DEVELOPMENT OF A PARAMETRIC MODEL FOR CALCULATING CUTTING FORCES IN EXTERNAL CYLINDRICAL TURNING OF 20CRMN STEEL (1.7147) USING AN SNMG 15 06 16-PR 4425 INSERT

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Abstract

This article develops and presents a mathematical model for calculating cutting forces during the machining of 20CrMn steel (1.7147) using an SNMG 15 06 16-PR 4425 T-Max® P insert for turning. We conducted experimental research on a specially designed test rig based on the 16D25 lathe. This setup measures spindle speed, feed rate, cutting depth, and the cutting forces generated during the machining process with high precision. We used the LTR-EU-8 workstation for data acquisition and analysis, equipped with galvanic isolated modules and a synchronized data transmission interface to ensure accurate measurements. The system transmitted real-time data to a computer for further processing, which helped verify the theoretical model. The results showed a high correlation with actual measurements: the deviation between calculated and experimental values did not exceed 5.68%, proving the model's accuracy in predicting cutting forces. This accuracy plays a key role in optimizing machining processes, reducing tool wear, and lowering energy consumption. The study also found that cutting forces provided by major tool manufacturers are often overestimated. In some cases, the discrepancies between calculated and actual forces reached 17.8%, potentially affecting the accuracy of process planning and the choice of optimal cutting parameters. Additionally, the study revealed that the cutting forces typically provided in calculations by leading tool manufacturers are often overestimated. In some cases, discrepancies between calculated and actual force values reached up to 17.8%, which can impact the accuracy of process planning and the selection of optimal cutting parameters.

Keywords: Modeling, cutting force, cutting speed, cutting force model.

I. Introduction

Cutting force is an integral parameter that determines the surface quality during machining. It reflects the interaction between the cutting tool and the workpiece material during material removal, directly impacting the final surface of the part [1]. Both the magnitude and direction of the cutting force significantly affect characteristics such as surface roughness, accuracy, and geometric deviations of the machined surface [1], [2].

An increase in cutting forces can lead to adverse effects, including higher surface roughness, accelerated tool wear, and potential workpiece deformation [3]. Conversely, reducing cutting forces typically improves surface quality and provides more accurate and stable part dimensions, though it may reduce productivity and increase the final product cost. This highlights the importance of controlling, optimizing, and predicting cutting forces as key factors in achieving the desired machining characteristics. In this context, selecting optimal cutting conditions, tool geometry, and machining strategies aimed at minimizing applied forces [4] is crucial to meeting the required quality standards for finished products.

Various methods and mathematical models are used in machining to predict cutting forces [4], including analytical, empirical approaches, and numerical modeling techniques. Analytical models include Merchant's circle diagram and the orthogonal cutting model, which based on the tool's geometric parameters, the material properties of the workpiece, and the cutting conditions [5]. In contrast, empirical models rely on experimental data to establish the relationship between cutting force and process input parameters.

Modern machining technologies increasingly employ numerical modeling to predict cutting forces, including the use of Computer-Aided Design (CAD) [6] and Computer-Aided Manufacturing (CAM) [7] software. However, the accuracy of these models often depends on several factors, including the quality of input data and assumptions made during modeling. Finite Element Analysis (FEA) and Finite Element Method (FEM) simulations allow for a more detailed examination of the cutting process, accounting for complex interactions between the tool, workpiece, and cutting conditions [6]. Despite their utility, these methods require extensive input data for accurate calculations. While numerical models play a key role in optimizing machining processes, improving surface quality, extending tool life, and enhancing overall manufacturing efficiency, they still require further refinement.

Empirical models offer a practical and accessible way to analyze and predict cutting forces during machining, allowing engineers to avoid complex mathematical calculations or laborious equations. Based on experimental data, such models establish relationships between input parameters and cutting forces [8], making them a valuable tool for quick assessments in real production environments. By using these models, engineers and technicians can make informed decisions, optimize cutting conditions, select tools [8], and ensure the required surface quality without needing complex computations or extensive practical research.

In recent years, there has been a noticeable simplification in approaches to modeling cutting forces, and many tool manufacturers often avoid using them. Instead, they prefer to rely on derived metrics such as energy consumption and tool life [9]. For instance, Walter (https://www.walter-tools.com), a leading cutting tool manufacturer, recommends using a specific formula to calculate cutting forces, where A is the cross-sectional area of the chip (mm2); h is the thickness of the chip (mm); kc is the specific cutting force (H/mm2); mc is the correction coefficient [10].

$$F_c = A \times k_c \times h^{-mc} \ (N) \tag{1}$$

It is important to note that cutting force depends on a number of additional factors, including the hardness of the workpiece material, the presence of scale on the surface, as well as the stability and accuracy of the workpiece. The coefficients kc and mc represent average values specific to certain materials and tools, which limits the precision of predictions and makes the model suitable only for preliminary assessments [11].

