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Research Article

Analysis of the main cutting force, cutting energy and specific cutting energy in turning of X155CrVMo12–1 steel

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Abstract: This paper presents an experimental study of dry longitudinal single–pass turning of X155CrVMo12–1 steel using two cutting inserts with different rake angles. Initially, the model based on dimensional analysis was developed to estimate the main cutting force, while considering three dimensionless groups with six parameters. After experimental validation, the developed dimensional analysis-based model was further for the analysis of the cutting energy and specific cutting energy. Detailed analysis included the analysis of the effects of feed rate, depth of cut and rake angle on considered process performances. The observed correlations between cutting parameters and process performances were compared with the previously published experimental results. It has been observed that the depth of cut has the greatest influence on the main cutting force and cutting energy, while the feed rate has a slightly more pronounced effect on the specific cutting energy.

Keywords: Turning; Main cutting force; Cutting energy; Specific cutting energy; X155CrVMo12–1 steel

I. INTRODUCTION

The turning process is among the most common processes in the manufacturing industry [1]. It is a process for pre–machining or finishing mostly cylindrical workpieces [2]. Due to the favourable characteristics of the cutting process, as well as a good balance between efficiency, processing quality and production costs, this process has an important role in modern industrial production [3]. Turning is a technologically demanding material removal process, the results of which depend largely on the conditions under which it is performed [4]. Cutting parameters are usually selected based on operator experience, tool manufacturer recommendations, or with the help of machining manuals [5]. Because of globalization and fierce market competition and volatility, there is continuous effort to improve the performance of turning operations with the aim of minimizing machining time, costs and improving product quality [6]. In recent years, monitoring of sustainable performance, ecological criteria and environmental impacts have also been brought into focus [7]. Consideration of all the aforementioned performances in an optimal way is a very complex task, often lengthy with an uncertain outcome, given the existence of multiple parameters, stochastics of the process, parameter interactions and existence of mutually contradictory requirements [8].

The cutting force has a significant influence on the cutting process [9]. By monitoring cutting forces, it is possible to improve machining efficiency, reduce energy costs, extend tool life, improve machining quality, reduce vibration, enable predictive maintenance and better understanding and optimization of the cutting process [10-12]. In addition, knowing the cutting forces makes it possible to design machine tool elements and fixtures that are sufficiently rigid and free from vibration [13].

Knowledge of cutting energy is a key characteristic that provides important information about the amount of energy required for cutting [14–16]. The energy consumption during the machining process largely depends on the workpiece material's machinability, which may be estimated by considering cutting force or cutting power, tool life or tool wear, surface roughness, chip form, and cutting temperature [16–18]. In production, reducing energy consumption contributes to more efficient use of machine tools, where in determination of optimal cutting conditions plays a major role [19]. Likewise, the estimation of specific cutting energy is suitable for comparative machinability analysis of different workpiece materials and cutting tools.

Many authors presented in their research studies different predictive models of the main cutting forces, as well as changes in energy consumption by varying various cutting parameters [20–27]. The largest number of studies analyzed the influence of three key parameters (cutting speed, feed rate and depth of cut) which are actually related to cutting regimes. However, cutting forces are also affected by the workpiece material, cutting tools, etc.

The research of this study is focused on the analysis of the main cutting force, cutting energy and specific cutting energy. Dry longitudinal single-pass turning of steel X155CrVMo12-1 was considered. To this aim, a model of the main cutting force was developed based on the application of dimensional analysis (DA). In this case, four dimensionless groups with seven different parameters were considered. A Taguchi orthogonal experimental design $3^3 \times 2^1$ was conducted for main cutting force experimental data acquisition. After experimental validation of the developed dimensional analysis-based main cutting force model, the detailed analysis included the consideration of the influence of input parameters on considered responses.

II. EXPERIMENTAL SETUP

The experiment was performed on POTISJE PA-C 30 universal lathe. Turning was performed on round bars with a diameter of 75 mm and a length of 250 mm. The workpiece material was high–alloy tool steel X155CrVMo12–1 (AISI D2) containing a high percentage of carbon, chromium, molybdenum and vanadium, **Table 1**. It is used for components that require excellent wear resistance, medium toughness and is intended for cold working. It has a wide application in the industry for making tools, moulds, dies, etc.

The hardness of the workpiece steel was ascertained by HRB method using a standard indenter and the prescribed test force. Based on the standard conversion table (A.1, ISO 18265:2003), the tensile strength was obtained indirectly, which in this case is 770 N/mm^2.

