Проведені дослідження процесу обробки різанням зношених пневматичних шин ріжучим інструментом зі сплавів марок Р6М5 і Т15К6. Отримана математична модель формування сил різання при розрізання пневматичних шин навпіл. Визначено ефективні режимні параметри: частота обертання шпинделя верстата і подача ріжучого інструменту, геометричні параметри і твердість матеріалу ріжучого інструменту, які забезпечують мінімальні енерговитрати

Ключові слова: розрізання шин, ріжучий інструмент, сили різання, математична модель, енергоефективність, оптимізація

Проведены исследования процесса обработки резанием изношенных пневматических шин режущим инструментом из сплавов марок Р6М5 і Т15К6. Полученная математическая модель формирования сил резания при резки пневматических шин пополам. Определены эффективные режимные параметры: частота вращения шпинделя станка и подача режущего инструмента, геометрические параметры и твердость материала режущего инструмента, которые обеспечивают минимальные энергозатраты

Ключевые слова: разрезание шин, режущий инструмент, силы резания, математическая модель, энергоэффективность, оптимизация

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STUDY OF ENERGY EFFICIENCY OF THE PROCESSES OF MECHANICAL DESTRUCTION OF WORN AUTOMOBILE TIRES

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1. Introduction

The storage and disposal of scrap automobile tires is today's acute problem in all developed countries. According to statistical data, the European countries account for three billion worn-out automobile tires (it is about two million tons). Only 23 % of tires out of this quantity are subsequently used (export to other countries, burning in order to generate energy, mechanical shredding to cover roads, sports facilities, etc.). The other 77 % of the worn tires are not used because there is no any profitable way of their recycling.

According to data from the State Automobile Transport Research and Design Institute of Ukraine, an annual growth of worn automobile tires in Ukraine varies in a range of 250–300 thousand tons, out of which about 72 % are the tires with metallic cord [1]. Up to now, rather that appropriately dispose of automobile tires, the used material is dumped or burned. As various estimates indicate, only up to 10 % of the used tires are destroyed in accordance with environmental rules [2].

In the process of disposal, the tires are divided in groups, cleaned, cut into pieces, crushed (depending on the method), rubber crumbs are separated from metallic cord and textile.

Mechanical shredding by cutting automobile tires with different stiffness of rubber is linked to certain known difficulties [3] predetermined by elastic properties of rubber, as well as by multiple layers of different materials: rubber, textile and metallic cord.

In the process of shredding by cutting, materials of a tire undergo various static and dynamic deformations: stretching, compression, bending, etc. The wrong choice of the geometry of cutting tools and cutting modes results in the increased wear of the cutting tool, and sometimes its failure, while energy consumption of technological equipment grows. Given this, it is a relevant task for the further improvement of technological processes of disposal of worn tires to choose and substantiate a totality of optimal geometric parameters and the material of a cutting tool, optimal operational parameters of the cutting process.

2. Literature review and problem statement

The process of disposal of worn pneumatic tires includes a stage of preliminary shredding, which consists of two operations: cutting tires in half along the treadmill and cutting out bead rings [4].

In the process of cutting, the cutting tool is exposed to certain efforts, that is, the cutting forces that occur when cutting a layer of rubber, cord, and the frame. The force of resistance is the result of influence of various forces that act on the cutting tool. The resultant force P of all pressure forces of the treated material on the cutting tool can be geometrically decomposed into three mutually perpendicular components: P_z, P_y, P_x. When shredding the pneumatic tires by cutting them in half, these are forces P_z and P_y. Vertical force P_z (from the side of the cutting tool) prevents rotation of the tire and bends it; radial force P_y tries to bend the tire transversely. Almost all the power required for cutting is spent to overcome force P_z. This is explained by the fact that force P_z coincides with the cutting speed by direction, which is hundreds of times larger than the speed of cutter feed. Power is not consumed for force P_y at cutting because there is no motion in this direction. That is why, for approximate practical estimations, the cutting effort at cutting is considered to be force P_z [5–7].

The force of cutting is important, because when multiplying it by the radius of the machined part we obtain torque. It shows how much the machine is loaded under given operational conditions, and whether this loading is safe for its weakest links. Multiplying cutting force by cutting speed determines the power required for cutting expressed in kW. By matching this power to the actual capacity of the machine, it is possible to tell how rationally the machine is utilized [5, 6].

