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Influence of the cutting force upon machining process efficiency

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ABSTRACT

The present paper has as main objective to highlight the influence of the cutting force, which is directly connected to the energy consumption, upon machining process efficiency. In this respect, it is developed an experimental research performed by the means of a turning process, using different cutting parameters. An experimental frame composed from: a longitudinal lathe, carbide cutting tools, steel pieces and the device for measuring the cutting force, which is a dynamometer was designed to measure the cutting forces during the turning process. The data collected were analyzed by the means of a statistical software package, in order to study the influence of the cutting force upon the energy consumption. The results indicated the conditions for reducing the energy consumption, without affecting the product quality nor the process productivity. In order to reduce the energy consumption and the energy costs the cutting force must be reduced. A solution is to reduce the depth of cut and to increase the feed rate, without negatively affecting the cutting process productivity. Another important aspect to be considered in energy consumption reduction is to reduce the cutting speed and to proportionally increase the depth of cut and the feed rate, in order to maintain the cutting process productivity.

Selection and peer-review under responsibility of the scientific committee of the 12th International Conference on Materials Science & Engineering, BraMat 2022.

1. Introduction

A very important goal of manufacturing industry is to save energy and the cutting processed in mechanical manufacture are known for the high energy consumption. Industrial companies from all over the world are aiming at economic efficiency of their manufacturing processes. The manufacturers will save money and increase the sustainability if the power demands are minimized.

The issue of energy consumption reduction has retained the attention of the researchers from all over the world. The study of connection between the cutting parameters and energy is an important issue in order to optimize the energy and power consumption in machining processes.

Literature presents a series of works that approach this problem.

According to Pusavec [1] it is estimated that two-thirds of the electrical power used by the machining process is utilized to operate motors and drives for cutting tools.

Increasing the energy efficiency of the production process implies good information on power demand as a means of the machining and cutting process itself [2].

Nur et al. [3] include in their paper that optimizing cutting conditions on sustainable machining of aluminum alloy minimizes power consumption. An experimental study of sustainable machining of Al-11 %Si base alloy was made, to assess the capacity in reducing power consumption and the results highlighted that the cutting speed has an effect on machining performance. The result showed that the minimum power consumption would be obtained by the lower level of cutting parameter [3]. The state parameters of a cutting process, under the precondition of satisfying the constraints set by controlling parameters always minimize cutting power consumption [4]. Proper selection of cutting parameters with energy consideration can effectively reduce energy consumption and improve energy efficiency of the machining process [5].

An estimation of the cutting parameters in turning of PEEK-CF30 using TiN tools, in order to attain minimum power consumption and the best surface quality was made by Hanafi et al. [6].

Bhushan et al. [7] aimed to optimize the cutting parameters by using Response Surface Methodology (RSM) and to realize a desirability analysis in order to obtain optimum values of cutting

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Nomenclature

Fc	cutting force [N]	Es	specific energy [J/mm^3]
f	feed rate [mm/rev]	Z	volume of material removal [mm^3]
d	depth of cut [mm]	p	significance level
s	cutting speed [m/min]	Cen	energy cost [Euro]
E	energy [J]		
P	power [kW]		

parameters that minimize power consumption and maximize tool life.

The cutting force is one of the most important variable in a machining process, because it affects the machining quality and determine machine power requirements and supply energy to the machining system which may result in excessive cutting temperatures or unstable vibrations [8]. Measuring cutting forces can give information on the material machinability, as well as optimal process parameters [9].

Bi and Wang [10] investigated analytical energy modelling for the explicit relations of machining parameters and energy consumption. It presents a modelling method based on the kinematic and dynamic behaviour of certain chosen machine tools. The results obtained indicate a 67 % energy savings for drilling processes.

An empirical model based on power measurement under various cutting conditions is presented by Li and Kara [11].

Zhong et al. [12] presents various experimental or empirical energy consumption models of spindle acceleration, spindle rotation, feed and material removal, using five evaluation criteria: applicability, accuracy, computational efforts, complexity of fitting coefficient and ease of data collection.

The cutting parameters optimization for minimization of energy consumption in turning process was approached by Velchev et al. [13]. The paper presents the results of experimental research highlighting the correlations among certain parameters (cutting parameters, cutting force, material removal rate, energy, power and specific energy) that strongly influence the energy consumption. The purpose was to identify major directions for energy savings, in order to make machining processes more efficient.

Sagar found that the feed rate was the most influencing parameter in the cutting force. Optimal values for cutting speed and feed rate were found, useful in the optimization of machining processes [14].

The aim of the present paper is to highlight the influence of the cutting force, which is directly connected to the energy consumption, upon machining process efficiency. The scope of the research is to obtain conditions for reducing the energy consumption, without affecting the product quality nor the process productivity. The method used proposed machining of a piece part with different cutting parameter and recording the developed forces. Some mathematical expressions can be developed for describing the correlation between the cutting parameters and the energy consumption. The limitation of the research is that the obtained results are valid for a normal universal lathe and for the considered material, which is C45 steel. Another important limitation is related to the vibrations that inevitably appear during cutting process.