The tool holder was PCLNR3225P12 (κ=95°, γ_{oh}=–6°), manufactured by Sandvik Coromant, **Fig. 1**. Two Dormer Pramet cutting inserts, CNMG 120408E–NF (γ_{oi}=25°, r=0.8 mm) and CNMG 120408E–SF (γ_{oi}=14.5°, r=0.8 mm), T8430 (PVD coated fine grained cemented carbide) were used, **Fig. 2**.

***Table 1.** Percentage composition of X155CrVMo12-1 steel*

Element	***Chemical composition [%]***
C	1.52
Cr	11.8
V	1.1
Mn	0.36
Mo	0.81
Ni	0.14
Si	0.25

***Figure 1.** Tool holder (PCLNR3225P12)*

***Figure 2.** Cutting inserts (CNMG 120408E–NF and CNMG 120408E–SF)*

The main cutting force during orthogonal single-pass turning was measured using a piezoelectric force transducer, Kistler type 9941. It was mounted on the lathe via a custom tool holder adapter. The load signal was generated by a dynamometer and amplifier, Kistler type 5007. Through the HBM QuantumX MX840 universal measuring amplifier measuring data were acquired, and then visualized and analyzed using the data acquisition software "Catman".

The machining parameters (ranges and levels) were defined based on the recommendations of the cutting tool manufacturer, as well as the capabilities of the machine tool. The constant and variable parameters used in the experiment were as follows: cutting speed, v=157 m/min, tool nose radius r=0.8 mm, depth of cut a_p=[1.2, 1.8, 1.9, 2.0, 2.9] mm, feed rate f=[0.196, 0.249, 0.321] mm/rev, rake angle γ_0=[8.5, 19]°, cutting edge angle κ=95°. With the defined processing parameters, according to their levels, based on the obtained model using dimensional analysis, an experimental matrix was adopted, i.e., Taguchi orthogonal design (L_6) $3^3 \times 2^1$ [28].

III. Dimensional Analysis-based model of the main cutting force

Dimensional analysis (DA) is widely used in various scientific and engineering fields, due to the wide spectrum of advantages it provides [29]. Its application can significantly reduce the number of experimental trials, which leads to greater efficiency, shorter experimentation time, and resource savings, while also providing a faster way to define relationships between the involved physical quantities [29–31]. Also, one should note that special attention should be given to how the levels of the identified dimensionless groups are arranged in the experimental design for the turning experiment.

The experimental results of measurements in laboratory conditions are given in **Table 2**. By applying the modelling methodology based on DA, as described in reference [31], a model for estimating the main cutting force in the turning process was obtained in the following form:

$$F_c = 0.4569 \cdot 770 \cdot f^2 \cdot \left(\frac{v}{v_f}\right)^{0.2865} \cdot \left(\frac{a_p}{f}\right)^{0.8875} \cdot \left(\frac{\kappa}{\gamma_0}\right)^{0.0372} \quad (1)$$

Based on **Table 2**., a graphical representation is presented showing that the values obtained by experimental measurement are close to the predicted values using DA, **Fig. 3**. The predicted values were compared with the experimental values to assess the model prediction accuracy, i.e., to determine the mean absolute percentage error (MAPE), which was approximately around 2%.

A limitation of the proposed DA-based model is that it would be necessary to extend this model in the case of significant parameter interactions.

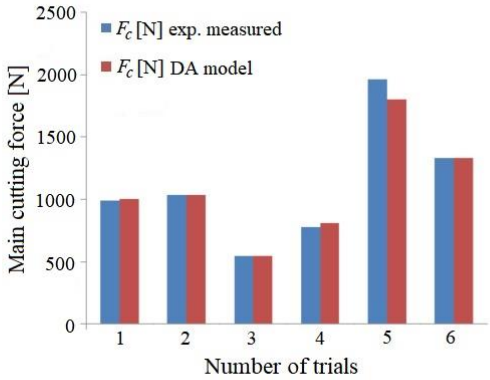

Figure 3. *Graphical representation of the main cutting force (exp. measurement and DA model)*

1. Validation and verification

To further validate the accuracy and generalization of the developed DA model, six additional cutting regimes were tested, **Table 3**.

The results of additional validation tests show that the predicted values of the main cutting force are close to the experimentally obtained values with MAPE of around 5.6%. As can be seen from **Table 4,** discrepancies between predicted and experimentally measured values of the main cutting force, both within and outside the initial experimental hyperspace, are acceptable.