The basic parameters of cutting process include: cutting depth and speed, feed, width and thickness of the layer of cut material, and rated area of it cross-section. The larger feed and cutting depth, the larger the forces acting on the cutter, as well as the cutting temperature. This affects intensive wear of the cutter and slows cutting speed of the cutting tool at the same resistance [6–10]. An increase in feed and cutting depth leads to the larger cross-sectional area of the layer of rubber and bigger volume of the deformed material. This results in the greater resistance of the material and the process of cutting proceeds with larger cutting forces. Larger feed increases the amount of deformations, but the width of the cut remains unchanged, that is, the forces of normal pressure and friction do not change. Therefore, the feed exerts less influence on the cutting forces than the depth of cutting [6–8].

The cutting speed during treatment of pneumatic tires is one of the main factors that determines performance efficiency of the cutting process. An increase in the cutting speed leads to the improvement of treatment performance, but the tools are worn out more intensively, as well as the associated costs. The speed of cutting is affected by the following factors: resistance of the cutting tool, physical-mechanical properties of the treated material, material of cutting part of the tool, feed and depth of cutting, geometric elements of the cutting part [5–9].

Significant impact on the speed of cutting is exerted by the geometric parameters of cutting part of the tool. An increase in the front angle γ reduces deformations of the treated material, cutting forces and, consequently, decreases wear of the cutter. If the front angle of the cutter is increased, then it worsens heat removal due to a decrease in the cross-sectional area of cutting part of the tool, which is why it is required to reduce the speed of cutting. Given this, there is a relevant problem on choosing geometrical parameters of the cutting tool and effective operational parameters of the treatment process [7, 8].

The right choice of the totality of optimal geometrical parameters and material of the cutting tool, optimal operational parameters of machining process by cutting should make the process of cutting maximally energy-efficient, and the cutting tool – maximally durable. This affects the overall efficiency and cost-effectiveness of the preliminary tire shredding by cutting [7–11].

A big problem is the complexity of mathematical modelling of the tire cutting process, because there are a large number of interrelated parameters of the cutting tools and the process of cutting, as well as various properties of a tire. A hollow shape of the tire, high mechanical durability, elastic properties of the material, the presence of a metallic cord and textile fibers, chemical composition of rubber, predetermine difficulties and instability of the process of cutting [11–13]. This explains a small number of publications [11–20] that address this issue, as well as the unambiguity of conclusions, which necessitates further research in this direction.

3. The aim and objectives of the study

The aim of present work is to determine operational parameters, material and geometry of the cutting tool to ensure minimum energy consumption by the technological equipment for preliminary shredding of worn tires.

To achieve the set aim, the following tasks have been solved:

– to obtain a mathematical model for the formation of cutting forces when cutting worn pneumatic tires in half;

– to determine correction factors that would take into consideration the strength of material for various types of tires in order to ensure adequacy of the mathematical model.

4. Materials and methods for studying energy efficiency of the process of cutting worn tires in half

At the first stage of work, using the COMPASS-3D V16 DSS, we created a diagram of arrangement of the reduced cutting forces along coordinate axes (Fig. 1) in the process of cutting an automobile tire in half. In this case, the longitudinal feed is missing in the process of cutting, which is why it is possible to assume that all of the forces act in the same plane. We selected six input factors – angles of the cutting tools: γ, ε, α; hardness of the cutting tools HRA; operational parameters of cutting process: n, S_p, and two output factors: cutting forces P_z and P_y.

At the second stage, the values of these factors were encoded by the linear transformation of coordinates of the factor space with a transfer of the coordinate origin to a zero point and with a selection of scales along the axes in the units of intervals of factor variation:

$$x_i = \frac{c_i - c_{0i}}{\Delta c}, \tag{1}$$

where x_i is the encoded value of the factor (a dimensionless magnitude); $c_i - c_{i0}$ is the natural value of the factor (the current and at zero level, accordingly); Δc is the natural value of the variation interval [10].

Upon encoding, we obtain the values of factors, level +1 (upper level) and –1 (lower level).

The magnitude of shoulder α of the «star» points was determined from formula:

$$\alpha = \sqrt{\frac{n \cdot \varphi - 2^k}{2}},$$

where

$$\varphi=\sqrt{\frac{2^k}{n}};\quad n=2^k+2k+1, \tag{2}$$

but, since at the estimated magnitude a the lower levels of variation of some parameters do not match physical capabilities of the equipment, then we chose other tabular values $\alpha=1.596$ and $\varphi=0.863$ [10, 21].