2. Experimental setup

The technological system used for this research contains the following elements: a universal lathe (SN 320 Arad), carbide cutting tools, steel pieces and the device for measuring the cutting force, which is a dynamometer with an elastic element (produced in the department of Industrial Management and Engineering from Transilvania University of Brasov). As seen in Fig. 1, the experimental setup consists of a work piece fixed on the turning machine, cutting tool, dynamometer and comparator watch. The used cutting tool is a carbide cutting insert P type, with front clearance angle of 5○, the back rake angle was 6○ and the side cutting edge angle of 45○ (produced by Mitsubishi).

The processed workpiece is C45 steel, which has the following chemical composition, in accordance to [15]: C = 0.45 %, Si = 0.22 %, Mn = 0.56 %, P = 0.025 %, S = 0.034. The tensile strength of C45 (1.0503) steel is 660 MPa and the hardness is 224 HB.

The experimental study was performed as follows: The work piece was fixed in the chuck of the lathe and was subjected to some processing, with different working regime: depth of cut, feed rate and speed, without cooling liquid. During machining, the main component of the cutting force, developed in the cutting direction (Fc) was measured, using the dynamometer. The values of the cutting parameters considered for the developed experimental study are presented in Table 1.

3. Results and discussion

First of all, using the mathematic apparatus presented in section 3.1, the indicators of energy consumption were calculated based on cutting parameters. The evolution between those indicators and cutting parameters has been evaluated by the means of regression analysis.

3.1. Used mathematical apparatus

According to [16] the amount of energy used in machining (E), depends on the cutting force component (Fc) and the cutting speed (s) of the machining operation, as seen in equation (1).

$$E = F_c \cdot s \tag{1}$$

The specific cutting energy depends on the energy used (E) and the volume of material removal (Z). Z is calculated based on feed rate (f), depth of cut (d) and cutting speed (s).

$$E_s = E/Z \tag{2}$$

$$Z = f \cdot d \cdot s \tag{3}$$

Also, the machine power was calculated, as shown in relation (4):

$$P = E/t \tag{4}$$

The energy costs is based on relation (5):

$$Cen = P \cdot t \cdot Kcoefficient \cdot costkW \tag{5}$$

The chosen value for the K coefficient is 0.7 as recommended in the specialty literature, for the considered parameters. The kwH price is 0.20 Euro/kW.

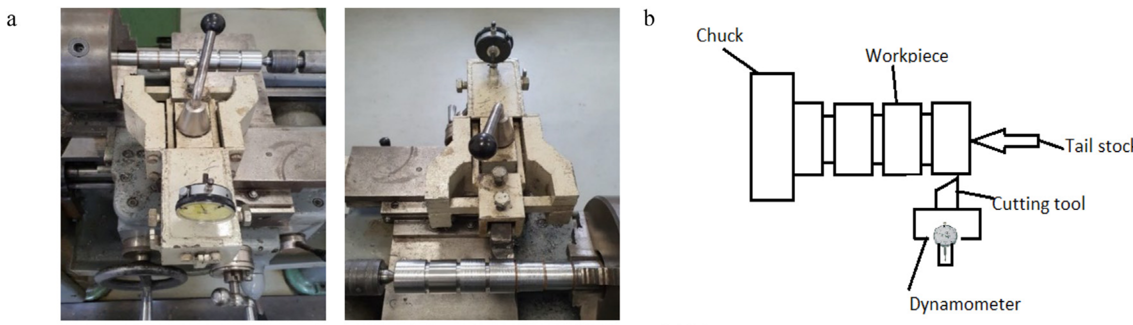

Fig. 1. Experimental setup (a) Picture; (b) Diagram.

Fig. 1. Experimental setup (a) Picture; (b) Diagram.

Table 1
Cutting parameters.

Spindle rotation (rev/min)	Feed rate (mm/rev)	Depth of cut (mm)	Spindle rotation (rev/min)	Feed rate (mm/rev)	Depth of cut (mm)	Spindle rotation (rev/min)	Feed rate (mm/rev)	Depth of cut (mm)
1000	0.24	0.25	630	0.24	0.25	250	0.24	0.25
1000	0.24	0.25	630	0.24	0.5	250	0.24	0.5
1000	0.24	0.5	630	0.24	0.75	250	0.24	0.75
1000	0.24	0.75	630	0.24	1	250	0.24	1
1000	0.24	0.25	630	0.24	0.25	250	0.24	0.25
1000	0.32	0.25	630	0.32	0.25	250	0.32	0.25
1000	0.56	0.25	630	0.56	0.25	250	0.56	0.25
1000	0.72	0.25	630	0.72	0.25	250	0.72	0.25

3.2. Effect of the feed rate (f), depth of cut (d) and cutting speed (s) on Fc (cutting force), E(energy), Es (specific energy)

Fig. 2 presents the evolution of the cutting force on the feed rate variation. The cutting force, developed during the turning process is increasing, validating the statement that feed rate variation influences cutting force variation.

