXCEL application based on restrictions (2). In cells H12-H17, values calculated based on the Taylor empirical model (1). As you can see, the discrepancies in the data obtained during the experiment and the values of the cutting force calculated on the basis of the selected coefficients are insignificant and amount to no more than 0.12% (0.54 H at a value of 450 H).

4. Conclusions
As a result of the experiment of processing the 20CrMnTi material with the Sandvik CNMG 120408 16P25T tool, a model for calculating the cutting force was obtained (4):

\[ P = 10 \times 271.2887 \times t^{0.956236} \times s^{0.51191} \times V^{-0.32398} \times 1.2797 \]  

(4)

Where t, S, V – parameters of cutting conditions.

As calculations show, the deviation of the theoretical model was not more than 0.12% of the results obtained at the test bench. According to the results of preliminary modeling of the cutting forces of a
similar material with a tool with a similar geometry and cutting conditions $s = 0.11 \text{ mm} / \text{rev}$, $t = 1.53 \text{ mm}$, $V = 306 \text{ m} / \text{min}$, the following results were obtained:

- according to the source https://www.walter-tools.com, the cutting force will be $494.15 F_{c}$ | N, with a specific material removal of $49.73 \text{ cm}^3 / \text{min}$ and a power of $2.58 \text{ P}_{\text{mot}}$ | KW;

- according to the source https://www.sandvik.coromant.com, the specific volume of material removal will be $48.00 \text{ cm}^3 / \text{min}$ and cutting power $2.32 \text{ P}_{\text{mot}}$ | KW; according to indirect calculations, it can be assumed that the cutting force will be about $460 \text{ H}$;

- due to the use of new materials and increased cutting speeds, the calculation of cutting forces according to the methods of Baranovsky and Kosilova is not relevant.

As you can see, the results presented by online services are expected to be overstated. Their task is to guarantee the declared durability. At the same time, the results of the actual test show cutting forces that are overstated by more than 1.5 times.

References

[1] Baranovsky Yu.V. Modes of cutting metals / Ed. 4th. rewrited and add. M. : Research Institute Avtoprom, 1995. -- 456 p.

[2] Metal cutting and cutting tools: Textbook / V.G. Solonenko, A.A. Ryzhin. - M. : INFRA-M, 2011. -- 416 p. 60x90 I/16. - (Higher education). ISBN 978-5-16-004719-5 - Access mode http://znanium.com/catalog/product/258644

[3] SANDVIK COROMANT Manual 2019 Manual Machining (https://www.sandvik.coromant.com) Retrieved: 31.10.2019

[4] Turning/ lathe machining ISO (https://www.walter-tools.com/ SiteCollectionDocuments/wmc/index-bakup.html#content) Retrieved: 31.10.2019

[5] Computer modeling: textbook / V. M. Gradov, G. V. Ovechkin, P. V. Ovechkin, I. V. Rudakov-M.: COURSE: INFRA-M, 2018. - 264 p.

[6] A.G. Kondrashov, D.T. Safarov, A.I. Faskhutdinov, G.K. Davletshina Single-Turn Worm Mills for Conical Round-Tooth Gears / Russian Engineering Research, 2017, Vol. 37, No. 9, pp. 812–813.

[7] Weiss Denis, The Effect of Cutting Edge Rounding Geometry on Tool Wear, Machine tool Park № 12,2016.

[8] Kasyanov S.V., Kondrashov A.G., Safarov D.T. Research of characteristics of wearproof coating for cutting tools / INTERFINISH-SERIA 2014: International Conference on Surface Engineering for Research and Industrial Applications. 2014. P. 62.

[9] Faskhutdinov A. I., Emelyanov D. V., Blinova A. S. Influence of the size of the cut layer on the productivity of mechanical processing / Proceedings of scientific articles of the 2nd international youth scientific and practical conference "Progressive technologies and processes" September 24-25, 2015 in 3 volumes. Kursk.: ZAO Universitetskaya knigа. - 2015. Pp. 111-115

[10] Chatterjee-Fisher, R, Eisell, F. et al., Nitriding and carbonitriding, TRANS/ edited by Supov A.V. M.: metallurgy, 1990. 280s.