At the third stage, we built a planning matrix for a full factorial experiment. Under condition of the presence of six input factors ((γ, ε, α, HRA, n, S_p), we used as the core a full factorial experiment, the number of experiments in the core $2^k=64$, in the «star» points – $2k=12$, in the center of the plan – 1. Variation of factors in the planning matrix is performed in the following way: in the first column, the signs alternate in one, in the second – in two, in the third – in four, in the fourth – in eight, etc. by the power of two [10, 21]. In the «star» points, the values of all factors, except for the factor with shoulder α, remain at zero level. In the central point of the plan, the values of all factors are at zero level. Variants for the interaction among factors were found by the brute-force method. Taking into consideration the interaction between factors, the matrix of a full factorial experiment contains seven vectors-columns of independent variables, where x_0 represents the encoded value of a free term, as well as 63 vectors-columns of interacting factors.

At the fourth stage, we conducted an experimental study in accordance with the plan using a complex of measuring equipment. The measuring complex consisted of the measuring head UDM-100, milliammeter and the amplifier TA-5, and an experimental installation based on the lathe-screw machine 16K20 [9]. We used threaded cutters made of alloy of grades R6M5 and T15K5 as the cutting tool.

Experimental installation based on the lathe-screw machine 16K20 (Fig. 2) is a console with the measurement head UDM-100 (Fig. 3), which is mounted on the machine table, which is driven perpendicular to the axis of the spindle. The spindle holds a conductor with a tire mounted onto it.

Cutting forces were determined while cutting the Bridgestone kart tires, size 7.1/11.0-5 with a textile cord, in half. Tensile strength at stretching a sample of the material of the tire is $\sigma_p=4.6$ MPa [8].

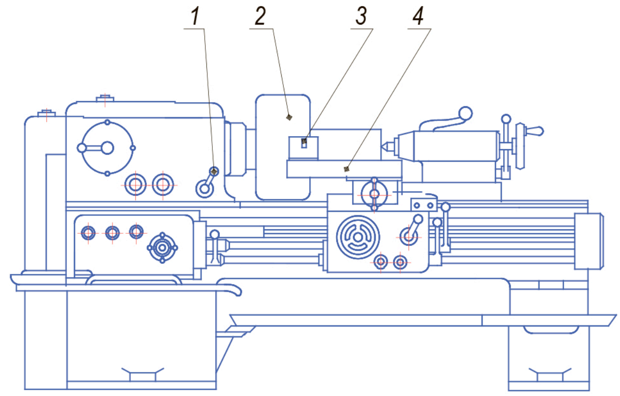

Fig. 2. Schematic of the experimental installation for shredding tires by cutting: 1 — lathe-screw machine 16K20; 2 — pneumatic tire; 3 — measuring head UDM-100 with a cutter; 4 — transitional console

Fig. 3. Measuring head UDM-100 with a cutter

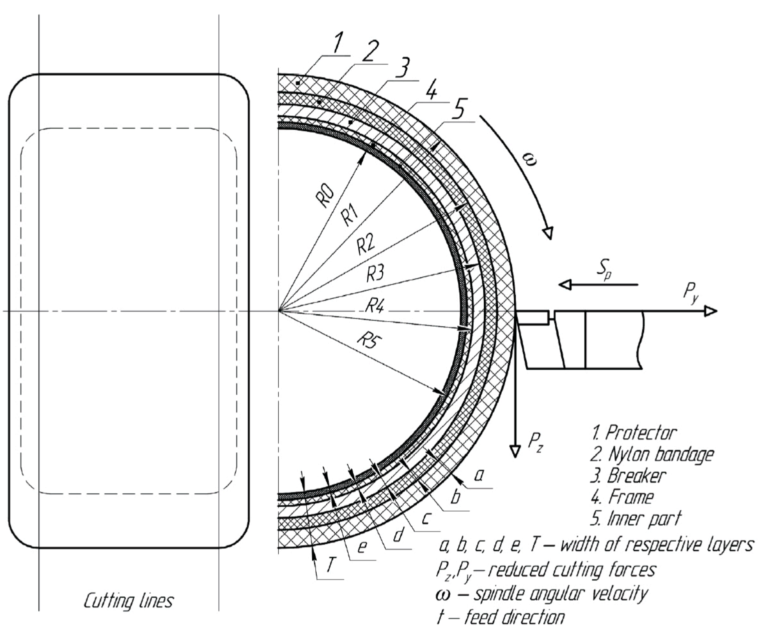

Fig. 1. Location diagram of the reduced cutting forces P_z and P_y along coordinate axes

At the fifth stage, we performed an analysis of the obtained experimental data for the presence of certain gross errors in measurements (emissions), as well as estimated reproducibility variance of the experimental data.