With the advancement of computer modeling technologies, Finite Element Method (FEM) and Finite Element Analysis (FEA) are becoming increasingly significant in modern manufacturing [12]. These approaches allow for detailed analysis of cutting processes at relatively low costs [13]. However, approximate models often yield conditional results, which are unacceptable in automated design environments. This highlights the need for more accurate and reliable models for predicting cutting forces.

An example of such models is the Taylor empirical equations (2) [14], also known as the Taylor-Bühl model. These equations are widely used to estimate cutting forces and tool wear based on machining conditions. The Taylor model enables engineers to predict tool life, evaluate cutting forces, and analyze the impact of various machining parameters on tool wear. By adjusting variables such as cutting speed, feed rate, and depth of cut, it is possible to optimize the process, extend tool life, and improve the quality of the machined surface. It is important to emphasize that the constants in this model must be determined experimentally for specific materials and tools, which underscores its empirical nature [15].

$$P = 10 \times Cp \times t^{x} \times s^{y} \times V^{n} \times K \tag{2}$$

Where t, S, and V represent cutting parameters; K adjusts for cutting conditions; Cp, x, y, and n serve as empirical coefficients and exponents.

Kosilova and Baranovsky developed methods based on empirical models and experimental data [13]. These approaches rely on practical measurements and observations of machining processes to create equations and dependencies that describe cutting forces in various operations. Their models consider key factors such as cutting speed, feed rate, and depth of cut, tool geometry, material properties, and tool wear. Kosilova and Baranovsky focused on analyzing real cutting conditions and identifying relationships between input parameters and cutting forces. Through experiments and data collection, they built mathematical models that predict cutting forces with high accuracy [13]. Engineers and machinists use these empirical models to optimize machining processes, reduce tool wear, and achieve the desired surface quality in production.

This study follows an empirical approach, but the coefficient tables for different steel types have remained unchanged for over 40 years. These outdated tables fail to reflect modern advances in tool design, manufacturing, and new materials.

The primary goal of this research aims to develop a new empirical cutting model based on the Taylor equation for machining 20CrMn-1.7147 steel with a specific cutting tool. The objective focuses on creating a methodology that allows quick generation of cutting force models for specific materials and tools [14]. These models will support precise simulations of machining processes using computer tools.

II. Methods

The experimental setup used a universal lathe model 16D25, which was equipped with numerical control (CNC). The main technical specifications of this machine include a maximum spindle speed of 2000 revolutions per minute (RPM), a maximum feed rate of 2 millimeters per revolution, and a maximum workpiece diameter over the lathe bed of up to 500 millimeters. To accurately measure the actual cutting speed, an inductive rotational speed sensor, the Balluff BES M12MI-PSC40B-BV03, installed on the spindle pulley (see Table 1). Four grooves machined into the pulley to ensure that the sensor would trigger four pulses per revolution, allowing for the implementation of an error-checking system to verify the accuracy of the measurements taken [15].

Table 1: *Characteristics of Balluff BES M12MI-PSC40B-BV03*

Characteristic	Malue
Operating temperature, °C:	-25..70
Thread size of the housing:	M12
Tripping distance, mm:	4
Supply voltage, V:	10-30 DC
Switching frequency, Hz:	2500

To monitor actual movements, linear displacement sensors mounted on brackets were used, allowing measurements of up to 1000 mm in the longitudinal direction and 100 mm in the transverse direction relative to the spindle axis, with high precision of 0.01 mm. Additionally, a three-coordinate force sensor, installed on a DCLNR 2525 M15 tool holder, was utilized, having undergone preliminary calibration. The cutting tool employed was a new SNMG 15 06 16-PR 4425 T-Max® P insert for turning. All sensors and devices connected to the LTR-EU-8 workstation via galvanically isolated LTR modules and a synchronization interface. The force sensor linked to a TR212M, equipped with a 24-bit analog-to-digital converter (ADC) with a frequency of 7.6 kHz and designed to connect up to eight strain gauges with resistance from 100 Ω to one kΩ [16]. The other sensors connected to LTR24 modules (with four parallel channels, a 24-bit ADC, and a frequency of 117 kHz) and LTR11, which supports multi-channel data acquisition (up to 32 channels for single-channel signals with a 14-bit ADC and a frequency of 400 kHz) [20].