As seen in Fig. 3, the evolution of the energy used in machining is ascending and much increased at spindle rotation of 1000 [rev/min].

Fig. 4 presents the evolution of specific energy while the feed rate varies. It can be observed that, while the feed rate is ascending, the specific energy decreases.

The increasing evolution of the cutting force versus depth of cut variation can be seen in Fig. 5.

In comparison with the evolution of the cutting force versus the feed rate, from Fig. 2, as it can be seen from Fig. 5, the evolution of the cutting force in respect with the depth of cut is more evident than the evolution of the cutting force in respect with the feed rate. That means that the influence of the depth of cut upon the cutting force is greater than the influence of the feed rate.

Fig. 6 presents the evolution of the used energy upon depth of cut.

The evolution of the specific energy can be seen in Fig. 7.

Even if the cutting speed does not explicitly appear in the cutting force equation, as literature presents [17] the experimental research has highlighted that this parameter, influences the cutting force, energy and power because there is a direct connection between the cutting speed and the spindle rotation. In Fig. 2, as the feed rate increases, the cutting force increases too, and is the highest when talking about the highest spindle rotation. Energy has the same evolution, as Fig. 3 presents. Fig. 4 shows that the highest specific energy is for the highest value of the spindle rotation but is has a descending evolution. In respect with the influence of the depth of cut upon the cutting force and energy, the depth of cut has a different influence when talking about different values of the spindle rotation. As it can be seen from Fig. 5, the cutting force starts to decrease at higher values of the spindle rotation. At the highest value of the spindle rotation, the energy evolution is almost linear and tempered in respect with the depth of cut (Fig. 6). The specific energy is less in case of high spindle rotation (Fig. 7).

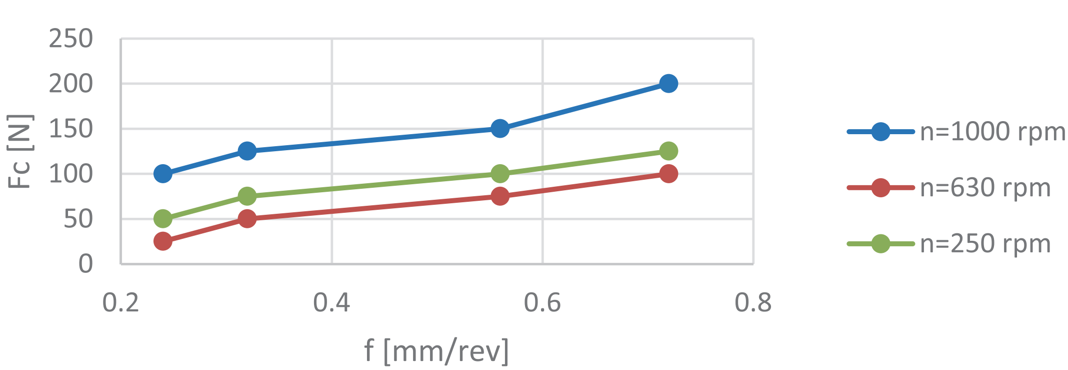

Fig. 2. Fc evolution versus feed rate.

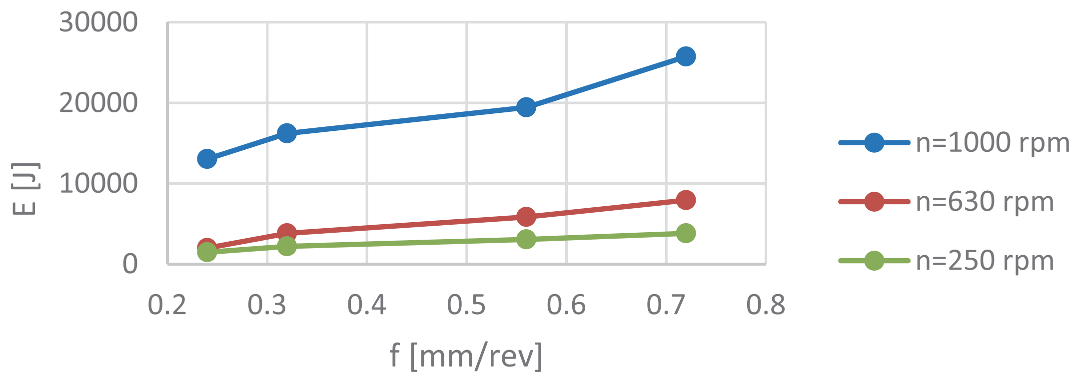

Fig. 3. E evolution versus feed rate.