In order to estimate reproducibility variance and to check equal accuracy of measurements, we conducted uneven duplication of measurements at certain points of the plan, the number of which is $N_1=5$, the experiments were carried out γ_u times at each of them, $u=1\div N_1$. The test of equal accuracy of measurements (the homogeneity of a series of variation estimation $S^2_{y1}, S^2_{y2}, \ldots, S^2_{yN1}$) is performed using the Cochran's criterion (G-statistics).

At the sixth stage, after analyzing the obtained experimental data, we calculated regression coefficients and estimated significance.

During orthogonal planning regression equation coefficients are determined independently from the following formulae:

$$b_0=\frac{\sum_{u=1}^{n}y_u}{n};\quad b_i=\frac{\sum_{u=1}^{n}x_{iu}\bar{y}_u}{\sum_{u=1}^{n}x^2_{iu}}; \tag{3}$$

$$b_{ij}=\frac{\sum_{u=1}^{n}x_{iu}x_{ju}\overline{y}_u}{\sum_{u=1}^{n}\left(x_{iu}x_{ju}\right)};\quad b_{ij}=\frac{\sum_{u=1}^{n}\left(x'_{iu}\right)^2\overline{y}_u}{\sum_{u=1}^{n}\left[\left(x'_{iu}\right)^2\right]^2},\tag{4}$$

where i, j are the numbers of columns in the planning matrix; x_{iu} are the elements of the i-th column; x_{ju} are the elements of the j-th column; y_u is the value of response at the u-th point of the plan; $\overline{y}_u$ is the mean arithmetic value of the response at the u-th point of the plan; $\left(x'_{iu}\right)^2$ is the quadratic variable [10].

The testing of significance of the regression equation coefficients was performed using the Student t-criterion [21].

At the seventh stage, we constructed regression equations at orthogonal central compositional planning of the second order taking into consideration significance of the regression equation coefficients and conditions of factor encoding, for each of the forces – P_z and P_y, in the form:

$$\begin{aligned}P_z={}&1053.22571-12.94811\cdot HRA-595.81317\cdot S_P+\\&+5.51321\cdot\alpha-14.76805\cdot\varepsilon-0.08923\cdot n+\\&+12.47315\cdot S_P\cdot\alpha+8.64754\cdot S_P\cdot\varepsilon-\\&-0.61847\cdot S_P\cdot n+0.00124\cdot\alpha\cdot\varepsilon-0.01086\cdot\alpha\cdot n-\\&-0.00089\cdot\varepsilon\cdot n+9.92229\cdot HRA\cdot S_P+\\&+0.0483\cdot HRA\cdot\alpha+0.02266\cdot HRA\cdot\varepsilon+\\&+0.00035\cdot HRA\cdot n-0.64906\cdot HRA\cdot S_P\cdot\alpha-\\&-0.17842\cdot HRA\cdot S_P\cdot\varepsilon+0.001\cdot HRA\cdot S_P\cdot n-\\&-0.00121\cdot HRA\cdot\alpha\cdot\varepsilon+0.00004\cdot HRA\cdot\alpha\cdot n-\\&-0.00001\cdot HRA\cdot\varepsilon\cdot n-0.18637\cdot S_P\cdot\alpha\cdot\varepsilon+\\&+0.00693\cdot S_P\cdot\varepsilon\cdot n+0.00011\cdot\alpha\cdot\varepsilon\cdot n+\\&+0.04049\cdot S_P\cdot\alpha\cdot n-0.00058\cdot S_P\cdot\alpha\cdot\varepsilon\cdot n+\\&+0.0093\cdot HRA\cdot S_P\cdot\alpha\cdot\varepsilon+0.07148\cdot HRA^2+\\&+762.22222\cdot S_P{}^2-0.0984\cdot\alpha^2+\\&+0.12431\cdot\varepsilon^2+0.0001\cdot n^2;\end{aligned}\tag{5}$$

$$\begin{aligned}P_y={}&481.6126-2.99736\cdot HRA-\\&-6.04416\cdot S_P-2.16\cdot\alpha-8.07467\cdot\varepsilon-\\&-0.06393\cdot n+0.00024\cdot HRA\cdot n-\\&-0.03189\cdot S_P\cdot n+0.01497\cdot HRA^2+\\&+82.22222\cdot S_P{}^2+0.0672\cdot\alpha^2+\\&+0.0676\cdot\varepsilon^2+0.00001\cdot n^2.\end{aligned}\tag{6}$$