To determine the coefficients of the empirical cutting model, the team developed a method for finding the optimal solution through constraint enumeration, demonstrating high accuracy and effectively utilizing specialized software[17]. In this case, the team used the "Solver" function in MS Excel for calculations [18]. To compute the model coefficients, they measured cutting forces under various combinations of cutting speed, feed rate, and depth of cut [19]. The cutting speed range varied from 230 to 330 m/min in increments not exceeding 50 m/min. The machine featured a stepped spindle speed adjustment system, which defined the relationship between cutting speed, workpiece diameter, and spindle RPM. During the experiments, they recorded the actual spindle speeds from the Balluff BES M12MI-PSC40B-BV03 sensor [20].

$$V = \frac{\pi \times d \times n}{1000} \tag{3}$$

The thickness of the removed allowance varied from 0.5 to 2.5 mm in increments not exceeding 0.5 mm, which depended on the capabilities of the transmission. It is important to note that the normal operating thickness for the SNMG 15 06 16-PR 4425 insert is ap = 5 mm (1.5 - 8). To eliminate errors in longitudinal feed caused by equipment wear, the team measured the actual feed rate using displacement sensors. They set the feed values at 0.11, 0.13, 0.22, and 0.25 mm/rev. The machining occurred on workpieces from the same batch, which had a hardness of 193 HB after prior measurement. The team conducted the machining process without cutting fluids, due to the presence of sensors and the inability to measure the temperature of the cutting insert and tool holder using a laser-based sensor.

III. Results

Table 2 presents a data sample reflecting the dependencies of cutting speed (V), feed rate (s), thickness (t), and pressure (P). Adjusting parameters to achieve desired results through changes in input values represents a fundamental method in various fields of science and engineering. This approach involves systematically optimizing variables to meet specific goals. Such techniques enable the optimization of a system or process, ensuring their most efficient and productive operation.

Table 2: *Selective Experimental Results*

	V (m/min)	fa (mm/rev)	a (mm)	P (H)
1	232,1	0,505	1,51	324,9
2	250,9	0,807	1,51	468,1
3	264	0,751	1,02	316,6
4	282,3	0,251	0,74	205,2
5	299,8	0,251	1,02	256,9
6	332,2	0,251	1,02	268,3

For instance, in mechanical engineering, engineers can vary parameters such as cutting speed, feed rate, and tool geometrical characteristics to ensure the required accuracy and quality of machining. Similarly, in data analysis, adjusting model parameters can enhance the accuracy of predictions and results. By carefully selecting and modifying input parameters, one can fine-tune the process to meet specific criteria and achieve the desired outcome. This methodological approach serves as a universal tool for specialists across various disciplines, allowing them to optimize performance and accomplish their objectives.

