УДК 621.9.04
UDC 621.9.04

R. Redko, O. Povstyanoy, R. Polinkevich, T. Chetverzhuk, O. Zaleta
Lutsk National Technical University

INVESTIGATION OF CUTTING FORCE DURING BORING OF SCREW NON-RIGID MACHINE PARTS

In the work, the peculiarities of boring of screw workpieces are described. The regularities of the processes of boring screw non-rigid parts have been established. The specifics of the design of the equipment for boring screw non-rigid parts and the expediency and prospects of using screw workpieces are substantiated. It is based on theoretical and experimental studies. A theoretical generalization and a new solution to the scientific and technical problem expressed in the development and creation of technological processes for processing non-rigid screw workpieces, are presented. This will make it possible to ensure the expansion of technological capabilities and the improvement of technical and economic parameters. Calculations were carried out using a package of applied statistical programs for processing and analyzing the results of experimental studies for a PC. According to these results, the dependences of the response surfaces of the optimization parameter and the two-dimensional section of the response surfaces were constructed and analyzed for a visual representation of the results of the experimental studies. The dependences of the change in cutting force on feed and cutting depth were constructed and analyzed. The dependences of the optimization parameter, that is, the dependence of the cutting force on the change of one input factor with a constant value of the other two factors, were also substantiated. After carrying out research using the program «Statistika», a two-dimensional section of the response surface of the dependence of the cutting force on the feed and depth of cut and the response surface of the dependence of the cutting force on the feed and depth of cut were constructed. The obtained experimental broken line was built based on the results of the conducted research. Approximation of it was carried out according to known standard methods, while the amount of deviation (mismatch) was determined by the method of least squares.

Key words: cutting process, feed, cutting depth, nature of loads, boring process, statistical analysis, lathe and screw-cutting machine.

INTRODUCTION

Modeling of cutting processes depends on many factors: physical and mechanical properties of the material, feed, cutting depth, nature of loads, etc. The specified factors are of a stochastic random nature, so it is necessary to conduct a set of experimental studies to determine the dominant factors that significantly affect the boring process. In order to perform a statistical analysis of the obtained results, empirical dependencies should be introduced into the selected mathematical model. They will show the change in the cutting force depending on the cutting depth and feed.

ANALYSIS OF LITERATURE DATA AND STATEMENT OF THE PROBLEM

To determine the cutting force during boring screw non-rigid machine parts [3-4], experimental studies were carried out on a screw-turning machine with different spindle speeds. Cutter material of the brand T16K5 was chosen for the boring process [4-5].

The part was installed in a special device and fixed in a three-jaw chuck of the lathe and screw-cutting machine 16K20 so that the researched process could be carried out on machines that are widely used in repair shops of enterprises engaged in equipment repair. The workpiece was installed in the device manually.

In addition, experiments were conducted for different values of feed and cutting depth [3]. In this way, an experimental array of optimization parameter data was obtained depending on the feed and cutting depth. From the entire obtained experimental array of data, a data sample of one specific feed value with different values of the cutting depth was created [1-2]. The obtained numerical results of the cutting force were entered in the table of a conditional full-factor experiment [1].

Processing of the obtained data of the experimental array was carried out according to well-known methods of correlation and regression analysis of experimental data to obtain the final result of empirical regression equations [1].

To obtain a regression model of the optimization parameter in the form of a full quadratic polynomial, a suitable conditional plan of a full factorial experiment was chosen. Its implementation was carried out in a specified sequence.

PURPOSE AND TASKS OF THE RESEARCH

The purpose of the work is to analyze the features of the boring process of screw workpieces and to establish the regularity of the boring processes of screw non-rigid parts.

The tasks of the research: plot the dependencies of the response surfaces of the optimization parameter and a two-dimensional section of the response surfaces for a visual representation of the results of the experimental studies; plot and analyze the dependence of the change in cutting force on feed and cutting depth; plot the dependence of the optimization parameter, that is, the dependence of the cutting force on the change of one input factor with a constant value of the other two factors; plot a two-dimensional section of the response surface of the dependence of the cutting force on the feed and cutting depth and the response surface of the dependence of the cutting force on the feed and depth of cutting on the basis of research results using the program «Statistika».

RESEARCH RESULTS

Since, in the process of conducting experiments, variable independent factors are heterogeneous and have different units of measurement, and the numbers expressing the values of these factors are of different orders, they were brought to a single system of calculations by replacing real values with coded ones.