In **Fig. 4**. the correlation coefficient and analysis of residuals, taking into account the experimental data from the main experiment and additional validation tests, are given. The very high correlation coefficient of about 0.99 confirms the validity of the developed main cutting force prediction model. Likewise, residuals do not follow any recognizable pattern and are scattered above and below zero [32].

Table 2. *Taguchi experimental design $3^3 \times 2^1$ and main cutting force results*

Trial	A	B	C	v/v_f	a_p/f	κ/γ_o	F_c [N] exp. measured	F_c [N] DA model
1	0	0	–1	946.26	7.63	5.00	993	1002.2
2	0	0	1	946.26	7.63	11.18	1035	1032.7
3	1	–1	–1	1202.14	6.12	5.00	547	547
4	1	1	1	1202.14	9.18	11.18	781	807.7
5	–1	1	–1	734.02	9.03	5.00	1964	1799.1

Table 3. *Results of main cutting force measurements under different validation regimes*

Trial	v/v_f	a_p/f	κ/γ_o	F_c [N] exp. measured	F_c [N] DA model
1	734.02	3.74	5.00	767	822.1
2	660.00	3.36	11.18	868	924.8
3	1101.03	7.48	5.00	729	759.3
4	826.73	7.72	11.18	1353	1314.9
5	1323.70	14.61	5.00	1111	1003.4
6	1101.03	11.21	11.18	1162	1121.2

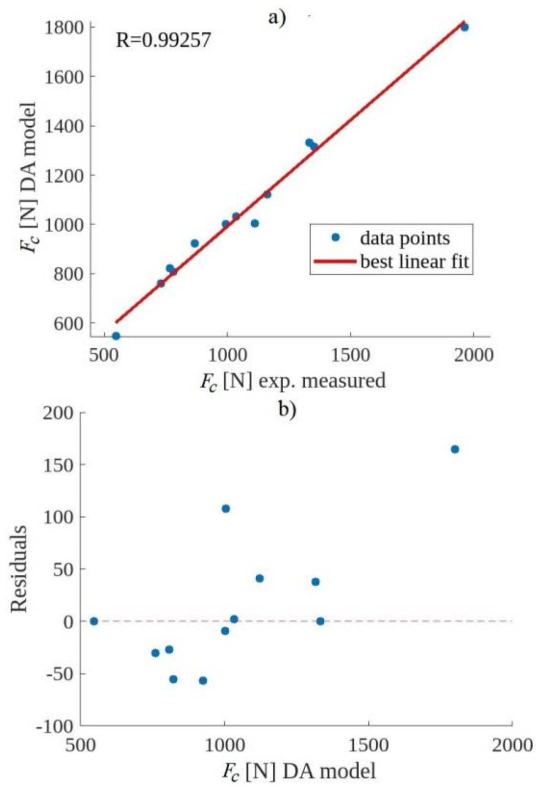

Figure 4. *a) Correlations between the predicted and the experimentally measured values of the main cutting force, b) Residual plot of the main cutting force*

IV. Determination of cutting energy and specific cutting energy

The determination of cutting force is important because it allows the evaluation of the cutting power (P_c). As a basic technical quantity, it represents the product of the cutting force (F_c) and cutting speed (v) [4, 33]:

$$P_c = \frac{F_c \cdot v}{60} \tag{2}$$

Cutting power is crucial because it connects the cutting force, cutting energy and specific cutting energy required to process the material, i.e. by knowing the cutting power it is possible to determine these quantities [4, 33].

The cutting energy (E_c) represents the product of the cutting power (P_c) and cutting time (t_c) [19, 32]:

$$E_c = P_c \cdot t_c \cdot 60 \tag{3}$$

The specific cutting energy (E_{sc}) in the turning process represents the amount of energy required to remove a unit volume of material [16, 19]. It is considered crucial in machining processes because it allows a better understanding of efficiency and energy consumption during turning [7, 12] and can be expressed as a ratio of cutting power (P_c) and material removal rate (*MRR*) [16, 33]:

$$E_{cs} = \frac{P_c}{MRR} \tag{4}$$

Specific cutting energy is often used in industrial applications to optimize the process, reduce energy consumption and improve machine efficiency [16].

V. Results and discussion

Based on a developed prediction model, as well as the models discussed in the previous chapter, analyses of the influence of depth of cut, feed rate and rake angle on the main cutting force, cutting energy and specific cutting energy were performed, at a reference cutting length of L=100 mm. For the purpose of a more detailed analysis, three-dimensional surface plots are presented, illustrating the effects of cutting parameters, **Fig. 5–7**.

