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RESEARCH ON THE DETERMINATION OF THE ENERGY CHARACTERISTICS OF A MILLING MACHINE

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Abstract: *The most important criteria on the basis of which the optimal cutting regimes are determined are the criterion of maximum productivity and the criterion of minimum processing cost. When determining the cutting regimes based on these criteria, the problem in the efficiency with which the machine-tool works and the consumption of energy for cutting is not often raised. The lack of knowledge of the connection between the working parameters of the machine-tool and its efficiency, as well as the effects of the operation of the machine-tools at the highest possible efficiency on the specific consumption of electrical energy and the productivity of cutting constitute an explanation of how to approach this problem. In this paper, the energy characteristics of a milling machine are determined, optimized by creating a loading device for the main shaft and analyzed by different types of regression.*

Key words: *Machining, Regression, optimization, mathematical model, energy*

1. INTRODUCTION

The efficiency of a machine tool provides some insight into how available power is utilized for cutting. The particular electrical energy consumption is a more comprehensive measure that accounts for both the productivity of the cutting and the machine tool's efficiency. The greater the cutting productivity, the lower the specific electricity consumption will be for the same power supplied at the main shaft. Various productivities can be achieved based on how the cutting regime's parameters are combined. The link between yield, cutting productivity, and specific consumption demonstrates that when cutting productivity rises, machine tool yield rises as well while particular electrical energy consumption falls.

The primary feature of a processing system is the yield, which varies depending on a number of variables including work speed, frictional losses, the quality of surfaces moving relative to one another, and the degree of lubrication of moving parts. The information available in the specialized literature on the efficiency of a machine tool and its particular electrical energy consumption is too low to enable the development of programs for processing condition optimization. There are machine tools with high installed power that have light regimes, low cutting productivity, high specific electrical energy consumption, and very low efficiency levels. A technical system can request to use either a braking force or a cutting force to do energy testing. It is not possible to directly determine the braking force in the processing area when using equipment that produces braking force or moment via friction or electricity.

The objective of this study [1] is to define the optimal cutting regime and the mathematical models for the machining of AISI4140. The task involves assessing the effects of five cutting parameters on radial force (F_r) and surface roughness (R_a) in dry hard turning 42CrMo4 steel with mixed ceramic tool (CC650). These parameters include major cutting edge angle (χ_r), cutting speed (V_c), feed rate (f), depth of cut (a_p), and tool nose radius (r).

Even though research has been done on predicting the energy consumption of machine tools, a practical solution has not yet been found. Consequently, a new method for estimating the energy consumption of a machine tool's main driving system during a machining process is proposed [2]. By measuring the energy consumption data of the start-up and idle processes at different speeds, the functions of the

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fitted curves of the energy consumption at this periods are derived. This makes it possible to predict the energy consumption of the start-up and idle periods at any different speed.

A hybrid solution powered by Digital Twin (DT) is investigated to achieve dependable predictive maintenance of CNC machine tools. Cutting tool life prediction is the subject of a case study [3], the outcome of which demonstrates that the suggested strategy is workable and more accurate than a single approach.

The possibilities and difficulties of deep learning (DL) for tool monitoring and intelligent machining are discussed in the work [4]. An intelligent monitoring framework's constituent parts are shown. Lastly, the research gaps were defined and the data-driven issues in smart manufacturing were discussed. These challenges included those related to data size, data nature, model selection, and process uncertainty. One of the main obstacles to precise positioning during cutting operations is the correction of thermal inaccuracies in machine tools.

A novel technique for updating characteristic diagram-based compensation models is presented by Naumann et al. [5] through the combination of current models with fresh measurements. As a result, it is possible to optimize compensation for load scenarios in serial production without having to compute a new model that has been verified on a 5-axis machining center.

Variations in surface roughness, tool wear, cutting force, and other machining responses cause significant changes in productivity and dimensional accuracy. As a result, the paper [6] addresses the online trend of contemporary methods for tracking tool status during various machining operations. Dynamometers, accelerometers, acoustic emission sensors, current and power sensors, image sensors, and other sensor systems are the sensor systems used to track tool wear. These systems make it possible to address the issues of technological parameter modeling and automation for the primary cutting processes, including drilling, grinding, milling, and turning.