Effective cutting power is determined from formula [22]:

$$N_e=\frac{P_z\cdot v}{1020\cdot 60},\tag{7}$$

where v is the speed of cutting, which is determined from formula:

$$v=\frac{\pi\cdot D\cdot n}{1000},\tag{8}$$

where D is the outer diameter of the cut tire; n is the rotation frequency of the machine spindle.

We shall further consider that in order to solve a problem on the optimization of energy consumption in the process of cutting tires, force P_z has the priority.

At the eighth stage, we carried out optimization of the operational parameters of the cutting process, specifically, rotation frequency of the machine spindle – n, in the range of 160–1.600 rpm at feed S_p in the range of 0.06–0.6 mm/rev and at constant values of hardness (HRA 64) and angles ($\gamma=10°$, $\varepsilon=45°$, $\alpha=10°$). To do this, using equation (5), we built a table of the optimization of spindle rotation frequency at different feed and constant values of hardness and geometrical parameters of the cutting tool (Table 1).

At the ninth stage, we optimized geometrical parameters of the cutting tool at five values of hardness: HRA 38, 64, 77, 90, 144. For this purpose, we built a table of the optimization of front angle γ for different values of hardness, constant operational parameters (n, S_p) and angles $\varepsilon=45°$, $\alpha=10°$ (Table 2).

Table 1

Optimization of spindle rotation frequency n at different feed S_p and constant values of hardness (HRA 64) and geometrical parameters of the cutting tool ($\gamma=10°$, $\varepsilon=45°$, $\alpha=10°$) (abridged)

Spindle rotation frequency, n, rpm	Feed, S_p, mm/rev	Hardness of material of the cutting tool, HRA	Front angle of the cutting tool, γ, degrees	Angle at top, ε, degrees	Rear angle, α, degrees	Cutting force P_z, N
160	0.06	64	10	45	10	146
250	0.06	64	10	45	10	116
630	0.06	64	10	45	10	84
1.000	0.06	64	10	45	10	80
1.600	0.06	64	10	45	10	92

Table 2

Optimization of front angle γ for different values of hardness, constant operational parameters ($n=1000$ rpm, $S_p=0.25$ mm/rev) and angles $\varepsilon=45°$, $\alpha=10°$ (abridged)

Spindle rotation frequency, n, rpm	Feed, S_p, mm/rev	Hardness of material of the cutting tool, HRA	Front angle of the cutting tool, γ, degrees	Angle at top, ε, degrees	Rear angle, α, degrees	Cutting force P_z, N
1.000	0.25	38	6	45	10	89
1.000	0.25	38	10	45	10	85
1.000	0.25	38	20	45	10	85
1.000	0.25	38	30	45	10	92
1.000	0.25	38	48	45	10	99
...	...	...	...	...	...	...
1.000	0.25	144	48	45	10	58

At the third stage, we built a table for the optimization of angle at the top ε at different values of hardness, constant operational parameters (n, S_p) and angles $\gamma=20°$, $\alpha=10°$ (Table 3).

We shall construct a table of the optimization of rear angle α at different values of hardness, constant operational parameters (n, S_p) and angles $\gamma=20°$, $\varepsilon=60°$ (Table 4).

Table 3

Optimization of angle at the top ε at different values of hardness, constant operational parameters ($n=1.000$ rpm, $S_p=0.25$ mm/rev) and angles $\gamma=20°$, $\alpha=10°$ (abridged)

Spindle's rotation frequency, n, rpm	Feed, S_p, mm/rev	Hardness of material of the cutting tool, HRA	Front angle of the cutting tool, γ, degrees	Angle at top, ε, degrees	Rear angle, α, degrees	Cutting force P_z, N
1.000	0.25	38	20	27	10	120
1.000	0.25	38	20	45	10	85
1.000	0.25	38	20	60	10	70
1.000	0.25	38	20	75	10	111
1.000	0.25	38	20	120	10	162
1.000	0.25	64	20	27	10	95
...	...	...	...	...	...	...
1.000	0.25	77	20	27	10	73
...	...	...	...	...	...	...
1.000	0.25	90	20	27	10	74
...	...	...	...	...	...	...
1.000	0.25	144	20	27	10	86
...	...	...	...	...	...	...
1.000	0.25	144	20	120	10	122

