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APPLICATION OF FRACTIONAL FACTORIAL DESIGN FOR ANALYSIS OF CUTTING ENERGY IN TURNING

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ABSTRACT

Energy consumption in machining processes is a very important aspect that has been given increased importance in recent times. This article, therefore, proposes an approach for identification of the most important main and interaction effects of turning parameters regarding the cutting energy in dry longitudinal single-pass turning of low-alloyed and high-alloyed steels. Fractional factorial design 2^{5-1} was applied to arrange five parameters, namely, depth of cut, feed rate, cutting speed, rake angle and cutting edge angle at two levels. Based on the cutting tool manufacturer's machining calculator and well-known analytical relationships, cutting energy was estimated for sixteen cutting regimes for both workpiece material groups. The analysis of obtained results involved the analysis of main and interaction effects, determination of statistically significant effects and development of cutting energy prediction models.

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1. INTRODUCTION

Turning is a widely used machining process in which material is removedfrom the rotating cylindrical workpiece by a single point cutting tool with a geometrically defined cutting edge. In order toremain current in modern industry, numerous research aimed at studying process mechanics, developing improved cutting tools and machine tools are conducted worldwide. Improvement of machining performances such as minimization of cost [1, 2], analysis of machinability aspects and quality issues [3-5], maximization of production rate [6, 7] are of particular interest. Due to the economic and energetic crisis,a number of research are focused on analysis of energy consumption in machining processes [8-10] and analysis of energy consumption of different machine tools [11-16].

By reducing the energy footprint one can effectively help companies to accomplish green production [12], make economic benefit and improve their environmental performance [13]. This reduction of energy consumption can be achieved either by development and use of energy-efficient machine tools or by optimizing machining processes for each given case study [17]. Therefore, one can argue that energy reduction requires knowledge about energy consumption as a function of machine tool and parameters of a given machining process [13]. At the same time, it should be kept in mind that the energy consumed for non-cutting operations dominates the total energy consumption in machining [18, 19]. As noted by Gutowski et al. [20] energy requirement for the actual machining does not exceed 15% of the total energy consumed. Regarding energy consumption, one should also be aware that the energy requirement decreases as the material removal rate increases [21].

Given that with proper selection and optimization of main cutting parameters one can achieve energy savings, the present study deals with the analysis of the effect of cutting parameters on the resulting cutting energy in dry longitudinal single-pass turning of low-alloyed and high-alloyed steels. Walter was selected as cutting tool manufacturer. Walter machining groups P7 (low-alloyed steels, hardness 175 HB) and P11 (high-alloyed steels, 200 HB) were used.Fractional factorial design 2^{5-1} was applied to study main and interaction effects of five parameters, three related to the machining process (depth of cut, feed rate and cutting speed) and two related to the cutting tool geometry (rake angle and cutting edge angle). Data for the analysis wereobtained using a machining calculator of the cutting tool manufacturer [22]. The analysis of results involved the analysis of main and interaction effects, determination of statistically significant terms by Lenth's method [23], as well as development of quasi-linear models for the prediction of cutting energy for arbitrarily chosen set of cutting parameters.

2. EXPERIMENTAL DATA

Turning diameter was set to 72 mm, length of cut to 50 mm, and machine tool efficiency to 0.8 (gear train driven machine tool). The cutting tools were toolholders PCLNR2525M12 (cutting edge angle of $\kappa = 95°$, rake angle of $\gamma_{0h} = -6°$) and PCBNR2525M12 ($\kappa = 75°$, $\gamma_{0h} = -6°$), with CNMG120412-MP3 WPP05S ($\gamma_{0i} = 22.5°$) and

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CNMG120412-MP5 WPP05S (γ_{0i} = 15°) inserts for medium machining. Cutting parameter ranges and levels were selected considering availability and capabilities of machining calculator and recommended cutting conditions for the inserts. Factors with their names, units, labels, and values on low level (-1) and high level (+1) are shown in Table 1.