In order to realize the concept of Industry 4.0, Serin et al. [7] first provide an overview of tool condition monitoring, then go over the theory behind some of the most recent deep learning techniques. Lastly, they aim to find new prospects in tool condition monitoring.

In recent years, there has been a growth in the development of more precise and in-depth energy consumption models through the use of soft computing techniques. It has been noted that online machining process optimization is achieved by real-time energy data monitoring. The use of microanalysis, benchmarking, and standardization of energy evaluation indices require more investigation. Data analytics and AI applications, industry 4.0 integration, and the application of machining energy models to enhance the sustainability of machine tools are examples of new research opportunities in the field [8].

Zhou et al. [9] concluded that a more comprehensive scientific evaluation index system is required for assessing and testing the energy efficiency of machine tools. Additionally, they noted that the accuracy of existing energy consumption models could be enhanced by incorporating correlation analysis among machine tools, parts, and processing conditions.

2. MATERIALS AND METHODS

Determining some energy characteristics of technological processing systems, at idle, involves measuring the effective speed of the main shaft n, the active electrical power consumed from the network N_{mo}, the voltage U and the intensity of the supply current I. Practically, during the idle rotation movement of the main shaft of the machine tool and corresponding to each revolution n, the supply voltage U and the intensities I_1, I_2, I_3 of the currents on the three phases, as well as the active power N_{mo}, were measured. The apparent power P_a was determined by applying the definition relation: $P_a = \sqrt{3} \cdot 10^{-3} \cdot U \cdot I$ [kVA] and the power factor cos φ - according to the definition relation: $\cos \varphi = N_{mo}/Pa$.

From the analysis of the values of the energy characteristics, it can be observed that, with the increase of the main shaft speed, the quantities I, P_a, N_{mo} and $\cos\varphi$ have a decisively increasing variation. The increase in speed, from the minimum value to the maximum value, determines the increase in idle power. These jumps may be due to deficiencies in the execution or assembly of the gears that achieve the respective rotations, and the existence of zones with power consumed above normal values is due to the wear of the gears following the intensive use.

The request by axial force carries out the loading of the technological systems by applying force on the front surface of the disc type specimen, mounted in the main shaft of the machine-tool. In order to apply axial force, a stressing device (Fig. 1) was designed which mainly consists of the base plate 1, the body 2, the axial bearing 3, the elastic element 4, the fork 5, the ring 6, the disk 7 and the plates 8. Through the base plate 1, the device is mounted on the table of the milling machine, and the attachment of a conical tail to this plate makes it possible to mount the device also on a lathe (in the spindle of the movable chuck). Through the axial movement of the device, the Ferodou plates 8 come into contact with the front surface of the test piece 10. Results, due to the friction, a torsional moment that tends to rotate the subassembly formed by the disk, the bolt 9, the ring and the forks. Between the disk and the body, the axial bearing is mounted to take over the axial forces that occur during stress. The rotation of the subassembly stresses the elastic element 4, its deformation being sensed by the inductive transducer 12.

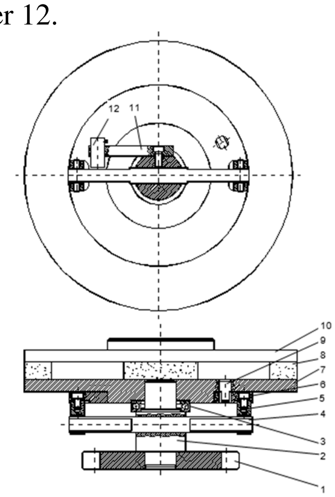

Fig. 1. Loading device

In order to see the behavior of technological processing systems, determinations were made using the axial stress device on the FV32 milling machine. The experimental researches were carried out under the following conditions: the torque of the materials used was C45 - Ferodou, the range of spindle speeds of the main shaft - 37.5 - 475 rot/min, without cooling. Analyzing the values of the energy characteristics, it is found that with the increase of the braking force and the rotation of the main shaft, they have a significant increasing variation. The experimental data are presented in table 1 where *n* - spindle speed [rot/min], *F* - force [daN], I - intensity [A], P_a - apparent power [kVA], *P* – active power [kW], P_u – useful power [kW], $\cos\varphi$ - power factor and η – yield.