Table 4

Optimization of rear angle α at different values of hardness, constant operational parameters ($n=1.000$ rpm, $S_p=0.25$ mm/rev) and angles $\gamma=20°$, $\varepsilon=60°$ (abridged)

Spindle rotation frequency, n, rpm	Feed, S_p, mm/rev	Hardness of material of the cutting tool, HRA	Front angle of the cutting tool, γ, degrees	Angle at top, ε, degrees	Rear angle, α, degrees	Cutting force P_z, N
1.000	0.25	38	20	60	6	67
1.000	0.25	38	20	60	10	70
1.000	0.25	38	20	60	15	72
1.000	0.25	38	20	60	20	69
1.000	0.25	38	20	60	34	65
1.000	0.25	64	20	60	6	41
...	...	...	...	...	...	...
1.000	0.25	77	20	60	6	17
...	...	...	...	...	...	...
1.000	0.25	144	20	60	34	26

5. Results of studying energy efficiency of the process of cutting worn tires in half during disposal

As a result of the performed work, we derived a quadratic mathematical model of the formation of cutting forces in process of cutting a worn tire, which consists of two regression equations (5) and (6), respectively, for forces P_z and P_y.

The mathematical model constructed expresses a cutting forces dependence on the totality of geometrical parameters and hardness of a material of the cutting tool, as well as operational parameters of cutting, respectively. By using a mathematical model, it is possible to determine a set of optimal geometrical parameters and material of the cutting tool and operational parameters, which will ensure minimization of the cutting forces, and, therefore, of energy consumption required for the process of cutting in general.

The resulting mathematical model was next employed to optimize operational parameters of the process of cutting worn tires in half and to select the optimal geometrical parameters and material of the cutting tool.

For this purpose, we investigated function P_z for the extremum at variable n at fixed values $\alpha=10$, $\gamma=10$, $\varepsilon=45$, HRA=64 for different values of S_p. The functions obtained in line with model (5), and the determined points of minimum of spindle rotation frequency n, as well as the magnitudes of force P_z at these points, are given in Table 5.

Fig. 4 shows charts of functions $P_z(n)$ investigated for the extremum at spindle rotation frequency n.

We determined minimum point $n_{\min}=969.3$ rpm at feed of the cutting tool at 0.25 mm/rev. According to Table 5, we note that the minimum point corresponds to the frequency of 1.000 rpm.

Using mathematical model (5), we determined a function of dependence of P_z on angle at the top ε of the cutting tool at different values of hardness HRA and fixed magnitudes $\alpha=10$, $\gamma=20$, $S_p=0.25$ mm/rev, $n=1.000$ rpm and investigated it for the extremum. The functions, obtained for certain values of hardness HRA, and their points of minimum, as well as magnitudes of force P_z at these points, are given in Table 6.

Minimum point $\varepsilon_{\min}=53.254°$ at HRA=77. Therefore, this minimum point corresponds to $\varepsilon=53°$. Fig. 5 shows charts of functions $P_z(\varepsilon)$ investigated for the extremum by ε.

Table 5

Results of investigating function $P_z(n)$ for the extremum at fixed values of HRA, γ, ε, α and certain values of S_p

S_p	Function $P_z(n)$	Point of minimum n_{min}	Minimal value $P_z(n_{min})$
0.06	$P_z(n)=0.0001n^2-0.175103n+202.882$	875.515	126.229
0.1	$P_z(n)=0.0001n^2-0.179052n+202.072$	895.26	119.923
0.25	$P_z(n)=0.0001n^2-0.19386n+211.26$	969.3	117.306
0.4	$P_z(n)=0.0001n^2-0.208668n+256.749$	1043	147.893
0.6	$P_z(n)=0.0001n^2-0.228412n+370.755$	1142	240.325

