Society of Production Engineering

ICPES 2025

40th INTERNATIONAL CONFERENCE ON PRODUCTION ENGINEERING - SERBIA 2025

DOI: 10.46793/ICPES25.054S

University of Nis Faculty of Mechanical Engineering

Nis, Serbia, 18 - 19th September 2025

DIMENSIONAL ANALYSIS BASED PREDICTION MODEL OF THE MAIN CUTTING FORCE: COMPARISON AND VALIDATION

Jelena STANOJKOVIĆ[1,*], Miloš MADIĆ[2], Milan TRIFUNOVIĆ[2]
Orcid: 0000-0002-2323-493X; **Orcid:** 0000-0002-2310-2590; **Orcid:** 0000-0002-4653-6957
[1]University of Priština, Faculty of Technical Sciences, Kosovska Mitrovica, Serbia
[2]University of Niš, Faculty of Mechanical Engineering in Niš, Serbia
*Corresponding author: jelena.stanojkovic@pr.ac.rs

Abstract: *Cutting force acting on the cutting tool is an important aspect in machining. Its knowledge provides information about the machinability of the workpiece material and also enables determination of cutting power and cutting energy. Empirical modelling of cutting forces and the development of prediction models remain active area of research. For the purpose of cutting force model development, researchers have used various methods and approaches of various levels of complexity. This study presents the comparison and validation results of the dimensional analysis (DA) based model for the main cutting force prediction. The aim was to demonstrate the applicability of the DA-based cutting force prediction model on different case studies that have used different empirical models of different complexity.*

Keywords: *turning, cutting force, dimensional analysis, prediction, comparison.*

1. INTRODUCTION

Today, machining processes should satisfy all the strictest production requirements, including: productivity, efficiency, machining quality, reliability, and economy. The turning process, as one of the oldest and most widely used machining processes, is still widely used in industry and is a field of research for many researchers [1].

Cutting force plays a key role in the turning process. Knowledge of cutting force is necessary for machine tool manufacturers to assess the requirements for power, bearing loads on machine tools, as well as for designing machine tool elements, cutting tool holders, and fixture assemblies to be sufficiently rigid and to prevent vibrations [2]. Cutting force plays a significant role in improving machining performance, as it affects the tool wear and tool life, surface finish, dimensional accuracy and energy consumption to obtain the final product [3]. Moreover, a priori estimation of cutting forces helps prevent chatter and allows for achieving higher production rates.

Accurate prediction of cutting forces during turning, therefore, becomes an essential factor for process optimization and characterization, and above all for improving machining efficiency [2, 4]. Moreover, monitoring of cutting forces is often used to detect tool wear and breakage. In the literature, there are various methods and models used for modelling the cutting force [5]. For cutting force estimation in turning, different models are used, ranging from simple analytical models to data-driven models, such as empirical models, FEM models, AI models, as well as hybrid models [6], which combine different modelling paradigms. The aforementioned types of cutting force prediction models differ in complexity, required data for model development, prediction accuracy, interpolation and extrapolation capabilities, interpretability, etc. Empirical models are widely used for predicting cutting force with appropriate accuracy [2, 7]. The estimation of cutting force values based on empirical models is common in practice due to the ease of application and satisfactory accuracy for a wide range of workpiece materials, as well as the interval of variation of the cutting parameters [2].

This paper analyses the applicability of the dimensional analysis (DA) based models for the main cutting force prediction. To this aim, six case studies from the literature, that used different empirical models, different process parameters, different workpiece materials and cutting tools, different types of turning operations etc., were considered for comparison and validation of the proposed DA-based cutting force prediction models.

2. DA - BASED MODEL OF THE MAIN CUTTING FORCE

A model of the main cutting force in turning was developed using an approach based on DA [2], and can be represented by the following equation:

$$F_c = C \cdot R_m \cdot f^2 \left(\frac{v}{v_f}\right)^{x_1} \cdot \left(\frac{a_p}{f}\right)^{x_2} \cdot \left(\frac{\kappa}{\gamma_0}\right)^{x_3} \quad (1)$$

As given in Eq. 1, the main cutting force prediction model considered parameters related to the workpiece material (tensile strength - R_m), machining process (cutting speed - v, feed velocity - v_f, depth of cut -a_p, and feed rate - f), and geometry of the cutting tool (cutting edge angle - κ and rake angle -γ_o) [2].