Table 1

Experimental data

n	*F*	*I*	*Pa*	*P*	*Pu*	*cos φ*	*η*
37.5	16.5	5.3	3.56	0.34	0.05	0.09	0.15
37.5	40.3	5.36	3.60	0.51	0.12	0.14	0.24
37.5	63.6	5.4	3.62	0.65	0.19	0.17	0.30
37.5	86.2	5.46	3.66	0.8	0.27	0.21	0.33
37.5	107.9	5.52	3.70	0.88	0.33	0.23	0.38
37.5	128.3	5.6	3.76	1	0.40	0.26	0.40
37.5	147.3	5.64	3.79	1.12	0.46	0.29	0.41
37.5	164.7	5.7	3.83	1.18	0.51	0.30	0.43
118	16.5	5.4	3.62	0.64	0.16	0.17	0.25
118	40.3	5.55	3.72	1.15	0.39	0.30	0.34
118	63.6	5.8	3.89	1.53	0.62	0.39	0.40
118	86.2	6.15	4.13	2	0.85	0.48	0.42
118	107.9	6.3	4.23	2.4	1.06	0.56	0.44
118	128.3	6.5	4.36	2.76	1.26	0.63	0.45
118	147.3	7.18	4.82	3	1.45	0.62	0.48
118	164.7	7.86	5.28	3.24	1.62	0.61	0.50
235	16.5	5.5	3.69	1.25	0.32	0.33	0.26
235	40.3	5.9	3.96	1.95	0.79	0.49	0.40
235	63.6	6.3	4.23	2.55	1.25	0.60	0.49
235	86.2	7	4.70	3.3	1.69	0.70	0.51
235	107.9	7.6	5.10	3.7	2.12	0.72	0.57
235	128.3	8.4	5.64	4.28	2.52	0.75	0.59
235	147.3	9.2	6.18	4.6	2.90	0.74	0.63
235	164.7	10.4	6.98	5.46	3.24	0.78	0.59
475	16.5	7	4.70	1.31	0.65	0.27	0.50
475	40.3	8	5.37	2.76	1.60	0.51	0.58
475	63.6	8.95	6.01	3.8	2.53	0.63	0.66
475	86.2	9.64	6.48	4.39	3.43	0.67	0.78
475	107.9	9.98	6.71	5.05	4.29	0.75	0.85
475	128.3	10.62	7.13	5.85	5.10	0.81	0.87
475	147.3	11.25	7.56	6.54	5.86	0.86	0.89
475	164.7	12.38	8.31	7.24	6.55	0.87	0.90

The energy characteristics of the technological systems analyzed, including power factor, apparent power, active power, and yield are detailed in the following figures.

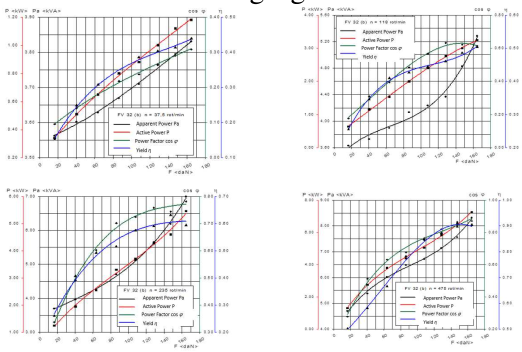

Fig. 2. The value of the energy characteristics

By increasing the force, the apparent power P_a (by 107.5 - 176.85 %) and the active power P (by 347 - 552.9 %) increase which leads, of also, at the increase of the efficiency η (by 287.16 – 180 %) and, respectively, of the power factor (by 322.73 - 312.5 %). Increasing the speed of the main shaft causes a rise in the apparent power P_a (by 132.1 - 217.23 %), the active power P (by 385.3 - 613.8 %), the yield (by 327.65 - 205.25 %) and the power factor (with 291.67 - 282.46 %).

3. MATHEMATICAL MODELS

Determination of energy characteristics are made as regression functions. The process functions can be theoretical or regression, the theoretical - introduced by definitions or deduced based on physical-mechanical or geometric considerations, and the regression - determined based on experimental results. The theoretical functions mainly refer to the geometry of the chip, the cutting force, the wear of the cutting tool, the roughness of the surface. In certain cases, however, the theoretical functions give results much different from those obtained experimentally, therefore, in these cases it is necessary to use the regression functions. These functions can be presented in the form of graphs, tables or analytical relations. Corresponding to this last way of representation, the form of the regression functions is polynomial or polytropic. To characterize a cutting process, process functions determined as regression functions can be used. Thus, for the determination of a process function of unknown form.

$$Y = \Gamma(X_1, X_2, \dots, X_j, \dots, X_k) \qquad (1)$$

where Y and X_j, j = 1, 2, ..., k are the dependent variables and the independent variables of the process and Γ - the shape of the function, an approximation function G is chosen.