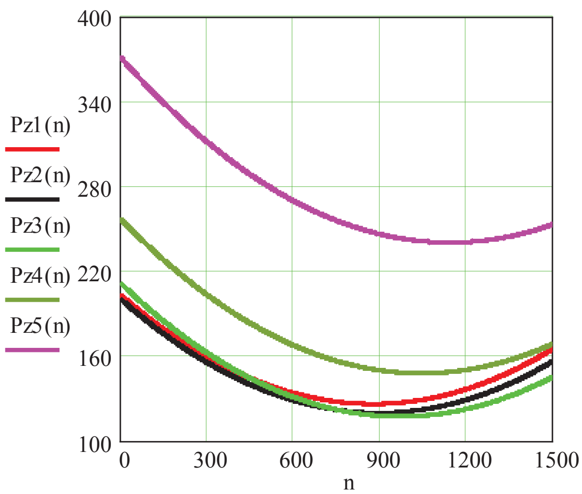

Fig. 4. Charts of functions $P_z(n)$ investigated for the extremum at spindle rotation frequency n

Table 6

Results of investigating function $P_z(\varepsilon)$ for the extremum at fixed values of n, S_p, γ, a and certain values of hardness HRA

HRA	Function $P_z(\varepsilon)$	Minimum point $y\varepsilon_{min}$	Minimal value $P_z(\varepsilon_{min})$
38	$P_z(\varepsilon)=012431\varepsilon^2-12.901\varepsilon+577.308$	51.89	242.589
64	$P_z(\varepsilon)=012431\varepsilon^2-13.127\varepsilon+491.086$	52.799	144.537
77	$P_z(\varepsilon)=012431\varepsilon^2-13.24\varepsilon+484.215$	53.254	131.674
90	$P_z(\varepsilon)=012431\varepsilon^2-13.353\varepsilon+501.505$	53.708	142.92
144	$P_z(\varepsilon)=012431\varepsilon^2-13.822\varepsilon+831.938$	55.595	447.722

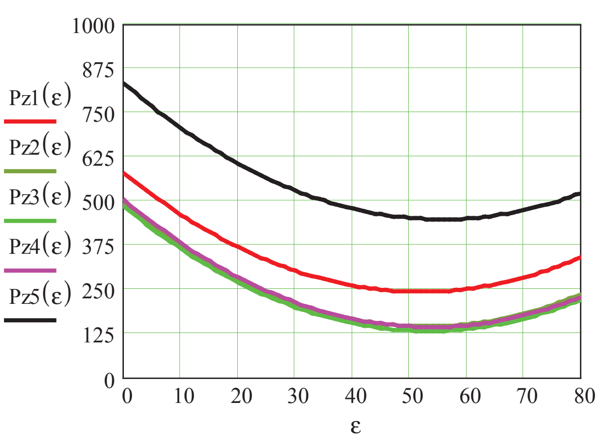

Fig. 5. Charts of functions $P_z(\varepsilon)$ investigated for the extremum by ε

We determined a function of force P_z depending on angle α for different values of hardness HRA and at fixed values n=1.000 rpm, S_p=0.25 mm/rev and angles γ=20°, ε=60°, and investigated it for the extremum. This function has a point of maximum. The functions obtained at certain values of HRA, their points of extremum, as well as maximal values of P_z at the points of extremum are given in Table 7.

Table 7

Results of investigating function $P_z(\alpha)$ for the extremum at fixed values of n, S_p, γ, ε and certain values of hardness HRA

HRA	Function $P_z(\alpha)$	Maximum point α_{max}	Maximal value $P_z(\alpha_{max})$
38	$P_z(\alpha)=-0.0984\alpha^2+13.664\alpha+205.176$	51.89	679.528
64	$P_z(\alpha)=-0.0984\alpha^2+13.481\alpha+88.351$	68.501	550.082
77	$P_z(\alpha)=-0.0984\alpha^2+13.389\alpha+66.178$	68.034	679.336
90	$P_z(\alpha)=-0.0984\alpha^2+13.297\alpha+68.106$	67.566	679.186
144	$P_z(\alpha)=-0.0984\alpha^2+13.915\alpha+335.039$	65.625	678.103

Fig. 6 shows charts of functions $P_z(\alpha)$ investigated for the extremum by α.