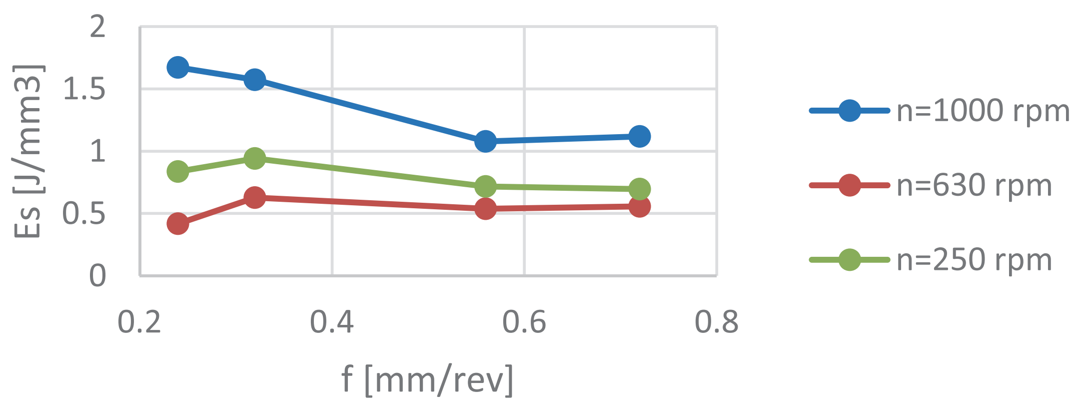

Fig. 4. Es evolution versus feed rate.

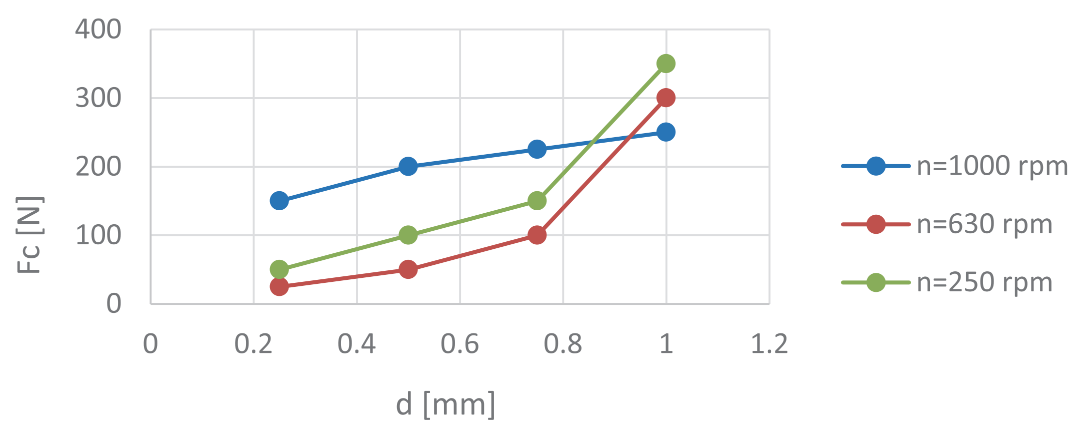

Fig. 5. Fc evolution versus depth of cut.

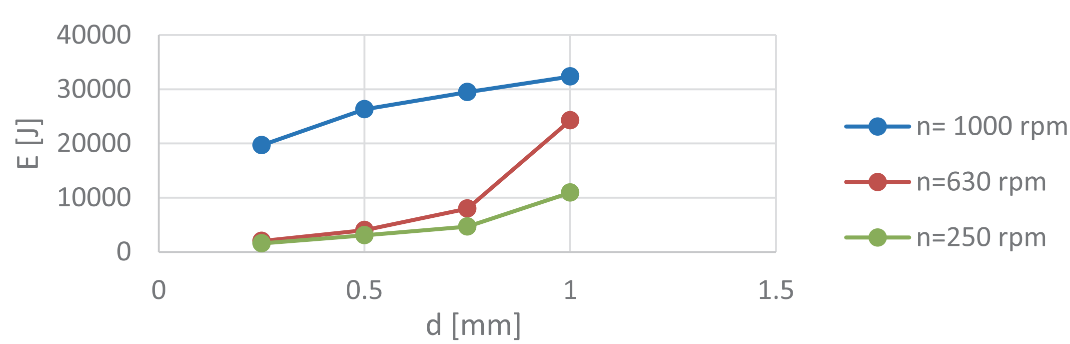

Fig. 6. E evolution versus depth of cut.