The coefficients attributed to the independent variables X_j, j = 1, 2, ..., k, are determined based on experimental data, taking into account their stochastic distribution. The approximation function, thus determined, is a regression function and the included regression coefficients. To determine the mathematical models, considering the experimental data obtained, for the energy characteristics Y - apparent power P_a, active power P, power factor $\cos\varphi$ and efficiency η - functions of polynomial and polytropic form, of degree one and two, were adopted.

To establish the experimental program, considering the fact that the stress on the main shaft of the technological system had a minimum value corresponding to the speed n = 37.5 rot/min and the tangential force F = 17 daN and a maximum value corresponding to n = 475 rot/min and, respectively, F = 164 daN, these values were chosen as the minimum and maximum levels of variation of the two working parameters of the machine tools. In this interval, an intermediate value was chosen, so that, together with the two limits, it forms an arithmetic progression, respectively a geometric progression. The possible combinations between the three levels of variation of the two working parameters correspond to an entire factorial program of type 32. For the encoded variables x_1 and x_2, the levels +1, 0, -1 were adopted. The independent variables are n and F, respectively the dependent variables are P, P_a, $\cos\varphi$, η (table 2).

Table 2

Values for studied functions (polynomial and polytropic)

No.	x_1	x_2	n	F	P	P_a	cos φ	η
1	-1	-1	37,5	17	0,344	3,528	0,097	0,156
2	-1	0	37,5	90,5	0,80	3,641	0,221	0,355
3	-1	1	37,5	164	1,18	3,789	0,312	0,436

4	0	-1	235	17	1,234	3,652	0,341	0,271
5	0	1	235	164	5,345	6,848	0,779	0,608
6	1	-1	475	17	1,369	4,633	0,298	0,499
7	1	0	475	90,5	4,610	6,387	0,727	0,782
8	1	1	475	164	7,253	8,157	0,893	0,898
9	0	0	235	90,5	3,279	4,679	0,701	0,547
10	0	0	235	90,5	3,264	4,7	0,69	0,532

Through the mathematical processing of the experimental data, the energy characteristics were obtained, as regression functions, for the milling machine FV 32. Using the regression analysis indicators for P_a, P, $\cos\varphi$ and η, the functions with the best adequacy and the smallest relative errors were determined.

Table 3

Analysis of the adequacy of the regression functions

	Polynomial Degree 1		**Polytropic Degree 1**	
	R*	**ε %**	**R***	**ε %**
cos φ	1,720	-71.8..27.8	0,295	-12,9...11,2
P_a	11,688	-26.5...30	0,485	-9,06...16,4
P	48,346	-141.2..318	2,557	-10,9...14,5
η	0,145	-25.2...14.6	0,521	-16...14,4
	Polynomial Degree 2		**Polytropic Degree 2**	
	R*	**ε %**	**R***	**ε %**
cos φ	0,157	-25,2...34,3	**0,109**	-6,3...4,6
P_a	5,273	-7,7...8,6	**0,023**	-2,3...1,9
P	3,108	-15,8...40,8	**0,226**	-5,1...5,6
η	**0,009**	-4,5...5	0,147	-6,2...4,9

Based on the lowest adequacy coefficient (R* < 1) and the relative errors (%) for the energy characteristics, the following functions were chosen:

$$P = e^{a_0 + a_1 \cdot \ln n + a_2 \cdot \ln F + a_{11} \cdot (\ln n)^2 + a_{22} \cdot (\ln F)^2 + a_{12} \cdot \ln n \cdot \ln F} \quad (2)$$

$$\eta = a_0 + a_1 \cdot n + a_2 \cdot F + a_{11} \cdot n^2 + a_{22} \cdot F^2 + a_{12} \cdot n \cdot F \quad (3)$$

The coefficients of these functions are presented in the table 4.