The relationship between coded x_i and natural X_i variable factors was established by dependence:

$$x_i = \frac{X_i - X_{i0}}{\Delta X_i}, \quad (1)$$

where X_{i0} – natural value of the *i*-th factor at the zero level;

ΔX_i – variation interval of the *i*-th factor.

The zero level or average value of the input factor was determined by the formula:

$$X_0 = \frac{X_{max} + X_{min}}{2}, \quad (2)$$

where X_0 – the numerical value of the zero level of the input factor;

X_{max} – numerical value of the upper level of the input factor;

X_{min} – numerical value of the lower level of the input factor.

The intervals of variation by factors are determined:

$$\Delta X_i = \frac{X_{max} + X_{min}}{2}. \quad (3)$$

Conventional designations of the upper, lower, and zero levels of factor variation were entered, respectively +1, -1, 0 to construct a conditional plan-matrix for the planning of experiments. The results of the coding of the experimental factors and the levels of their variation are shown in Table 1.

Table 1 – Results of factors coding and their levels of variation

Factor	Natural designa-tions	Coded designa-tions	Variation interval	Levels of variation					
				natural			code		
				upper	lower	zero	upper	lower	zero
Feed, *S*, mm/stroke	X_1	x_1	0,08 mm	0,2	0,04	0,12	+1	-1	0
Cutting depth, *t*, mm	X_2	x_2	1,0 mm	2,5	0,5	1,5	+1	-1	0

After coding the input factors, a plan-matrix of a conditional full factorial experiment of the FFE 3^3 type was compiled for the total number of experiments $N=P^k$, where *P* is the number of levels of variation (three), *k* is the number of active input factors (three) in the experiment, shown in Table 2.

Table 2 – Conditional plan-matrix of the FFE 3^3 type experiment

No. of the experi-ment	Factor levels			Interaction of factors	Optimization parameter, *Y*			Average values *Y*
					Frequency			
	x_0	x_1	x_2	x_1x_2	1	2	3	$Y_{cep.}$
1	+1	-1	-1	+1	Y_{11}	Y_{12}	Y_{13}	Y_{1c}

2	+1	+1	-1	-1	Y_{21}	Y_{22}	Y_{23}	Y_{2c}
3	+1	0	-1	0	Y_{31}	Y_{32}	Y_{33}	Y_{3c}
4	+1	-1	+1	-1	Y_{41}	Y_{42}	Y_{43}	Y_{4c}
5	+1	+1	+1	+1	Y_{51}	Y_{52}	Y_{53}	Y_{5c}
6	+1	0	+1	0	Y_{61}	Y_{62}	Y_{63}	Y_{6c}
7	+1	-1	0	0	Y_{71}	Y_{72}	Y_{73}	Y_{7c}
8	+1	+1	0	0	Y_{81}	Y_{82}	Y_{83}	Y_{8c}
9	+1	0	0	0	Y_{91}	Y_{92}	Y_{93}	Y_{9c}

In order to reliably estimate the cutting force when boring screw non-rigid parts during experimental studies, the required number of measurements of the controlled parameters (repetition of experiments) was determined according to the methodology outlined in [1-2]. The experiments were carried out three times.

To implement the plan-matrix and to preclude the influence of uncontrolled and unregulated factors on the research result, randomization of the plan-matrix was carried out using the method of random balance, which was implemented by getting the serial numbers of the experiments from the urn.

The obtained results of the calculations were entered in the **table** of the obtained results of experimental studies. The analysis of the obtained results of the experiments was carried out using a well-known method of processing and analysis of the conducted experimental studies [1-2].

At the same time, the response function (optimization parameter) was taken as an approximate mathematical model of a full quadratic polynomial [1-2], which describes the real experimental process:

$$Y = P_z = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1^2 + b_{11}x_2^2, \quad (4)$$

where P_z – experimental value of cutting force, H;

b_0, b_1, b_2, b_{12}, b_{11}, b_{22}, – regression coefficients of the corresponding values of the input factors x_i;

x_1, x_2 – input coded factors.