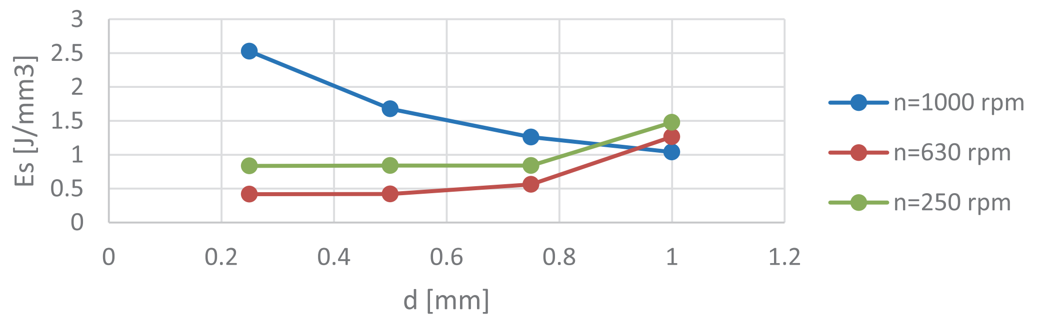

Fig. 7. Es evolution versus depth of cut.

3.3. Comparison among E, Fc, Es, Cen for different cutting parameters

Figs. 8, 9, 10 and 11 present an overview upon the evolution of the parameters: E, Fc, Es and Cen in respect with different values of cutting parameters. As it can be seen, higher the rotational speed, higher the energy, cutting force, and energy costs. Another important observation is that the depth of cut has a greater influence upon all these indicators than the feed rate.

3.4. Statistical analysis

The data analysis was performed using IBM SPSS® Statistics Version 20 software. The purpose of this analysis is to find certain correlations among the parameters and indicators analysed in the previous sections that are significant from statistical point of view. Another purpose of this statistical analysis is to find certain functions that correlate the parameters Fc, E and P with the cutting parameters in case of machining the same part. In this respect, regression analysis was performed. The significance level was considered for p = 0.05.

In Table 2 it is presented the correlation between the cutting force and the cutting speed. A value of 0.254 for Pearson correlation is obtained for correlation between Fc and s, as it can be seen from Table 2. A correlational value above 0.9 is considered to be very strong, values between 0.7 and 0.89 are considered strong, values between 0.4 and 0.69 are considered moderate, values between 0.1 and 0.39 are considered weak and any value<01 is considered to be negligible [18].

Table 3 presents the correlation between energy used (E), power (P) and specific energy (Es) and the cutting parameters (s, f, d). It can be seen that there is a strong correlation between E and s (Pearson correlation = 0.783, p < 0.01), P and s (Pearson correlation = 0.720, p < 0.01), a moderate correlation between E and d (Pearson correlation = 0.449, p < 0.05), Es and s (Pearson correlation = 0.5, p < 0.05). A weak correlation can be observed between E and f (Pearson correlation = -0.023, p > 0.05), P and f (Pearson correlation = 0.392, p > 0.05), P and d (Pearson correlation = 0.013, p > 0.05), Es and f (Pearson correlation =-0.238, p > 0.05), Es and d (Pearson correlation = 0.127, p > 0.05).

Some regressions have been found between Fc, E and P and the cutting parameters.

Table 4 presents the model summary for the dependence between Fc and the cutting parameters (f, d, s). The coefficients of the regression are presented in Table 5.

Linear regression that best fits to the measured values, as developed by the specific software, is presented in relation (6). The correlation coefficient (R) is 0.852 and the coefficient of determination (R square) is 0.726, values which validate the function.

A function more accurately describes a real situation as the value of the correlation coefficient R is closer to 1. For values of R>0.8 it is considered that the obtained function describes with precision the studied phenomenon. The coefficient of determination (R square) interprets as a percentage how representative the regression line is for the investigated data.

$$Fc = -92.059 + 169.202 * f + 278,698 * d + 0.514 * s \qquad (6)$$

The coefficients of the regression are presented in Table 5.

Table 6 presents the model summary for the dependence between E and the cutting parameters (f, d, s) and Table 7 presents the coefficients of the regression. Linear regression that best fits to

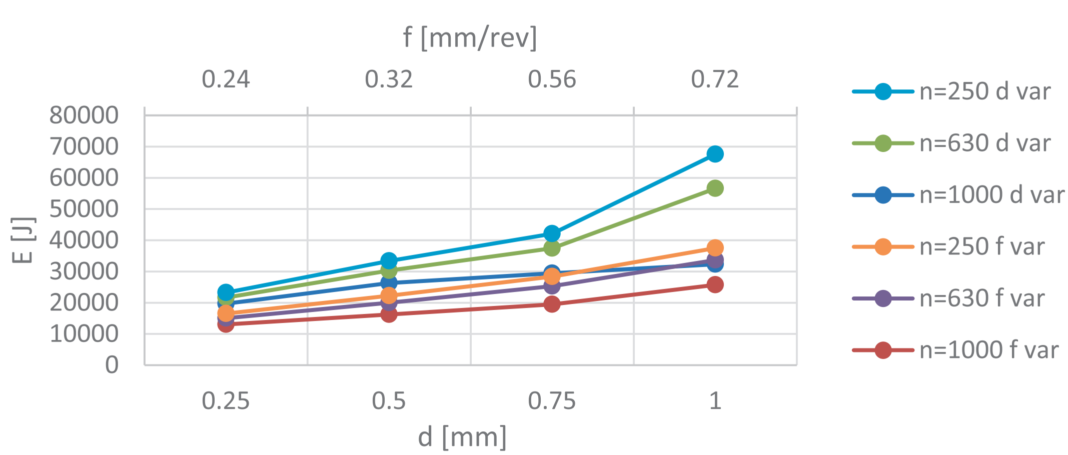

Fig 8. E evolution versus cutting parameters.