The unknown coefficients (C, x_1, x_2 and x_3) are to be determined based on experimental data by minimizing the sum of squared errors.

3. CASE STUDIES

Six case studies were considered to validate and compare the prediction results of the DA-based models of the main cutting force. These case studies were taken from the referential literature, and they originally used different types of prediction models for the estimation of the main cutting force in turning of steels (Table 1).

Based on the analysis of results from previous research [2] it was observed that the ratio of the depth of cut and feed rate, which represents the chip slenderness ratio, was the most important parameter affecting the main cutting force. Therefore, by using an experimental design with only 6 trials, for all six case studies, the unknown coefficients (C, x_1, x_2 and x_3) of the DA-based models for predicting the main cutting force were determined. The tensile strength (R_m) values of workpiece materials were taken from the manual [8].

Table 1. Considered case studies

Case study	Model	Exp. trials	Workpiece material	Operation
1	RSM	27	AISI 4340	roughing
2	OLS GP	20	AISI 1045	roughing
3	GPR SVM ANN	60	AISI 4340	roughing
4	FL	27	AISI 1040	roughing
5	Power model	21	C45 KO36 AS12	finishing
6	RSM Kienzle	20	34CrNiMo6	semi-finishing
Ordinary Least Squares (OLS) regression analysis, Genetic programming (GP), Gaussian Process				

Regression (GRP), Support Vector Machine (SVM), Artificial Neural Network (ANN), Fuzzy Logic (FL), Response Surface Methodology (RSM)

4.1 Case Study 1

For case study 1, experimental data from the study of Suresh et al. [9] were used. The authors developed the model of the main cutting force for hard turning of AISI 4340 steel using RSM. The cutting parameters were varied at three levels: cutting speed (v) = [140, 200, 260] m/min, feed rate (f) = [0.1, 0.18, 0.26] mm/rev, depth of cut (a_p) = [0.6, 0.8, 1.0] mm.

The predicted values of the DA-based main cutting force model were compared with the experimentally obtained values to determine the mean absolute percentage error (MAPE). The MAPE value for 6 trials, which were used for estimation of unknown model coefficients, is about 3.02%.

The MAPE values for the RSM model and the DA-based prediction model for the entire experimental plan of 27 trials, as well as the minimum and maximum absolute percentage error of the DA-based prediction model, are shown in Figure 1.

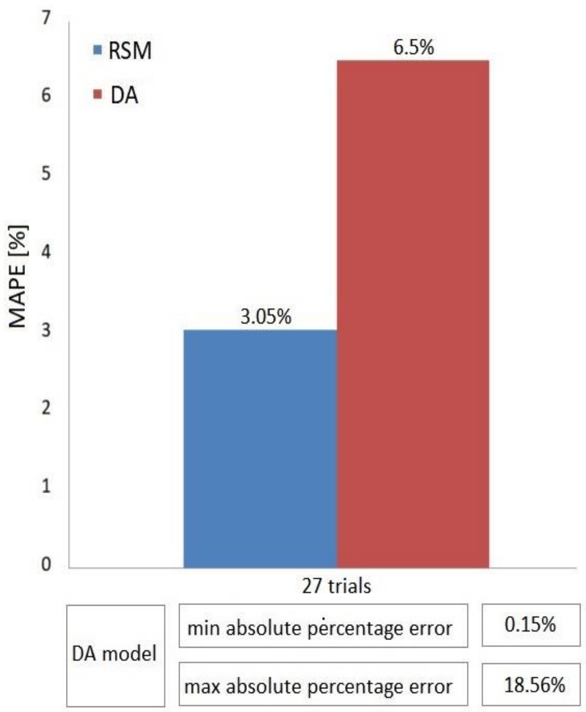

Figure 1. MAPE values of RSM and DA-based model of the main cutting force

Given that selected six trials for estimation of model coefficients considered the same cutting speed, the results indicate that the cutting speed has no significant effect on the main cutting force.