The coefficients of the approximating polynomial, presented in the form of a complete quadratic equation under the condition of orthogonality and symmetry, were determined according to the appropriate formulas [1]:

- free term b_0 and coefficients of the b_i *i*-th factor:

$$b_i = \frac{\sum_{u=1}^{N} x_{iu}\bar{y}}{\sum_{u=1}^{N} x_{iu}^2} = \frac{\sum_{u=1}^{N} x_{iu}\bar{y}_u}{N}; \quad (5)$$

- interaction coefficients b_{ij} and b_{ijk}:

$$b_i = \frac{\sum_{u=1}^{N} x_{iu}\bar{y}_u}{N}; \ b_i = \frac{\sum_{u=1}^{N} x_{iu}x_{ju}x_{ku}\bar{y}_u}{N}, \quad (6)$$

where x_{iu} – the value of the coded variable in the appropriate column of the experimental design;

$\bar{y}_u$ – the average result of the *u*-th experiment;

u – serial number of the experiment

i – factor number;

j, *k* – factor number other than the *i*-th factor;

N – the number of conducted experiments.

The statistical significance of the coefficients of the regression equation bi was performed according to the Student's test and determined in the following sequence:

- the dispersion of experimental errors in the lines of the FFE plan was determined as:

$$S_u^2 = \frac{1}{n-1}\sum_{j-1}^{n}(y_{ui} - \bar{y}_u)^2, \quad (7)$$

where n – number of parallel experiments (repetitions of one experiment);
j =1, 2,..., n.

- the dispersion of the reproduction of the experiment was determined as:

$$S_u^2 = \frac{1}{N}\sum_{u=1}^{N} S_u^2 \tag{8}$$

- the reproduction error was determined as:

$$S_y = \sqrt{S_y^3} \tag{9}$$

- the significance condition of the b_i coefficients of the regression equation was determined as:

$$b_{(jk)} > \frac{t_T S_y}{\sqrt{Nn}}, \tag{10}$$

where t_T – the tabular value of the Student coefficient, which is selected from the table depending on the degree of correspondence f and the level of significance α [1-2].

The degree of compliance is determined by the formula:

$$f=(n-1)N, \tag{11}$$

If (9) is not fulfilled, then the coefficient bi of the regression equation was taken equal to zero, and the appropriate term x_i was excluded from the regression equation.

Verification of the adequacy of the selected mathematical model with experimental data, that is, the correspondence of the mathematical model to the real process, was carried out according to Fisher's F test as follows [2]:

- the variance of adequacy was determined as:

$$S_{ag}^2 = \frac{n}{N-g'}\sum_{u=1}^{N}(\overline{y_u} - \widetilde{y_u})^2, \tag{12}$$

where N-g' – the number of degrees of freedom of the adequacy variance;
g' – the number of significant coefficients in the regression equation;
$\overline{y_u}$ – average response value in the u-th trial;
$\widetilde{y_u}$ – the response value at the u-th point of the plan, calculated by the regression equation;

- calculated Fisher's correspondence criterion F_p was determined as:

$$F_p = \frac{S_{ag}^2}{S_y^2}, \tag{13}$$

where S_y^2 – dispersion of experiment reproduction.

The tabular value of Fisher's F_T test was determined at a given level of significance α and two degrees of correspondence $f_{ag}=N\text{-}g$ та $f_y=N(n\text{-}1)$ [1].

The adequacy condition of the selected mathematical model was checked according to the inequality:

$$F_p<F_T \tag{14}$$

If the condition $\boldsymbol{F_p<F_T(0{,}05,\ f_{aq},\ f_y)}$ was fulfilled, i.e., the calculated value of F_p - Fisher's test is less than the table F_T for the 5% level of significance, the number of degrees of freedom of the variance of adequacy, $\boldsymbol{f_{aq}=N\text{-}g}$ and the number of degrees of freedom of the variance of reproducibility $\boldsymbol{f_y=N(n\text{-}1)}$, then the PFE regression equation is adequate to the experimental data.

DISCUSSION OF RESEARCH RESULTS

According to the results of the calculations, which were carried out with the help of a package of applied statistical programs for processing and analyzing the results of experimental studies for a PC, the dependencies of the response surfaces of the optimization parameter and a two-dimensional section of the response surfaces were built for a visual representation of the results of the experimental studies.

To build and analyze the dependence of the change in cutting force on feed and depth of cutting, we used the statistical program package for PC «Statistika». The analysis of randomness of the process was evaluated according to standard methods [2].

The dependence of the optimization parameter, that is, the dependence of the cutting force on the change of one input factor with a constant value of the other two factors, was built using the «MathCad 11» PC application package.