In order to assess the main and interaction effects of the considered factors on the resulting cutting energy, fractional factorial design 2^{5-1} was applied. Highest order interaction (ABCDE) was chosen as the generator of the fractional factorial design. This design has resolution of 5, that is the estimations of the main effects are not confounded with any other main effects, 2 or 3-way factor interactions. Likewise, 2-way factor interactions are confounded with 3-way factor interactions. Given that the main effects are only confounded with 4-way interactions or higher, this design provides good information about the system or process, assumed to be dominated by main effects and low-order interactions.

Based on the fractional factorial design 2^{5-1}, 16 different combinations of factor levels were tried in the "virtual" experiment and cutting energy (E_c) values were obtained (Table 2).

3. RESULTS AND DISCUSSION

When applying fractional factorial designs, the estimation of the main and interaction effects can be done as in the case of classical factorial experimental designs of 2^k type. While doing so, one should take into account the number of occurrences of the level of each factor in the experiment, as well as the number of experimental trial replicates [24]. To find the estimate of any model effect, the difference in means of the response between the high (+) and low (−) levels is used [25]. The necessary calculations needed to determine the main effects of considered factors on the cutting energy are shown in Fig. 1.

Table 1 *Factors that were varied for the calculation of cutting energy*

Factor	Unit	Label	Low level (-1)	High level (+1)
Depth of cut, a_p	mm	A	1.2	3.5
Feed rate, f	mm/rev	B	0.20	0.40
Cutting speed, v	m/min	C	280	313
Rake angle, γ_0	°	D	9.0	16.5
Cutting edge angle, κ	°	E	75	95

Table 2 *Estimated cutting energy valuesfor different cutting regimes for low-alloyed (P7) and high-alloyed (P11) steels*

Trial	A	B	C	D	E	E_c(P7) (kJ)	E_c(P11) (kJ)
1	-1	-1	-1	-1	1	30.83	36.36
2	1	-1	-1	-1	-1	87.94	103.36
3	-1	1	-1	-1	-1	26.18	30.83
4	1	1	-1	-1	1	73.25	86.20
5	-1	-1	1	-1	-1	31.13	36.60
6	1	-1	1	-1	1	87.15	102.50
7	-1	1	1	-1	1	25.97	30.53
8	1	1	1	-1	-1	73.89	86.94
9	-1	-1	-1	1	-1	28.80	33.84
10	1	-1	-1	1	1	80.48	94.63
11	-1	1	-1	1	1	23.95	28.22
12	1	1	-1	1	-1	68.21	80.28
13	-1	-1	1	1	1	28.53	33.56
14	1	-1	1	1	-1	81.08	95.39
15	-1	1	1	1	-1	24.15	28.44
16	1	1	1	1	1	67.64	79.57

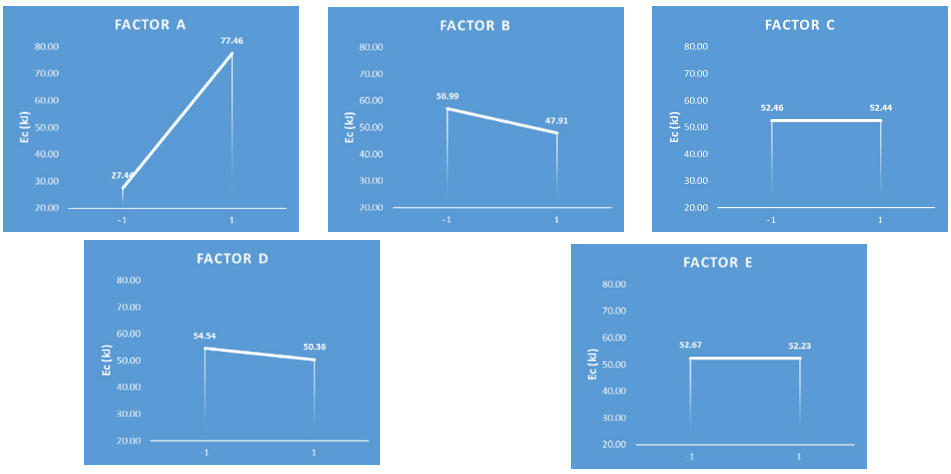


Fig. 1. Main effects plots of considered factors on cutting energy for low-alloyed steels (P7)