The DA-based model of the main cutting force provides satisfactory results, although the chip slenderness was very low (below 5) in over half of the experimental trials.

4.2 Case Study 2

The experimental study conducted by Cukor and Jurkovic [10] was considered as case study 2. In their study, the authors used OLS regression and GP models for predicting the main cutting force in rough longitudinal turning of AISI 1045 steel. Rotatable central composite design with 20 trials was used to arrange three cutting parameters: cutting speed (v), feed rate (f) and the depth of cut (a_p) at five levels. The predictive capabilities of the developed models were tested with an additional set of 26 experimental trials.

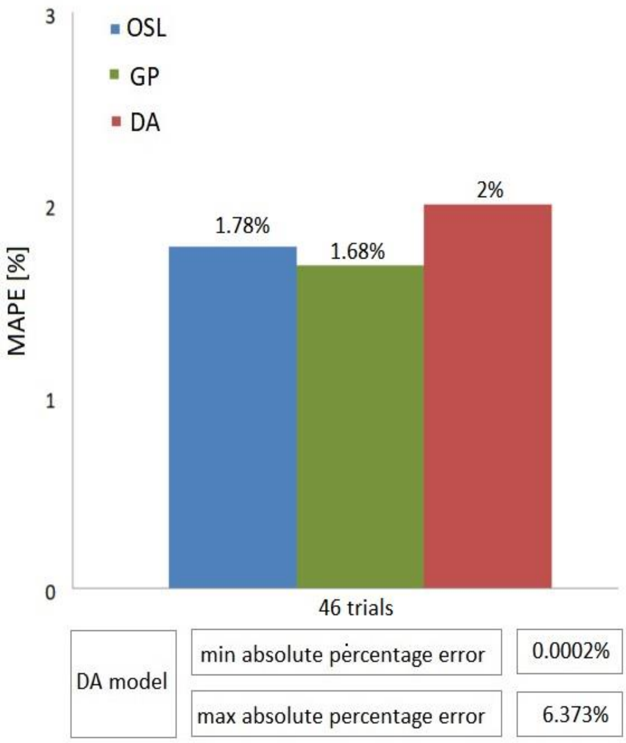

Figure 2. MAPE values of OLS, GP and DA-based models of the main cutting force

The MAPE value of the DA-based prediction model for initial 6 trials is below 0.05% and for the initial experimental plan with 20 trials is about 2.18%.

The MAPE values for the initial experimental design with 20 trials and an additional set of 26 trials are shown in Figure 2.

Again, the application of the DA-based model in this study showed that the cutting speed doesn't play a decisive role in the prediction of the main cutting force.

4.3 Case Study 3

For case study 3, the experimental study of Alajmi and Almeshal [11] was considered. The authors developed prediction models for the main cutting force in turning of AISI 4340 alloy steel using GPR, SVM and ANN. To this aim, an experimental design with 60 trials was used while considering four input parameters: cutting speed (v) = [75, 90] m/min, feed rate (f) = [0.04, 0.06, 0.08, 0.1, 0.12] mm/rev, depth of cut (a_p) = [0.5, 1.0, 1.5] mm, and tool nose radius (r_ε) = [0.4, 0.8] mm.

The MAPE value of the DA-based prediction model for 6 trials is below 0.05% and for the initial experimental plan with 20 trials is about 2.18%.