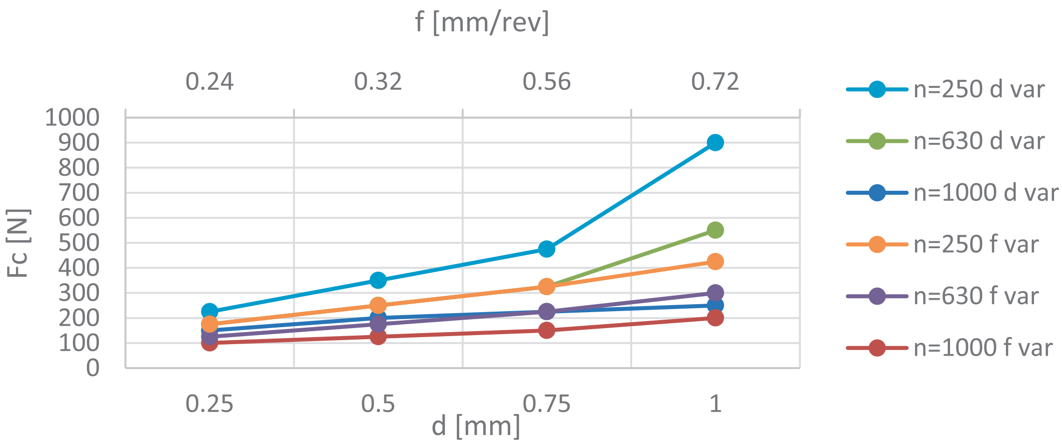

Fig. 9. Fc evolution for different cutting parameters.

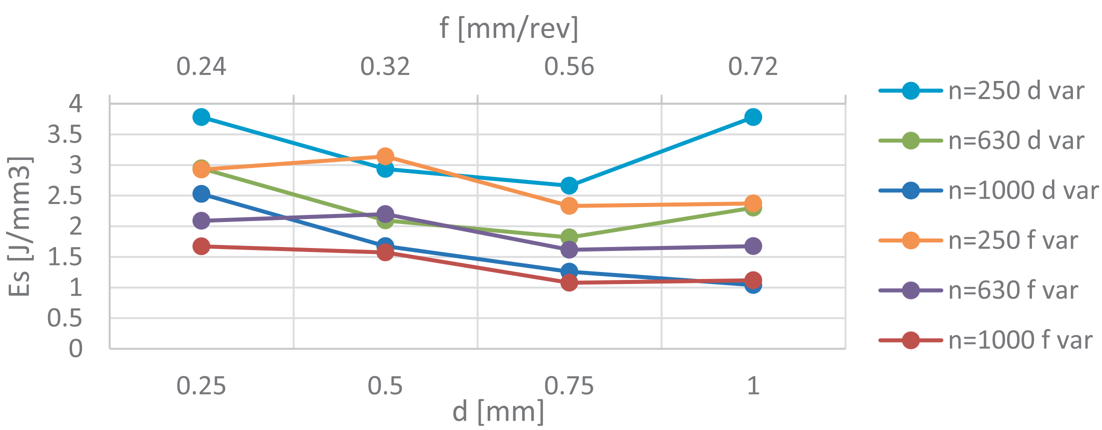

Fig. 10. Es evolution for different cutting parameters.

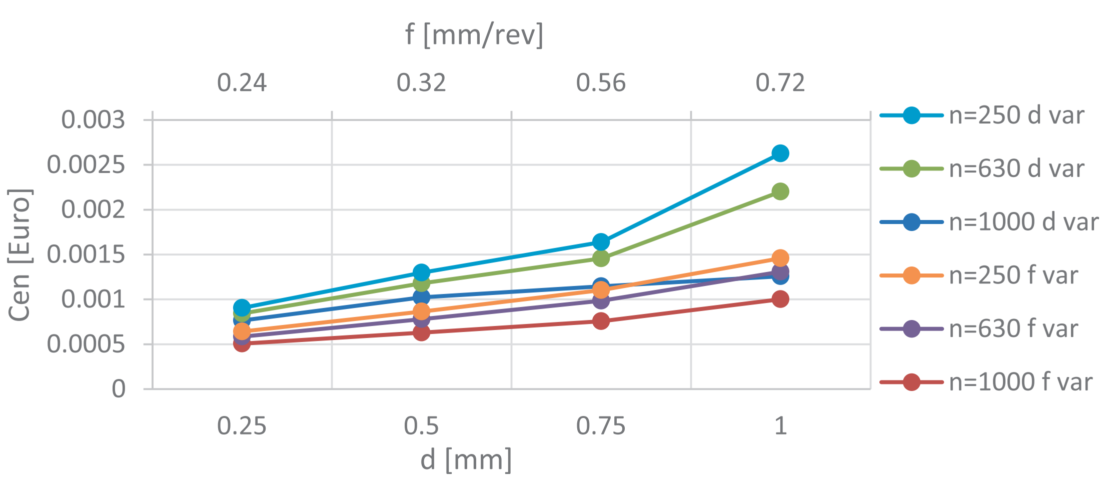

Fig. 11. Cen evolution for different cutting parameters.