Approximation of the obtained experimental broken line, which was constructed based on the results of the conducted research, was carried out according to known standard methods, while the amount of deviation («mismatch») was determined by the method of least squares, which is described by the dependence:

$$\Theta = \sum_{i=1}^{N} \varepsilon^2 = \sum_{i=1}^{N} (m_{i_e} - m_{i_m})^2 \quad (15)$$

where $\Theta = \varepsilon^2$ – amount of «mismatch»;

m_{i_e}, m_{i_m} – respectively, the theoretical, determined by the empirical formula, and the experimental value of the *i*-th experiment.

After conducting the research, a two-dimensional section of the response surface of the dependence of the cutting force on the feed and depth of cut and the response surface of the dependence of the cutting force on the feed and depth of cut were constructed using the program «Statistika».

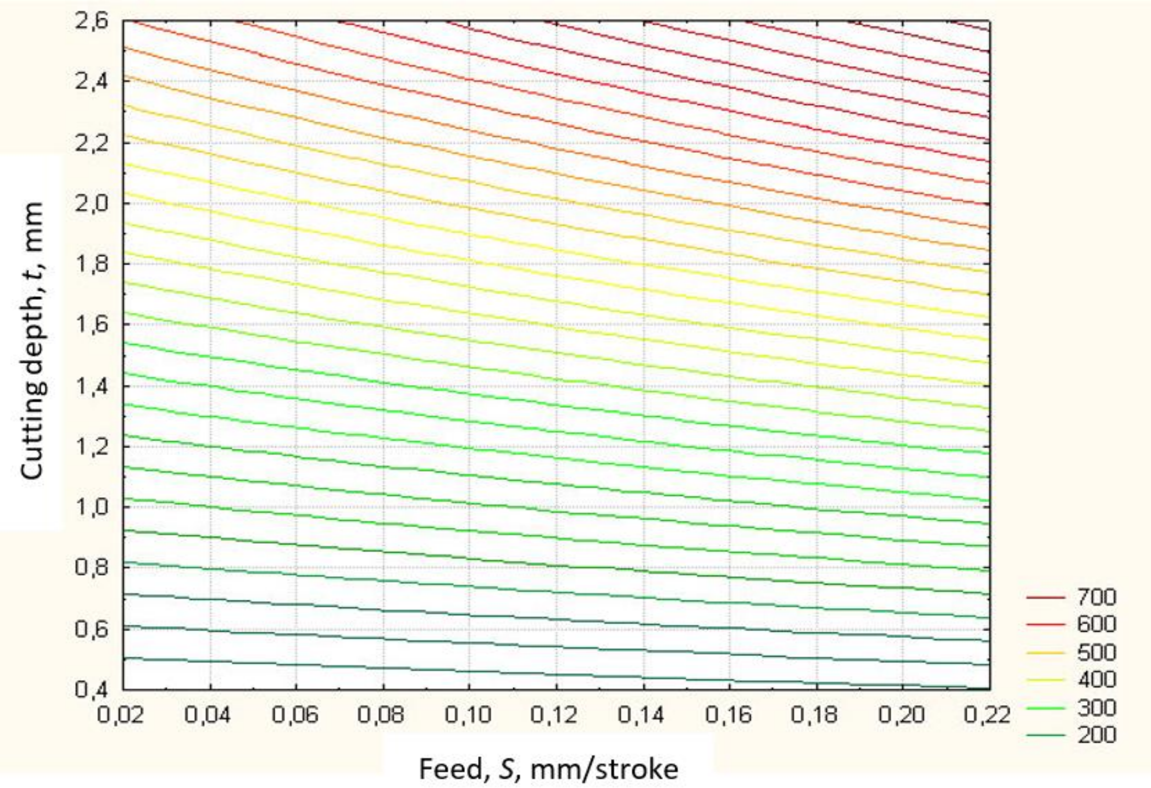

Figure 1 – Two-dimensional cross-section of the response surface of the dependence of the cutting force on the feed and cutting depth