From Fig. 1 it can be concluded that factor A has a positive correlation with the resulting cutting energy, i.e., an increase in the depth of cut sharply increases cutting energy and vice versa. On the other hand, factors B and D have a negative correlation with cutting energy, i.e., with an increase in their values one obtains lower cutting energy. The effect of the feed rate in this case is expected, considering that with an increase in feed rate, feed velocity is increased, which ultimately decreases cutting time. Increasing rake angle increases shear angle and results in chip thickness decrease, as well as in reduction of cutting force and thus reduction of cutting power [26, 27],which is in accordance with the previous observation. Nijin and Jagadesh [28] concluded that energy consumption decreasesas the rake angle increases,due to greater sharpness of the cutting edge and less friction between cutting tool and chip. Parle et al. [29] explained the observed trend of decreasing specific cutting energy with increasing rake angle by decreasingcutting forces due to reduced ploughing at larger rake angles. The obtained results indicate negligible effects of the cutting speed and cutting edge angle on the resulting cutting energy. With an increase in cutting speed, the required power rises, but simultaneously cutting time decreases, which in the end is not much reflected in estimated cutting energy. By decreasing the cutting edge angle, the chip contact length is increased and consequently chip thickness decreases. As a result, the cutting force is dispersed on a longer cutting edge and tool life is prolonged. However, due to decreased chip thickness and increased chip width, chip control and chip breaking may be difficult [30].

Considering the absolute values of the main effects, it can be concluded that the factor A (depth of cut), has the greatest effect on the cutting energy, followed by factor B (feed rate) and factor D (rake angle).

The applied 2^{5-1} design can estimate all five main effects, as well as all ten 2-way interactions. However, this unreplicated design has no degrees of freedom left for the estimation of error. In such situations Lenth's method [23] and normal probability plots may be applied to draw a reference line for statistical significance of analysed terms. Effects that are further from 0 on the normal probability plot of the effects are statistically significant. For determining critical distance for statistical significance of model terms Lenth'spseudo standard error (PSE)was used (Fig. 2).

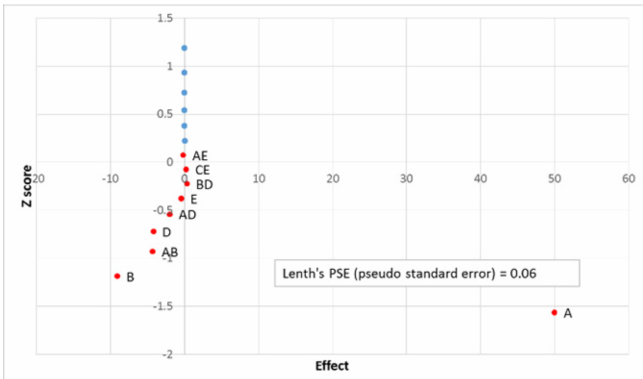
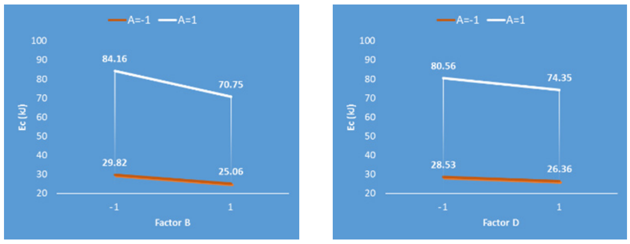


Fig. 2. Normal probability plot of the effects with calculated Lenth's PSE (low-alloyed steels (P7))