Increasing the depth of cut causes an increase in the main cutting force and cutting energy, **Fig. 5** and **Fig. 6**. According to the research of El–Hossaini et al. [32], a larger depth of cut causes higher values of the main cutting force due to the increase in the cross-section being machined. This implies greater contact of the cutting edge with the material, which leads to an increase in stress and total force application. Conversely, an increase in feed rate also

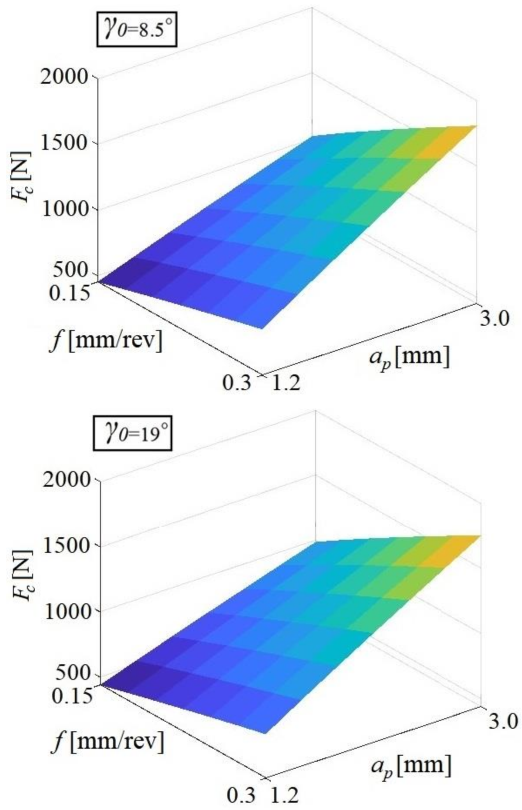

Figure 5. *Surface plot (3D plot) of the main cutting force (F_c) for different rake angles (γ_0)*

leads to higher values of the main cutting force, but

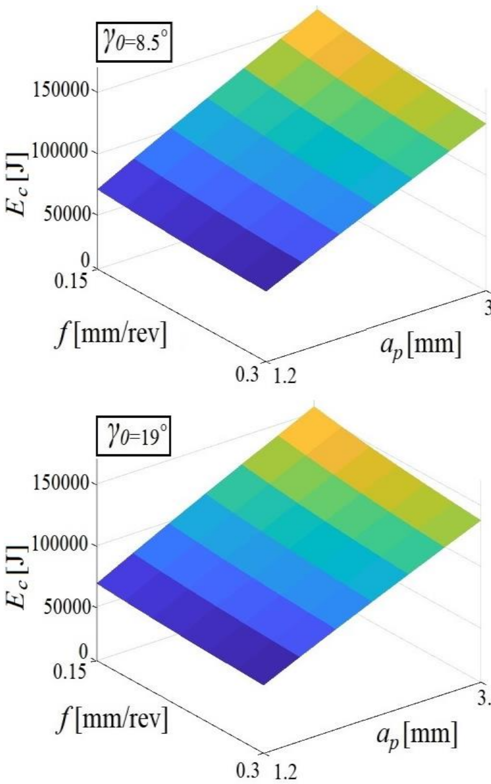

Figure 6. *Surface plot (3D plot) of the cutting energy (E_c) for different rake angles (γ_0)*

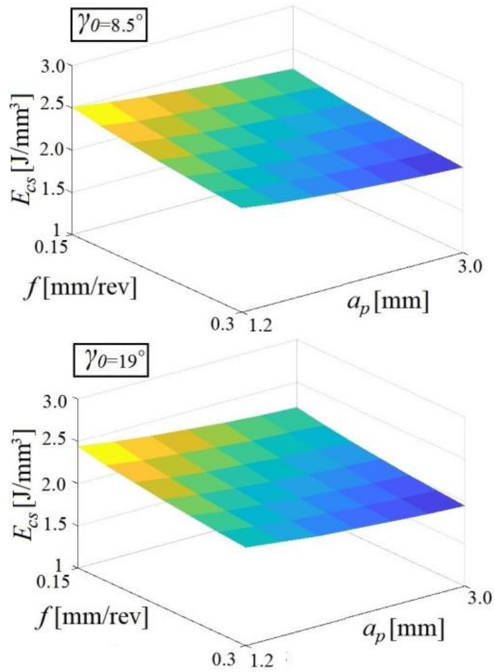

Figure 7. *Surface plot (3D plot) of the specific cutting energy (E_{sc}) for different rake angles (γ_0)*

this effect is of lesser intensity compared to the effect of depth of cut.

However, as shown in **Fig. 6**., increasing the feed rate leads to a decrease in cutting energy, which is a consequence of the shortened cutting time.