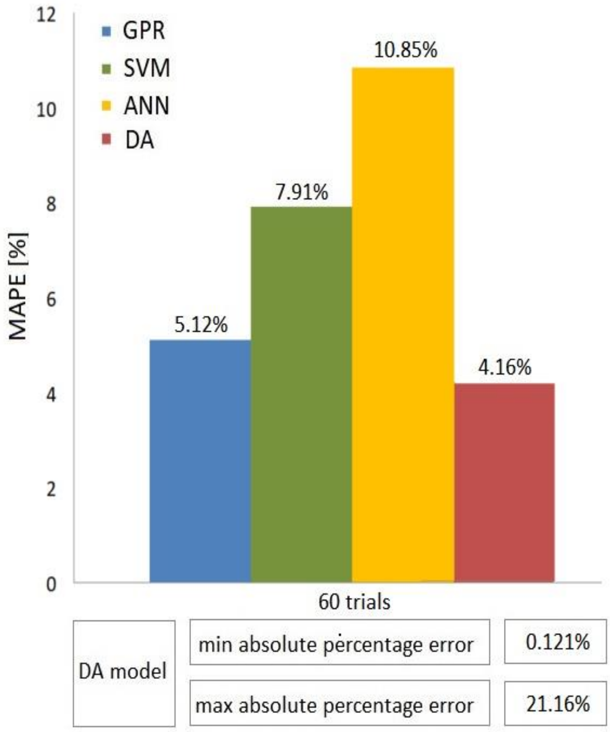

Figure 3. MAPE values of GPR, SVM, ANN and DA-based models of the main cutting force

The MAPE values for the entire 60 trials are shown in Figure 3.

Even though the range of chip slenderness ratio in the experiment was high (from 4 to 37.5) and the effect of tool nose radius was omitted, the DA-based model provided very good prediction results.

4.4 Case Study 4

For case study 4, the cutting force experimental data obtained by Yaldiz et al. [12] were considered. FL model was used in this study for predicting the main cutting force in turning of AISI 1040 steel. In the experiment, three cutting parameters were considered: cutting speed (v) = [96, 143, 203] m/min, feed rate (f) = [0.12, 0.16, 0.2] mm/rev and depth of cut (a_p) = [1.0, 1.5, 2.0] mm.

The MAPE value of the DA-based prediction model for 6 trials is about 2.89 %.

The MAPE values for the entire 27 trials are shown in Figure 4.

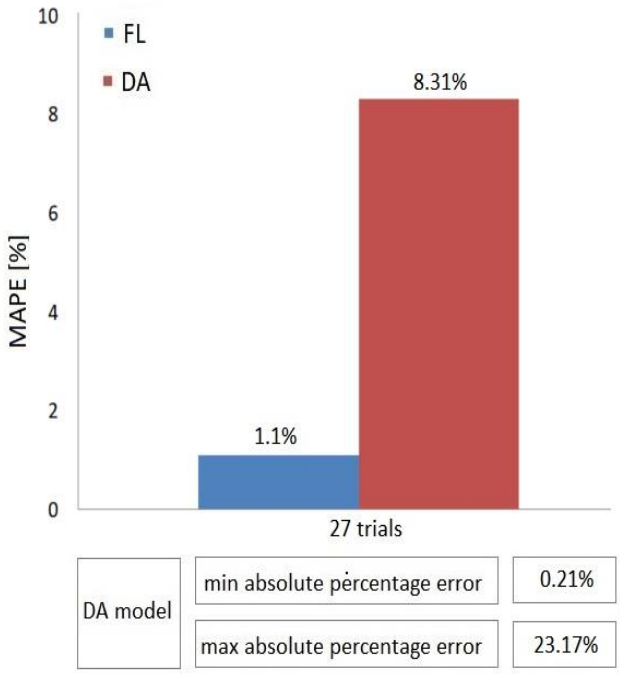

Figure 4. MAPE values of FL and DA-based models of the main cutting force

4.5 Case Study 5

The experimental study conducted by Horvath and Lukacs [13] was considered as case study 5. The authors created the adapted model of cutting force based on the theoretical parameters of the undeformed chip cross-section (h_{eq} is equivalent chip thickness and l_{eff} effective length of the edge of the tool) in fine turning of three different workpiece materials (C45 and KO36 steels and AS12 die-cast aluminum alloy).

The Victor-Kienzle model is suitable for estimating the main cutting force in the case of roughing, where the effect of the nose radius on the chip cross-section is neglected. However, in the case of finishing, where the chip removal takes places primarily not on the side cutting edge, but also on the tool nose radius ($a_p > r_\varepsilon$), or only on the tool nose radius ($a_p << r_\varepsilon$), the abovementioned Victor-Kienzle model cannot be used [13, 14].

The MAPE value of the DA-based prediction model for 6 trials is 2.68% for C45 steel, 4.57% for KO36 steel, and 1.68% for cast aluminum alloy AS12.