It is evident from Fig. 2 that out of 15 terms, four main effects (factors A, B, D and E) are, statistically significant along with four 2-way interaction effects. Given that the depth of cut (factor A) is by far the most influential term, only two 2-way interaction effects (AB and AD) will be considered for the analysis (Fig. 3).



a) *b)*

Fig. 3. The most important factor interaction effects on cutting energy (low-alloyed steels (P7))

From Fig. 3 one can observe that there are no significant interaction effects in terms of changing qualitative effect of the depth of cut on the resulting cutting energy when feed rate and rake angle change levels. However, from Fig. 3a) one can observe that when depth of cut is at high level (a_p = 3.5 mm), an increase in feed rate results in more decrease of cutting energy. The same is valid for the interaction of the depth of cut and rake angle (Fig. 3b)). When depth of cut is at high level (a_p = 3.5 mm), an increase in rake angle results in more decrease of cutting energy.

One should note that in the case of high-alloyed steels (P11) the analysis of data yielded the same results. That is, all main and interaction effects that were assessed as statistically significant in the case of low-alloyed steels (P7) are again significant. The same is true for the analysis of the 2-way interaction effects.

Based on a conducted analysis of the main effects of factors, as well as the main interaction effects on the resulting cutting energy, a suitable combination of factor levels that can be recommended for minimization of cutting energy is as follows:

A (-1) – because depth of cut has the biggest influence on cutting energy.

B (+1) – because feed rate has the second biggest influence, and analysis of Fig. 3a) reveals that this combination yields minimal cutting energy.

C (+1) – because an increase in cutting speed increases material removal rate.

D (+1) – because the rake angle has the third biggest influence on cutting energy, and analysis of Fig. 3 b) reveals that this combination yields minimal cutting energy.

E (+1) – because of better chip control and breaking, which can reduce the number of machinestops for unfavourable chipsremoval.

This combination of factor levels is not included in the initial experimental design. However, by using the following mathematical model, one can predict the resulting cutting energy for this cutting regime.

Based on determined main and interaction effects, average value of cutting energy for the experimental design, as well as considering the statistical significance of these terms, one can model the cutting energy for single-pass longitudinal turning of low-alloyed steels (P7) using the following prediction model:

$$E_{c(P7)} = 52,45 + 25.a_p - 4,54.f - 2,09.\gamma_0 - 0,22.k \\ - 2,16.a_p.f - 1.a_p.\gamma_0 - 0,1.a_p.k + 0,18.f.\gamma_0 + 0,1.v.k \quad (1)$$

For machining of high-alloyed steels (P11) the cutting energy prediction model has the following form:

$$E_{c(P11)} = 61{,}7 + 29{,}41.a_p - 5{,}33.f - 2{,}46.\gamma_0 - 0{,}26.k - 2{,}54.a_p.f - 1{,}18.a_p.\gamma_0 - 0{,}13.a_p.k + 0{,}21.f.\gamma_0 + 0{,}11.v.k \quad (2)$$

Estimated models' coefficients correspond to the coded values of cutting parameters.

The prediction of cutting energy for cutting regime (A=-1, B= +1, C= +1, D= +1, E= +1) in longitudinal turning of low-alloyed steels (P7) is E_{cpred}=24.14 kJ and is very close to the result of machining calculator (E_c=23.98 kJ). The prediction of cutting energy for cutting regime (A=-1, B= +1, C= +1, D= +1, E= +1) in longitudinal turning of high-alloyed steels (P11) is E_{cpred}=28.41 kJ and is very close to the result of machining calculator (E_c=28.18 kJ).