Table 2
Fc- s correlations.

		Fc (N)	s (m/min)
Fc (N)	Pearson Correlation	1	0.254
	Sig. (2-tailed)		0.231
	N	24	24

the measured values, as developed by SPSS software, is presented in relation (7). The correlation coefficient (R) is 0.920 and the coefficient of determination (R square) is 0.847, values which validate the function.

$$E = -16934.463 + 12470.834 * f + 19609.364 * d + 190.969 * s \quad (7)$$

Table 3
Correlations between Energy used, Power and Specific energy and cutting parameters (E, P, Es s, f, d)).

		s (m/min)	f (mm/rev)	d (mm)
Energy used (J)	Pearson Correlation	0.783[**]	−0.023	0.449[*]
	p	<0.01	0.916	0.028
	N	24	24	24
Power (kW)	Pearson Correlation	0.720[**]	0.392	0.013
	p	<0.01	0.058	0.953
	N	24	24	24
Specific energy (J/mm3)	Pearson Correlation	0.500[*]	−0.238	0.127
	p	0.013	0.263	0.555
	N	24	24	24

[**] Correlation is significant at the 0.01 level (2-tailed).
[*] Correlation is significant at the 0.05 level (2-tailed).

Table 4
Model Summary for the dependence between Fc and the cutting parameters.

Model	R	R Square	Adjusted R Square
1	0.852[a]	0.726	0.685

[a] Predictors: (Constant), s (m/min), f (mm/rev), d (mm).

Table 5
Coefficients.[a]

Model	Unstandardized Coefficients		t	p
	B	Std. Error		
(Constant)	−92.059	39.984	−2.302	0.032
f (mm/rev)	169.202	62.797	2.694	0.014
d (mm)	278.698	40.124	6.946	<0.01
s (m/min)	0.514	0.242	2.124	0.046

[a] Dependent Variable: Fc (N).

Table 6
Model Summary for the dependence between E and the cutting parameters.

Model	R	R Square	Adjusted R Square
1	0.920[a]	0.847	0.824

[a] Predictors: (Constant), s (m/min), f (mm/rev), d (mm).

Table 7
Coefficients.[a]

Model	Unstandardized Coefficients		t	p
	B	Std. Error		
(Constant)	−16934.463	3545.562	−4.776	<0.01
f (mm/rev)	12470.834	5568.493	2.240	0.037
d (mm)	19609.364	3557.988	5.511	<0.01
s (m/min)	190.969	21.453	8.902	<0.01

[a] Dependent Variable: Energy used (J).

Table 8 presents the model summary for the dependence between P and the cutting parameters (f, d, s) and Table 9 presents the coefficients of regression. Relation (8) presents the linear regression which express the evolution of the machine power (P) related to the cutting parameters. The function is validated by the correlation coefficient (R) which has the value 0.847 and by the coefficient of determination (R square) which has the value 0.717.

$$P = -2.893 + 4.090 * f + 1.165 * d + 0.026 * s \quad (8)$$

Table 8
Model Summary for the dependence between P and the cutting parameters.

Model	R	R Square	Adjusted R Square
1	0.847[a]	0.717	0.674

[a] Predictors: (Constant), s (m/min), f (mm/rev), d (mm).

Table 9
Coefficients.[a]

Model	Unstandardized Coefficients		t	p
	B	Std. Error		
(Constant)	−2.893	0.696	−4.156	<0.01
f (mm/rev)	4.090	1.093	3.741	0.001
d (mm)	1.165	0.698	1.668	0.111
s (m/min)	0.026	0.004	6.070	<0.01

The regression found can be used for identifying the solution for reduction the energy consumption.
[a] Dependent Variable: Power (kW).

In order to identify certain solutions for reduction of the energy consumption, the following conclusions are presented below.

As known, the trend of the industrial companies is to use high values of the rotational speed and implicitly for the cutting speed. Related to the performed research, the field of using high cutting speeds must be optimized. In order to reduce the energy consumption and of course the energy costs the cutting force must be reduced. A solution in this way is to reduce the depth of cut and to increase the feed rate, without negatively affecting the cutting process productivity.

Another important aspect to be considered in energy consumption reduction is to reduce the cutting speed and to proportionally increase the depth of cut and the feed rate, in order to maintain the cutting process productivity.