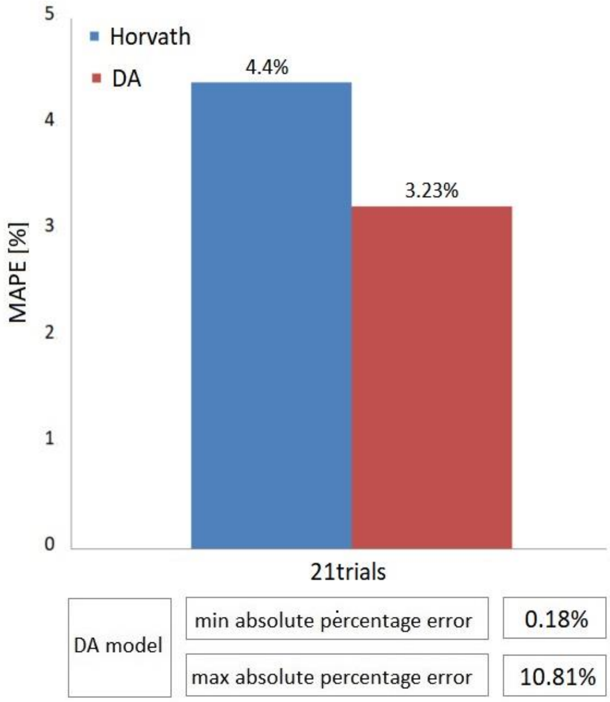

Figure 5. MAPE values of proposed and DA-based models of the main cutting force (C45 steel)

The MAPE values for the entire 21 trials for all workpiece materials are shown in Figures 5-7.

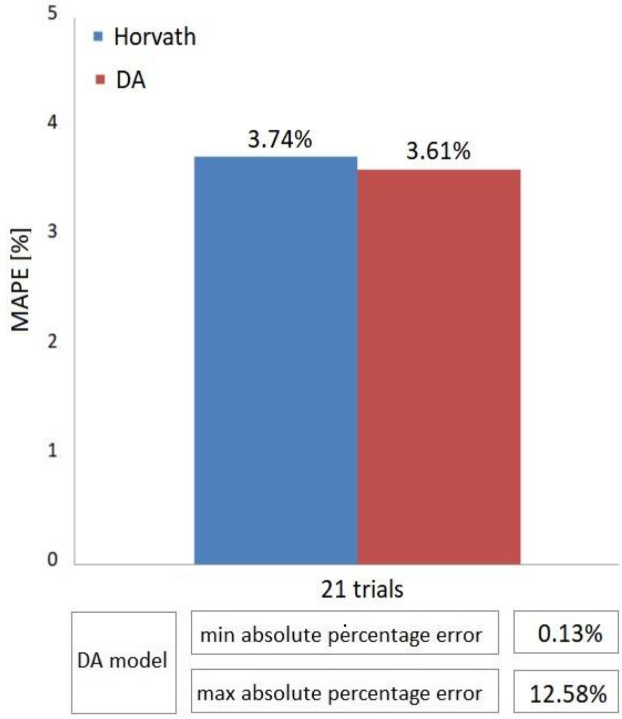

Figure 6. MAPE values of proposed and DA-based models of the main cutting force (KO36 steel)