Table 4

Coefficients of regression functions

The function coefficients	**cos φ**	**Pa**	**P**	**η**
a_0	-7.944	3.366	-3.673	0.053
a_1	1,329	-0,694	0,402	0.0004
a_2	0,782	-0,517	0,065	0.0047
a_{11}	-0,085	0,056	-0,006	0.0000006
a_{22}	-0,027	0,031	0,029	-0.000016
a_{12}	-0,012	0,086	0,075	0.0000018

The model of the energy characteristics is adequate and the variables of the model are significant.

From the study of the data presented, it is noted, for the appropriate functions, the relative errors between the measured and predicted values of model below 5 %. The graphic representation of the surfaces of the energy characteristics *P* and *η*, in the space of the three variables *n*, *F* and *P* respectively, *η* is given is presented in the following figure.

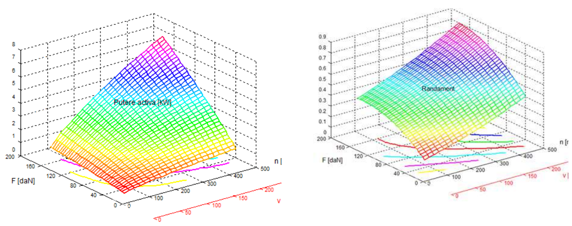

Fig. 3. The graphic representation of the surfaces of the energy characteristics P and η

The influence of the independent variables on the energy characteristics *P* and *η* (Fig. 4) is as follows: the increase in speed from n_{min} = 37.5 rot/min to n_{max} = 475 rot/min leads to an increase in the active power P by 397.27 - 612 .12 % and in the yield η by 319.3 - 205.94 %; the increase of the stress force from F_{min} = 17 daN to F_{max} = 164 daN causes a variation of the active power by 343.88 - 529.85 % and of the yield by 278.78 - 179.8 %.

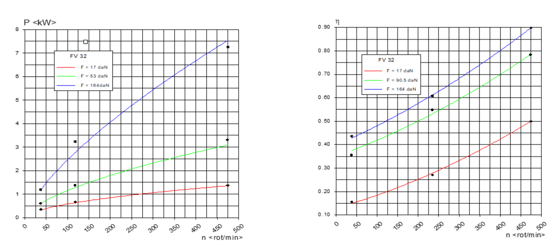

Fig.4. Influence of the independent variables on the P and η

4. CONCLUSION

With regard to the current state of research on the energy characteristics of processes and machining systems, the following conclusions can be noted. The material subjected to processing, the parameters of the cutting regime, the characteristics of the cutting tool and of the cooling-lubricating fluid have influence with different degrees of intensity on the cutting force. The yield value of a processing system is not constant, being influenced by a series of factors such the importance of determining the cutting regimes taking into account the efficiency of the machine-tool and the specific consumption of electricity. The quantities that generate the resistant torque in the process and the energy losses in the drive motors in operating mode must be taken into account for the energy characterization of the manufacturing manufacturing processes and technological systems. In order to carry out energy tests, the request of a technological system can be made by cutting force or braking force.

It is necessary to continue research in the following directions: improving the characteristics of the request device - to cover the entire range of speeds of the technological systems; adaptation of the experimental stand to allow the use of computing techniques for data acquisition.

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CERCETĂRI PRIVIND DETERMINAREA CARACTERISTICILOR ENERGETICE ALE UNEI MAȘINI DE FREZAT

Rezumat: Cele mai importante criterii pe baza cărora se determină regimurile optime de așchiere sunt criteriul productivității maxime și criteriul costului minim de prelucrare. La determinarea regimurilor de prelucrare pe baza acestor criterii nu se pune deseori problema eficienței cu care funcționează mașina-unelă și a consumului de energie. Necunoașterea legăturii dintre parametrii de lucru ai mașinii-unelte și eficiența acesteia, precum și funcționarea mașinilor-unelte la cea mai mare eficiență posibilă ținând cont de consumul specific de energie electrică și de productivitatea așchierii, constituie o explicaţie a modului de abordare al acestei probleme. În această lucrare, caracteristicile energetice ale unei mașini de frezat sunt determinate, optimizate prin crearea unui dispozitiv de încărcare pentru arborele principal și analizate prin diferite metode de regresie.

Cuvinte cheie: *Prelucrare, Regresie, optimizare, model matematic, energie*

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