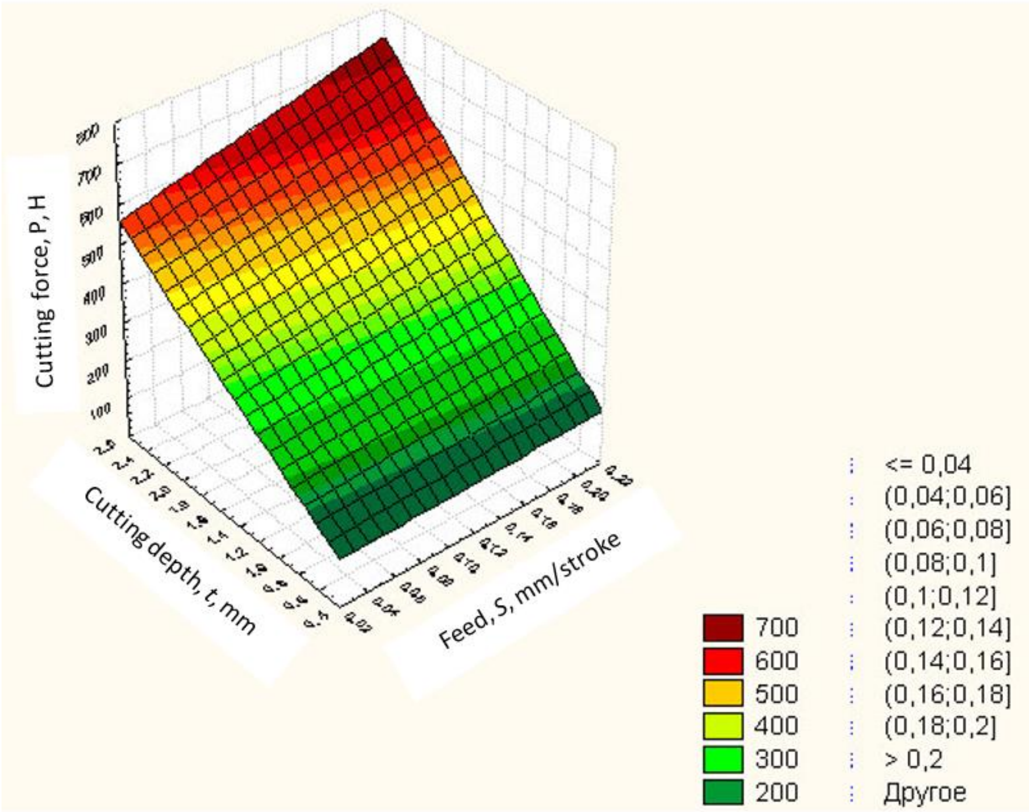

Figure 2 – Response surface of cutting force dependence on feed and cutting depth

CONCLUSIONS

The work examines the peculiarities of the process of boring of screw workpieces. The regularities of the processes of boring screw non-rigid parts have been established. The equipment for boring of screw non-rigid parts is presented on the basis of theoretical and experimental studies, substantiation of the feasibility and prospects of using screw workpieces. A theoretical generalization and a new solution to the scientific and technical problem, which is manifested in the development and creation of technological processes for processing screw non-rigid parts, are presented, which will allow to ensure the expansion of technological capabilities and the improvement of technical and economic parameters.

REFERENCES

1. Yu.S. Mishura. Tinsel Random processes: theory, statistics, application: a textbook / Yu.S. Mishura, K.V. Ralchenko, H.M. Shevchenko. – 2nd ed., corrected and supplemented. – K.: VOC «Kyiv University», 2021.– 496 p.

2. Kolomiets S.V. The theory of the randomness of processes: a workshop / S.V. Kolomiets // State Higher Educational Institution «Ukrainian Academy of Banking of the National Bank of Ukraine». – Sumy: DVZN UABS NBU, 2011. - 80 p.

3. Babenko A.E. Theory of elasticity. Part 1 [Electronic resource]: textbook / A. E. Babenko, M. I. Bobir, S. L. Boyko [and others]. – Electronic text data (1 file: 1.27 MB). – Kyiv: Osnova, 2009. – 244 p.

4. Walid Ibrahim Alnusirat, Litvin Oleksandr, Ibrahim Farhan Alrefo, Kravez Oleksandr. Tool for researching the dynamic system of metal-cutting machine/ World science № 9(37). September 2018, p. 5-9. DOI: 10.31435/rsglobal_ws.

5. Dolja V.M. Machine parts processing technology: a summary of lectures for students of the specialty 7.05050201 "Technology of mechanical engineering" of all forms of education. / V.M. Dolja, O.V. Dolja // Kharkiv: NTU «KhPI», 2015. – 112 p.