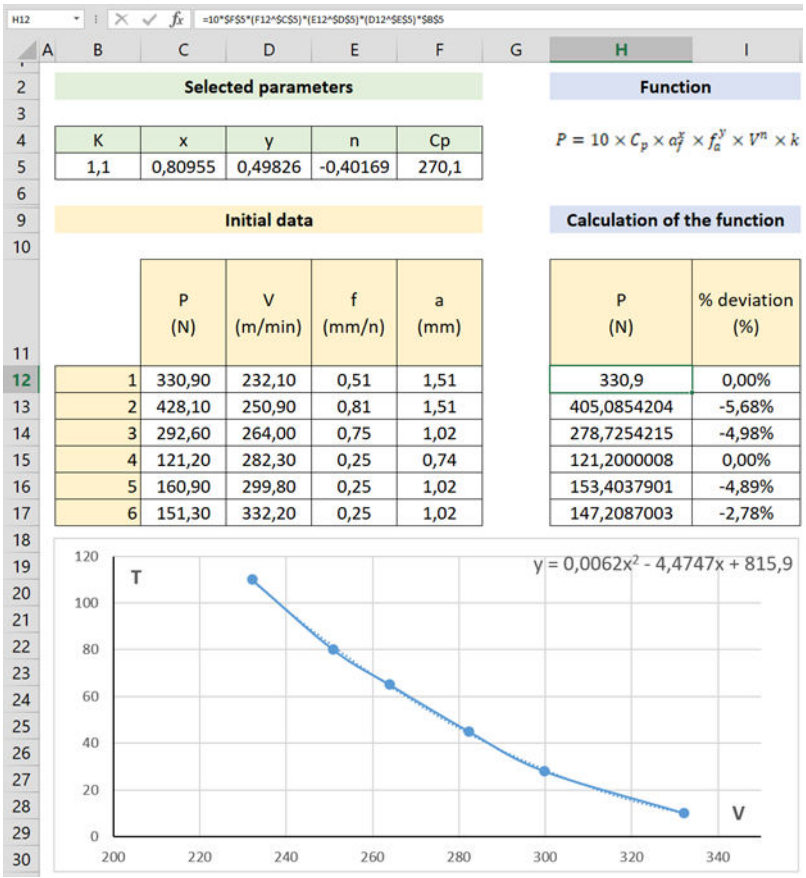

Figure 1: *Interface for Coefficient Selection in Cutting Model Construction*

Figure 1 presents the software interface designed for calculating the coefficients of the empirical cutting model, which implements a complete enumeration method considering constraints, utilizing built-in functions of MS Excel. Here the data obtained from the experiment, located in cells C12-C17. Cells B5-F5 indicate the values derived using the "Solver" function in MS Excel based on the specified constraints (2). Cells H12-H17 present the values calculated using Taylor's empirical model (1).

The calculation of the cutting force deviation in percentage occurred as follows: first, the absolute difference between the actual cutting force value and the theoretical (expected) value was calculated. The obtained difference divided by the theoretical cutting force value, and then the result multiplied by 100 to represent the deviation as a percentage. This percentage calculation allows for a standardized assessment of the difference between the expected and actual cutting force values. It provides a convenient comparison, enabling a clearer understanding of how much the actual results differ from the predicted ones, thus offering a better insight into the accuracy and precision of the forecasts.

The discrepancies between the experimental data and the calculated cutting force values, determined based on the fitted coefficients, appear to be minor and do not exceed 5.68%.

IV. Conclusions

As a result of the experiment on machining the 20CrMn material using the SNMG 15 06 16-PR 4425 T-Max® P insert for turning, the team developed a model for calculating the cutting force (4), where a, f, and V represent the cutting parameters:

$$P = 10 \times 271.289 \times a^{0.95624} \times f^{0.5119} \times V^{-0.32398} \times 1.2797 \tag{4}$$

As the calculations in Table 3 show, the deviation of the theoretical model did not exceed 5.68% from the results obtained on the test stand.

Table 3: *Analysis of model deviation*

№	Cutting force measured on the stand (H)	Cutting force measured on the stand (H)	Cutting force measured on the stand %
1	330,90	330,9	0,00%
2	428,10	405,0854204	-5,68%
3	292,60	278,7254215	-4,98%
4	121,20	121,2000008	0,00%
5	160,90	153,4037901	-4,89%
6	151,30	147,2087003	-2,78%

Based on the results of preliminary modeling of cutting forces for a similar material using a tool with analogous geometry and cutting parameters (feed rate s = 0.51 mm/rev, depth of cut t = 1.5 mm, cutting speed V = 238 m/min), the following data obtained:

- According to the source https://www.walter-tools.com, the cutting force will be 402.56 Fc/N at a specific material removal rate of 246.21 cm³/min and a power of 6.75 Pmot/kW.
- According to the source https://www.sandvik.coromant.com, the specific material removal rate will be 246.00 cm³/min, and the cutting power will be 6.70 Pmot/kW. This will result in approximately 400.0 Fc/N.

- Due to the use of new materials and increased cutting speeds, the cutting force calculations based on the methods of Baranovsky and Kosilova are no longer relevant.

As shown, the results presented by online services predictably inflated since their primary goal is to ensure the claimed tool life. However, actual tests demonstrate that the cutting forces are 17.8% lower than indicated by these services. Cutting tool manufacturers intentionally increase the calculated cutting force values to create a safety margin that guarantees the functionality of their tools even under higher loads. This practice aims to prevent breakage and extend tool life, which is critically important for customer satisfaction and reducing the likelihood of unexpected failures during production.

Nonetheless, it is essential for users to recognize the difference between theoretical data and actual performance metrics. Understanding that actual cutting forces may differ from specifications enables operators to make more informed decisions and adjustments during machining. This knowledge contributes to optimizing performance, reducing tool wear, and enhancing overall efficiency in production processes.

Recognizing that tool manufacturers inflate calculated cutting forces underscores the importance of designing machining processes based on empirical data. By conducting real tests and collecting actual results, operators and engineers can accurately adapt their processes to practical requirements. This approach not only ensures the safety and reliability of tools but also increases the overall efficiency of the production process.

In conclusion, the critical importance of designing and optimizing machining processes based on real data stands out. This enables manufacturers to make informed decisions, reduce production costs, enhance product quality, and maximize tool life, while effectively responding to the demands of specific machining tasks.

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