[11] Khusainov R. M., Golovko A. N., Petrov S. M., Yurasov S. Yu., Balabanov I. P., grechishnikov V. A., Romanov V. B., Pivkin P. M. / / Determination of tool parameters in technological cutting systems / STIN. 2016. No. 10. Pp. 17-20.

[12] S. V. Kasyanov, A. G. Kondrashov, D. T. Safarov Rapid Assessment of Wear-Resistant Tool Coatings / Russian Engineering Research, 2017, Vol. 37, No. 11, pp. 969–973.

[13] Khusainov R.M., Khaziev R.R. Modeling of forming technological errors in processing by gear shaping machine // IOP Conference Series: Materials Science and Engineering. - 2017. - Vol.240, Is.1. - Art. № 012045.

[14] Leushin, I.O. Technologies for Use in the Formation of a Differentiated Structure in Iron Billets Used in Glass Molds / I.O. Leushin, D.G. Chystyakov // METAL SCIENCE AND HEAT
TREATMENT. - 2016. - №5-6. - Т. 58. - p. 299-302.

[15] Leushin, I.O. Creep of the investment mold material / I.O. Leushin, L.I. Leushina, O.S. Koshelev // Russian Metallurgy. - 2017. - №13 (DEC. 2017). - С. 1092-1095.

[16] A.V. Shaparev and I.A. Savin, Influence of the State of the Contact Surfaces on the Formation of the Joint of Steel and Brass during Cold Cladding. Solid State Phenomena, Vol. 284, pp. 319-325, 2018 DOI: https://doi.org/10.4028/www.scientific.net/SSP.284.319

[17] R.V. Gavariev and I.A. Savin, Research of the Mechanism of Destruction of Compression Molds for Casting under Pressure of Color Alloys. Solid State Phenomena, Vol. 284, pp. 326-331, 2018 DOI: https://doi.org/10.4028/www.scientific.net/SSP.284.326

[18] Altintas Y, Engin S. Generalized modeling of mechanics and dynamics of milling cutters. Cirp Annals-Manufacturing Technology. 2001;50:25-30.

[19] Dong JL, Yu TB, Chen H, Li BC. An improved calculation method for cutting contact point and tool orientation analysis according to the CC points. Precision Engineering-Journal of the International Societies for Precision Engineering and Nanotechnology. 2020;61:1-13.

[20] Gaitonde VN, Karnik SR, Figueira L, Davim JP. Analysis of Machinability During Hard Turning of Cold Work Tool Steel (Type: AISI D2). Materials and Manufacturing Processes. 2009;24:1373-82.

[21] Mabrouki T, Rigal JF. A contribution to a qualitative understanding of thermo-mechanical effects during chip formation in hard turning. Journal of Materials Processing Technology. 2006;176:214-21.

[22] Reddy NSK, Rao PV. Selection of an optimal parametric combination for achieving a better surface finish in dry milling using genetic algorithms. International Journal of Advanced Manufacturing Technology. 2006;28:463-73.

[23] Saha P, Singha A, Pal SK. Soft computing models based prediction of cutting speed and surface roughness in wire electro-discharge machining of tungsten carbide cobalt composite. International Journal of Advanced Manufacturing Technology. 2008;39:74-84.

[24] Shrot A, Baker M. Determination of Johnson-Cook parameters from machining simulations. Computational Materials Science. 2012;52:298-304.

[25] Stephenson DA, Agapiou JS. CALCULATION OF MAIN CUTTING EDGE FORCES AND TORQUE FOR DRILLS WITH ARBITRARY POINT GEOMETRIES. International Journal of Machine Tools & Manufacture. 1992;32:521-38.

[26] Suresh R, Basavarajappa S, Gaitonde VN, Samuel GL. Machinability investigations on hardened AISI 4340 steel using coated carbide insert. International Journal of Refractory Metals & Hard Materials. 2012;33:75-86.

[27] Tournier C, Duc E. Iso-scallop tool path generation in 5-axis milling. International Journal of Advanced Manufacturing Technology. 2005;25:867-75.

[28] Yallese MA, Chaoui K, Zehib N, Boulanouar L, Rigal JF. Hard machining of hardened bearing steel using cubic boron nitride tool. Journal of Materials Processing Technology. 2009;209:1092-104.