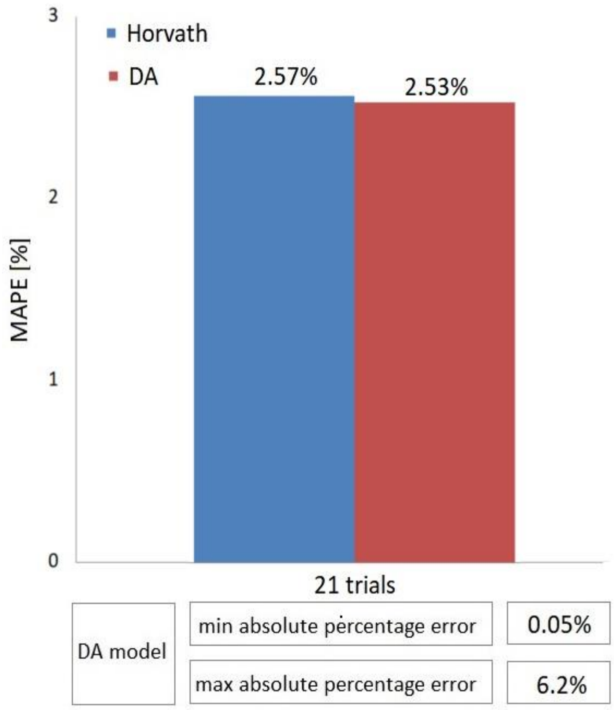

Figure 7. MAPE values of proposed and DA-based models of the main cutting force (cast aluminium AS12)

The DA-based model provided similar results to the newly proposed model for estimating the main cutting force in finishing based on geometrical parameters, such as equivalent chip thickness and effective cutting length.

4.6 Case Study 6

For case study 6, experimental data from the study of Cebalo et al. [15] were considered. The authors used RSM and well-known Victor-Kienzle models for predicting the main cutting force in semi-finish turning of 34CrNiMo6 steel. The three cutting parameters were varied at five levels: cutting speed (v) = [0.401, 0.821, 1,437, 2.0525, 2.4727] m/s, feed rate (f) = [0.12, 0.16, 0.22, 0.28, 0.32] mm/rev and depth of cut (a_p) = [0.4, 0.6, 0.9, 1.12, 1.4] mm.

The MAPE value of the DA-based prediction model for 6 trials is about 2.04%.

The MAPE values for the entire 20 trials are shown in Figure 8.

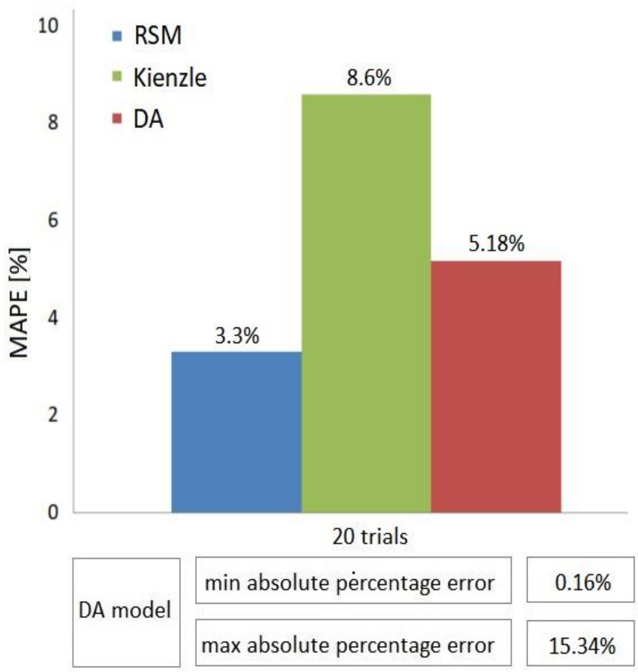

Figure 8. MAPE values of RSM, Victor-Kienzle and DA-based models of the main cutting force

Again, given that selected six trials for estimation of model coefficients considered the same cutting speed, the results indicate minor effect of the cutting speed on the resulting main cutting force.

5. CONCLUSION

This study presents the results of the comparison and validation of the DA-based models for predicting the main cutting force in turning operations. The DA-based models were not developed through a designed experiment, but only using a small fraction of data from previously conducted turning experiments.

From the analysis of the application of DA-based main cutting force prediction models to various case studies, the following conclusions can be drawn:

- In general, the DA-based models at least provide comparable results to other, more complex empirical models. One may argue that power-based models may be sufficient for cutting force modeling in turning.
- The chip slenderness ratio is a significant parameter in the DA-based model and is of essential importance for the prediction of the main cutting force in turning.
- The DA-based model yields good results across a wide range of cutting parameter values, workpiece materials, chip slenderness ratios, and can be applied in roughing, semi-finishing, and even finishing operations, where the removed chip cross-section is significantly smaller compared to roughing.
- The effects of the cutting speed and the tool nose radius on the resulting main cutting force are not so pronounced.