4. CONCLUSION

The present study focused on the analysis of main and 2-factorial interaction effects on the resulting cutting energy in dry longitudinal single-pass turning of low-alloyed (P7) and high-alloyed steels (P11). By considering the tool geometry and main cutting parameters, 2^{5-1} fractional factorial design was developed, and by using machining calculator and well-known analytical formulas, cutting energy for different cutting regimes and tool geometries was estimated. Based on conducted analyses, the following conclusions may be drawn for both workpiece material groups:

- The most important factor regarding cutting energy is the depth of cut, followed by feed rate. The main effects of rake angle, and particularly cutting edge angle, are less pronounced.
- The cutting speed is found be statistically insignificant regarding cutting energy, which may be explained by previous analysis, as well as by the fact that the cutting speed had narrow range, so that both material groups could be covered with recommended cutting regimes.
- There are some statistically significant 2-way interactions, particularly related to the depth of cut.However, none of them show qualitative change in factor effects. In other words, in all 2-way interactions, none of considered factors fundamentally change its effect.
- If process engineers consider equal various regimes, which are being arbitrarily chosen within covered parameter hyper-space, there may exists difference in resulting cutting energy of approximately 370%.
- Due to better mechanical properties, such as tensile strength and hardness, turning of high-alloyed steels (P11) requires approximately 17% higher cutting energy in comparison to machining of low-alloyed steels (P7) under the same cutting regimes.
- The conducted analysis is restricted to single-pass turning. For a given case study more comprehensive consideration is needed to examine the required quality characteristics, process variation, chip control and breaking, cutting time and number of passes, as well as tool life. The applied approach represents adequate preparation for practical experimental investigation and process planning and offers cost effective way to gain knowledge and perform engineering analysis.

In order to verify the observed effects and constancy of influence, for both main and interaction effects, performing of a high-resolution experiment will be in focus for the future research. Also, the analysis of multiple performance characteristics will be considered.

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REFERENCES

[1] Trifunović M., Madić M., Radovanović M. Pareto optimization of multi-pass turning of grey cast iron with practical constraints using a deterministic approach. The International Journal of Advanced Manufacturing Technology 110(7-8) (2020) 1893-1909

[2] Chung C., Wang P.C., Chinomona B. Optimization of turning parameters based on tool wear and machining cost for various parts. The International Journal of Advanced Manufacturing Technology 120(7-8) (2022) 5163-5174

[3] Chowdary B.V., Jahoor R., Ali F., Gokool T. Optimisation of Surface Roughness when CNC Turning of Al-6061: Application of Taguchi Design of Experiments and Genetic Algorithm. Journal of Mechanical Engineering 16(2) (2019) 77-91

[4] Trung D.D., Nguyen N.T., Duc D.V. Study on multi-objective optimization of the turning process of EN 10503 steel by combination of Taguchi method and MOORA technique. EUREKA: Physics and Engineering 2(2021) 52-65

[5] Jadeja N.N., Zala S.H. Optimization of surface roughness in turning martensitic steel by using Taguchi method. International Journal of Mechanical Engineering 7(1) (2022) 118-123

[6] Suresh A., Diwakar G. Optimization of Machining Process Parameters in Turning and Drilling by using Design of Experiments with Aluminum 6061-O Alloy and Austenitic Stainless Steel. International Journal of Innovative Technology and Exploring Engineering 8(11) (2019) 625-633

[7] Abas M., Sayd L., Akhtar R., Khalid Q.S., Khan A.M., Pruncu C.I. Optimization of machining parameters of aluminum alloy 6026-T9 under MQL-assisted turning process. Journal of Materials Research and Technology 9(5) (2020) 10916-10940

[8] Warsi S.S., Jaffery S.H.I., Ahmad R., Khan M., Ali L., Agha M.H., Akram S. Development of energy consumption map for orthogonal machining of Al 6061-T6 alloy. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 232(14) (2018) 2510-2522

[9] Nur R., Yusof N.M., Sudin I., Nor F.M., Kurniawan D. Determination of Energy Consumption during Turning of Hardened Stainless Steel Using Resultant Cutting Force. Metals 11(4) (2021) 565