Even if the surface quality of the work piece, expressed by the roughness, was not considered by the study developed by the present paper, it is a very important parameter. It must be considered because the cutting parameters, especially the feed rate and the cutting speed have a significant influence upon it. The roughness of the work piece is better at increased cutting speeds, but tends to decrease at higher feeds and larger depth of cut.

Beside energy consumption optimization, as the energy costs are increasing, as a global trend, industrial companies should also consider other forms of energy, including the use of green energy and also high performance machine-tools that allow an energy consumption reduction.

4. Conclusions

As known, cutting processes are energy consumers and one of the modalities of increasing the machining process efficiency is energy consumption optimization. The cutting forces are one of the inherent phenomena of the cutting process.

The present paper presents the influence of the cutting force, which is directly connected to the energy consumption, upon machining process efficiency. In this respect, an experimental research was performed by the means of a turning process, using different cutting parameters. The data collected from the measures are then processed and analyzed by the means of a statistical software package, in order to study the influence of the cutting force upon the energy consumption.

The experimental research revealed the following conclusions: energy increases as the feed rate and cutting force increase and is the highest when the spindle rotation has the maximum value; the specific energy has a decreasing evolution in respect with the spindle rotation.

Higher the rotational speed, higher the energy, cutting force, and energy costs. Another important observation is that the depth of cut has a greater influence upon all these indicators than the feed rate.

The obtained results indicate the conditions for reducing the energy consumption, without affecting the product quality nor the process productivity.

A solution is to reduce the cutting force, by reducing the depth of cut and increasing the feed rate. Another solution has the purpose to reduce the cutting speed and to proportionally increase the depth of cut and the feed rate.

As a main conclusion, the machining conditions should aim for optimization and not maximization, in order to reduce the energy consumption and the related costs and to provide high performance and machining economic efficiency.

In further studies, the authors intend to develop a mathematical model for optimizing the cutting parameters for reducing the energy consumption and the energy costs, as well.

CRediT authorship contribution statement

Petre Ioana: Conceptualization, Data curation, Methodology, Investigation, Software, Writing – original draft, Writing – review & editing, Supervision. **Găvruş Cristina:** Data curation, Investigation, Writing – review & editing, Software, Validation, Visualization.

Data availability

Data will be made available on request.

Declaration of Competing Interest

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.

References

[1] F. Pusavec, D. Kramar, P. Krajnik, J. Kopac, J. Cleaner Prod. 18 (12) (2010) 1211–1221.
[2] W. Li, A. Zein, S. Kara, C. Herrmann, Glocalized Solutions for Sustainability in Manufacturing, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, 2011, pp. 268–273.
[3] R. Nur, M.A. Suyuti, T.A. Susanto, AIP Conf. Proc. (2017) 1855.
[4] H. Shi, Metal cutting theory, Springer Series, Adv. Manuf. (2018).
[5] X. Chen, C.B. Li, Y. Tang, L. Li, H. Li, Front. Mech. Eng. 16 (2021) 221–248.
[6] I. Hanafi, A. Khamlichi, F.M. Cabrera, E. Almansa, A. Jabbouri, J Clean. Prod. (2012) 28.
[7] R. Bhushan, S. Kumar, S. Das, Int. J. Adv. Manuf. Technol. 50 (5–8) (2010) 459–469.
[8] D.A. Stephenson, J.S. Agapiou, Metal cutting theory and practice, CRC Press, 2019.
[9] K. Venkatesan, K. Manivannan, S. Devendiran, A.T. Mathew, N.M. Ghazaly, S.M. N. Aadhavan, Proc. Manuf. 30 (2019) 611–618.
[10] Z.M. Bi, L. Wang, J. Manuf. Syst. 31 (4) (2012) 420–428.
[11] W. Li, S. Kara, Proceedings of the Institution of Mechanical Engineers, Part B: J of Engineering Manuf 225 (9) (2011) 1636–1646.
[12] Q. Zhong, R. Tang, J. Lv, S. Jia, M. Jin, Int. J. Adv. Manuf. Technol. 82 (2016) 2087–2099.
[13] S. Velchev, I. Kolev, K. Ivanov, S. Gechevski, J. Clean. Prod. 80 (2014) 139–149.
[14] C.K. Sagar, T. Kumar, A. Priyadarshini, A.K. Gupta, Def. Technol. (2019).
[15] European Steel and Alloy Grades/Numbers. Available online: http://www.steelnumber.com/en/steel_composition_eu.php?name_id=152 (accessed on 1 February 2022).
[16] G. Boothroyd, W.A. Knight, Fundamentals Of Machining And Machine Tools, 3rd ed., CRC Press, 2005.
[17] S. Kalpakjian, S.R. Schmid, Manufacturing Engineering and Technology, 8th ed.,., Pearson, 2020.
[18] P. Schober, C. Boer, L.A. Schwarte, Anesth. Analg. 126 (5) (2018) 1763–1768.