From the stated conclusions, it can be observed that the DA model is easily adaptable for incorporating additional factors that are shown to have a significant influence on the main cutting force. Since the DA approach for predicting the main cutting force in turning uses a smaller number of experimental trials with satisfactory accuracy, it plays an important role with high cost-efficiency ratio, reduced experimentation time, and material and energy savings. The proposed DA-based cutting force models are useful in the planning of technological processes to estimate the generated cutting force with satisfactory accuracy.

ACKNOWLEDGEMENT

This research was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (451-03-137/2025-03/200109 and 451-03-18/2025-03/200155).

REFERENCES

[1] S. Wang, Z. Tao, D. Wenping, S. Zhanwen: Analytical modeling and prediction of cutting forces in orthogonal turning: a review, The International Journal of Advanced Manufacturing Technology, Vol. 119, pp. 1407-1434, 2022.

[2] J. Stanojković, M. Madić, M. Trifunović, P. Janković, D. Petković: A novel approach to predicting the cutting force in turning using dimensional analysis, Facta Universitatis, Series: Mechanical Engineering, online first, 2025.

[3] L. Tang, Z. Cheng, j. Huang, C. Gao, W. Chang: Empirical models for cutting forces in finish dry hard turning of hardened tool steel at different hardness levels, The International Journal of Advanced Manufacturing Technology, Vol. 76, pp. 691-703, 2015.

[4] B.Y. Lee, Y.S. Tarng: Prediction of specific cutting force and cutting force ratio in turning, Journal of Materials Processing Technology, Vol. 41, No. 1, pp. 71-82, 1994.

[5] R.W. Invester, M. Kenedy, M. Davies, R. Stevenson, J. Thiele, R. Furness, S. Athavale: Assessment of machining models: Progress report, Machining Science and Technology, Vol. 4, No. 3, pp. 511-538, 2020.

[6] S.V.A Laakso, A. Mityakov, T. Niinimäki, K. S. B Ribeiro, W.M. Bessa: Hybrid FE-ML model for turning of 42CrMo4 steel, CIRP Journal of Manufacturing Science and Technology, Vol. 55, pp. 333-346, 2024.

[7] J. Stanojković, M. Madić, D. Lazarević: *Empirical modeling methods of turning process: a review*, 18th International Conference on Tribology, 17-19.05.2023. Kragujevac, Serbia.

[8] M. Kalajdžić, Lj. Tanović, B. Babić, M. Glavonjić, Z. Miljković, R. Puzović, B. Kokotović, M. Popović, S. Živanović, D. Tošić, I. Vasić: Tehnologija obrade rezanjem-Priručnik, IX izdanje. Mašinski fakultet u Beogradu, Beograd, 1999.

[9] R. Suresh, S. Basavarajappa, G.L. Samuel: Some studies on hard turning of AISI 4340 steel using multilayer coated carbide tool, Measurement, Vol. 45, No. 7, pp. 1872-1884, 2012.

[10]G. Cukor, Z. Jurković,: Optimization of turning using evolutionary algorithms, Engineering Review, Vol. 30, No. 2, pp. 1-10, 2010.

[11]M.S. Alajmi, A.M. Almeshal: Modeling of cutting force in the turning of AISI 4340 using Gaussian Process Regression Algorithm, Applied Sciences, Vol. 11, No. 9, 4055, 2021.

[12]S. Yaldiz. F. Unsacar, H. Saglam: Comparison of experimental results obtained by designed dynamometer fo fuzzy model for predicting cutting force in turning, Materials and Design, Vol. 27, pp. 1139-1147, 2006.

[13]R. Horváth, J. Lukács: Application of a Force model adapted for the precise turning of various metallic materials, Journal of Mechanical Engineering, Vol. 63, No. 9, pp. 489-500, 2017.

[14]R. Horváth: A new model for fine turning forces, Acta Polytechnica Hungarica, Vol.12, No. 7, pp. 109-128, 2015.

[15]R. Cebalo, D. Bajić, B. Bilić: *Mathematical modelling of cutting force in the longitudinal turning process*, 10th International Scientific Conference on Production Engineering, 15-17.06.2025, Croatia, pp. 131-140.