According to **Fig. 7**., both increasing the depth of cut and increasing the feed rate have approximately the same effect on reducing the specific cutting energy. Therefore, when considering the efficiency in terms of energy consumed for removing a unit volume of material, it is preferable to apply higher values of depth of cut and feed rate.

A small rake angle results in higher values of all three cutting performances (main cutting force, cutting energy and specific cutting energy), **Fig. 5–7**. According to Saglam et al. [34], the main cutting force decreases with increasing rake angle, while it has been found that with increasing feed rate, cutting forces continuously increase, regardless of the rake angle value. This is because the volume of workpiece material coming in contact with the cutting tool or the volume of material being removed also increases with the increase in feed rate.

VI. Comparison of the obtained results

The results of this study were compared with the results reported in previous experimental studies, **Table 4**.

For all the steels machined, a positive correlation (direct relationship) was found between the feed rate or depth of cut on the main cutting forces, i.e., an increase in either of these two parameters leads to its increase. In contrast, a negative correlation (indirect relationship) was observed between the rake angle and the main cutting force, which means that a larger rake angle results in its decrease. However, even for similar steel alloys, the relationship between cutting speed and main cutting force is not always consistent, which can be explained by the fact that cutting speed has a very small, often negligible effect on the main cutting force itself [24]. The results obtained in this study regarding the influence of process parameters are consistent with observations reported in previous experimental studies.

VII. Conclusion

Based on the developed DA-based prediction model, this study focused on examining the main cutting force which was the starting point for determining other process performances, i.e. cutting energy and specific cutting energy. Longitudinal turning was performed without the use of coolant in the single-pass turning of X155CrVMo12-1 (AISI D2) steel. Based on the analysis and the obtained

Table 4. *Dependence of cutting performance on cutting parameters when turning different steel workpieces*

Ref.	***Range of v [m/min]***	***Range of f [mm/rev]***	***Range of*** a_p ***[mm]***	***Range of*** γ_0 ***[°]***	***Wokpiece material***	F_c	E_c	E_{sc}
Osička et al. [20]	130–180 ↓↑	0.05–0.1 ↓	0.2–0.35 ↓	–6	AISI 52100 steel	↓		
Reddy and Sng [21]	600–800 ↓	0.5–0.7 ↓	0.3–0.5 ↓	12	AISI 4140 steel	↓		
Gunay et al. [22]	80–180 ↑	0.25	2.5	–5–12.5 ↑	AISI 1040	↓		
Rao et al. [23]	50–90 ↓	0.05–0.15 ↓	0.25–0.75 ↓	–6	AISI 1050	↓		
Zerti et al. [24]	80–340 ↓↑	0.08–0.24– ↓	0.1–0.25 ↓	–6	AISI 420 steel	↓		
Bagaber et al. [25]	90–190 ↑	0.06–0.23 ↑	0.8–1.6 ↓	–6	AISI 202		↓	
Sekar et al. [26]	90–224 ↑	0.35–0.45 ↑	0.1–0.4 ↑	–6	AISI 304 steel			↓
Zhao et al. [27]	90–240 ↑	0.05–0.07 ↑	0.5–1.0 ↑	–10	AISI 1045 steel			↓
Present study	141	0.196–0.321 ↓↑↑	1.2–2.9 ↓↓↑	8.5–19 ↑↑↑	X155CrVMo12-1 steel (AISI D2)	↓	↓	↓

results, the following conclusions can be distinguished:

- For the investigated experimental hyperspace, the depth of cut has the most significant influence on the main force and cutting energy, the feed rate has a slightly smaller influence, while the effect of rake angle is least pronounced.
- Feed rate has a slightly more pronounced effect on the specific cutting energy.
- A smaller rake angle gives approximately 3% higher values for all three investigated and analyzed process performances.
- The obtained experimental and modeling results regarding the influence of parameters on the considered performances are consistent with previously published results from referential literature.
- For a given case study, it is necessary to formulate and solve optimization problems in order to determine specific combinations of cutting parameters to optimize process efficiency, while considering available machine tool power.

Comparative analysis of discussed process performances in turning of different workpiece materials and formulating and solving some optimization studies is the future research scope.

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Author Contributions

J. Stanojković: Conceptualization, Experiments, Writing, Theoretical analysis.

M. Madić: Conceptualization, Experiments, Theoretical analysis.

M. Trifunović: Experiments, Review.

P. Janković: Experiments, Review.

D. Petković: Experiments, Review.

D. Marinković: Supervision.

Disclosure Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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