[10] He Y., Tian X., Li Y., Wang S., Sutherland J.W. Modeling machining energy consumption including the effect of toolpath. Procedia CIRP 90 (2020) 573-578

[11] Gu W., Li Z., Chen Z., Li Y. An energy-consumption model for establishing an integrated energy-consumption process in a machining system. Mathematical and Computer Modelling of Dynamical Systems 26(6) (2020) 534-561

[12] Guo Y., Loenders J., Duflou J., Lauwers B. Optimization of energy consumption and surface quality in finish turning. Procedia CIRP 1 (2012) 512-517

[13] Kara S., Li W. Unit process energy consumption models for material removal processes. CIRP Annals - Manufacturing Technology 60(1) (2011) 37-40

[14] Pawanr S., Garg G.K., Routroy S. Modelling of Variable Energy Consumption for CNC Machine Tools. Procedia CIRP 98 (2021) 247-251

[15] Shin S.J., Woo J., Rachuri S., Meilanitasari P. Standard Data-Based Predictive Modeling for Power Consumption in Turning Machining. Sustainability 10(3) (2018) 598

[16] Jiang Z., Gao D., Lu Y., Kong L., Shang Z. Electrical energy consumption of CNC machine tools based on empirical

modeling. The International Journal of Advanced Manufacturing Technology 100(9-12) (2019) 2255-2267

[17] Duflou J.R., Sutherland J.W., Dornfeld D., Herrmann C., Jeswiet J., Kara S., Hauschild M., Kellens K., Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals - Manufacturing Technology 61(2) (2012) 587-609

[18] Dahmus J.B., Gutowski T.G. An environmental analysis of machining. In: Proceedings of the ASME 2004 International Mechanical Engineering Congress and Exposition, (2004) pp. 643-652

[19] Rajemi M.F., Mativenga P.T. Machinability analysis from energy footprint considerations. Journal of Machine Engineering 8(2) (2008) 106-113

[20] Gutowski T., Dahmus J., Thiriez A. Electrical Energy Requirements for Manufacturing Processes. In: Proceedings of the 13th CIRP International Conference on Life Cycle Engineering (2006) pp. 623-628.

[21] Rajemi M.F., Mativenga P.T., Jaffery S.I. Energy and carbon footprint analysis for machining titanium Ti-6Al-4V alloy. Journal of Machine Engineering 9(1) (2009) 103-112

[22] Walter Machining Calculator (2022) https://mac.walter-tools.com/

[23] Lenth R.V. Quick and Easy Analysis of Unreplicated Factorials. Technometrics 31(4) (1989) 469-473

[24] Radovanović M., Madić M. Design and Analysis of Experiments. Niš: University of Niš, Faculty of Mechanical Engineering in Niš (2019)

[25] Montgomery, D.C. Design and Analysis of Experiments, 9th Edition. New York: John Wiley & Sons (2017)

[26] Vedashree K.N., Shailesh Rao. A Study on the Effect of Rake Angle and depth of cut on Cutting Forces during Orthogonal Cutting. International Journal of Innovative Research in Science, Engineering and Technology 9(5) (2020) 3175-3179

[27] Kalpakjian S., Schmid S.R. Manufacturing Engineering and Technology, 5th Edition. Upper Saddle River: Pearson Education (2006)

[28] Nijin J.R., Jagadesh T. Numerical simulation of the influence of tool geometry on energy consumption during micro turning of titanium alloy. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 236(4) (2022) 1411-1420

[29] Parle D., Singh R.K., Joshi S.S. Modeling of Specific Cutting Energy in Micro-Cutting using SPH Simulation. In: Proceedings of the 9th International Workshop on Microfactories (2014) pp. 121-126.

[30] Mitsubishi Materials – Technical Information / Cutting Formula (2022) https://www.mitsubishicarbide.com/en/technical_information/tec_turning_tools/tec_hsk-t/tec_hsk-t_technical/tec_turning_cutting_edge