Редько Р., Повстяной О., Полінкевич Р., Четвержук Т., Залета О. **Дослідження сили різання при розточуванні гвинтових нежорстких деталей машин.**

У роботі розглянуто особливості процесу проточування навивних заготовок. Встановлено закономірності процесів розточування гвинтових нежорстких деталей. Обгрунтовано особливості конструкції оснащення для розточування ГНЗ на основі теоретичних і експериментальних досліджень, а також доцільності та перспектив використання гвинтових заготовок. Наведено теоретичне узагальнення і нове вирішення науково-технічної задачі, що виявляється в розробці і створенні технологічних процесів обробки нежорстких гвинтових заготовок, що дозволить забезпечити розширення технологічних можливостей та покращення техніко-економічних показників. За результатами розрахунків, які проводили за допомогою пакету прикладних статистичних програм оброблення та аналізу результатів експериментальних досліджень для ПК, побудовані і проаналізовані залежності поверхонь відгуку параметру оптимізації та двомірного перерізу поверхонь відгуку для наочного зображення результатів проведених експериментальних досліджень. Побудовані і проаналізовані залежності зміни сили різання від подачі і глибини різання. Також обґрунтовані залежності параметру оптимізації, тобто залежність сили різання від зміни одного вхідного фактору з постійним значенням двох інших факторів. Після проведення досліджень за допомогою програми Statistika побудовано двомірний переріз поверхні відгуку залежності сили різання від подачі й глибини різання та поверхню відгуку залежності сили різання від подачі й глибини різання. Апроксимацію отриманої експериментальної ломаної лінії, яка побудована за результатами проведених досліджень, проводили за відомими стандартними методиками, при цьому величину відхилення (неузгодження) визначали за способом найменших квадратів.

Ключові слова: процес різання, подача, глибина різання, характер навантажень, процес розточування, статистичний аналіз, токарно-гвинторізний верстат.

РЕДЬКО Ростислав Григорович – кандидат технічних наук, доцент, завідувач кафедри прикладної механіки та мехатроніки, Луцький національний технічний університет, e-mail: redkorg@ukr.net. https://orcid.org/0000-0001-5066-0224.

ПОВСТЯНОЙ Олександр Юрійович – доктор технічних наук, професор кафедри прикладної механіки та мехатроніки, Луцький національний технічний університет, e-mail: povstjanoj@ukr.net. https://orcid.org/0000-0002-1416-225X.

ПОЛІНКЕВИЧ Роман Миколайович – кандидат технічних наук, доцент кафедри прикладної механіки та мехатроніки, Луцький національний технічний університет, e-mail: r.polinkevych@lntu.edu.ua. https://orcid.org/0000-0002-4243-5585.

ЧЕТВЕРЖУК Тарас Іванович – кандидат технічних наук, доцент кафедри прикладної механіки та мехатроніки, Луцький національний технічний університет, e-mail: eti_tar@ukr.net. https://orcid.org/0000-0002-4445-4632.

ЗАЛЕТА Ольга Михайлівна – кандидат технічних наук, доцент кафедри прикладної механіки та мехатроніки, Луцький національний технічний університет, e-mail: olga_zaleta@ukr.net. https://orcid.org/0000-0002-0777-9972.

Rostyslav REDKO – PhD in Engeneering, associate professor, head of Applied Mechanics and Mechatronics department, Lutsk National Technical University e-mail: redkorg@ukr.net. https://orcid.org/0000-0001-5066-0224.

Oleksandr POVSTYANOY – DSc, professor of Applied Mechanics and Mechatronics department, Lutsk National Technical University e-mail: povstjanoj@ukr.net. https://orcid.org/0000-0002-1416-225X.

Roman POLINKEVICH – PhD in Engeneering, associate professor of Applied Mechanics and Mechatronics department, Lutsk National Technical University e-mail: r.polinkevych@lntu.edu.ua. https://orcid.org/0000-0002-4243-5585.

Taras CHETVERZHUK – PhD in Engeneering, associate professor of Applied Mechanics and Mechatronics department, Lutsk National Technical University e-mail: eti_tar@ukr.net. https://orcid.org/0000-0002-4445-4632.

Olha ZALETA – PhD in Engeneering, associate professor of Applied Mechanics and Mechatronics department, Lutsk National Technical University e-mail: olga_zaleta@ukr.net. https://orcid.org/0000-0002-0777-9972.

DOI 10.36910/automash.v1i20.1030