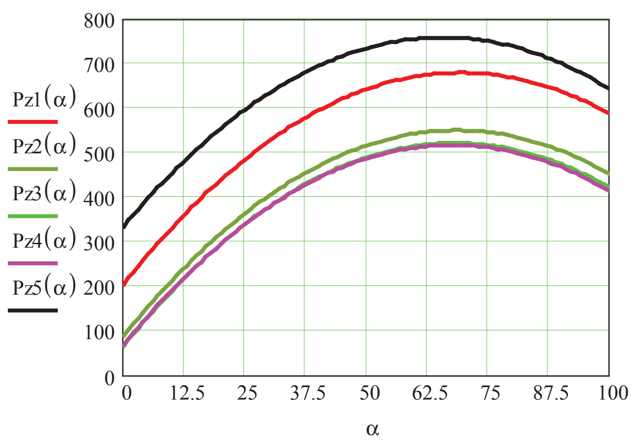

Fig. 6. Charts of functions $P_z(\alpha)$ investigated for the extremum by α

In order to achieve maximal energy efficiency of cutting worn pneumatic tires, it is required to carry out this process at the following operational parameters: spindle rotation frequency n=1.000 rpm, cutting tool feed S_p=0.25 mm/rev. The cutting tool should be made of the material with hardness HRA=77, with the following geometrical parameters: front angle γ=20°, angle at the top ε=53°, rear angle α=68°. It should be noted, however, that all these parameters will be optimal only when cutting tires made of the material and with the structure similar to the tires Bridgestone 7.1/11.0-5. In order to find optimal treatment parameters of other types of tires it is necessary to determine, and introduce to the regression equations, correction coefficients, which take into consideration strength of material for various types of tires.

First of all, to perform calculations in order to determine correction factors that take into consideration strength of the material for various types of tires, it is necessary to define the criterion that will determine a change in the cutting forces for the magnitude proportional to the examined coefficient.

A tensile strength limit – σ_{cTire}, MPa, was chosen as this criterion.

To determine tensile strength limit of the material that the examined tires are made of, we used the tensile testing machine UPM RIIZhT. Samples the size of 30×120 mm with thickness 7 mm were used for breaking. Research results are given in Table 8.

Table 8

Results of research on determining strength of the material of different tires

Tire name	Tire thickness (without protector), mm	Tensile strength limit – σ_{cTire}, MPa
Bridgestone 7.1/11.0-5 (Kart Tires)	7	4.6
Vega 7.1/11.0-5 (Kart Tires)	7	4
Hankook Ventus Prime 2 K115 195/55R15 (summer)	10	22
Hankook Ventus Prime 2 K115 195/55R15 (winter)	10	27
Michelin X MultiWay 3D XDE 315/70R22.5 (all-season)	16	115
Michelin XDW ice grip green 315/70R22.5 (winter)	16	121

Correction factor will be denoted K_σ; tensile strength limit of the tires Bridgestone 7.1/11.0-5, which were utilized in experiments for obtaining data for a mathematical model, – σ_{cModel}.

We shall express correction factors through the values of the tires' tensile strength limit.

The formula for determining a correction factor for different tires will take the form:

$$K_\sigma = \frac{\sigma_{cTire}}{\sigma_{cModel}}, \quad (9)$$

where σ_{cTire} is the material's tensile strength limit of the tire whose factor is being determined.

Fot the tires Bridgestone 7.1/11.0-5, K_σ is, respectively, equal to 1.

To confirm validity of influence of the correction factors, we performed additional experimental studies in order to determine cutting forces. We selected the following tires as experimental samples: Hankook Ventus Prime 2 K115 195/55R15 (summer) and Michelin XDW ice grip green 315/70R22.5 (winter). Results of research on determining forces when cutting tires, tensile strength limits and correction factors are given in Table 9.

Table 9

Results of research on determining forces when cutting tires, tensile strength limits and correction factors

Tire name	Tensile strength limit – σ_{cTire}, MPa	Cutting force – P_z, N	Correction factor K_σ of regression equation
Bridgestone 7.1/11.0-5 (Kart Tires)	4.6	14	1.000
Vega 7.1/11.0-5 (Kart Tires)	4	12	0.869
Hankook Ventus Prime 2 K115 195/55R15 (summer)	22	69	4.783
Hankook Ventus Prime 2 K115 195/55R15 (winter)	27	82	5.869
Michelin X MultiWay 3D XDE 315/70R22.5 (all-season)	115	350	25.000
Michelin XDW ice grip green 315/70R22.5 (winter)	121	365	26.300

Using the Microsoft Excel 2013 software, we constructed a chart of dependences of cutting forces on the tensile strength limit of different tires (Fig. 7), which is described by the following equation:

$$y = 3.0264x + 0.4068. \quad (10)$$

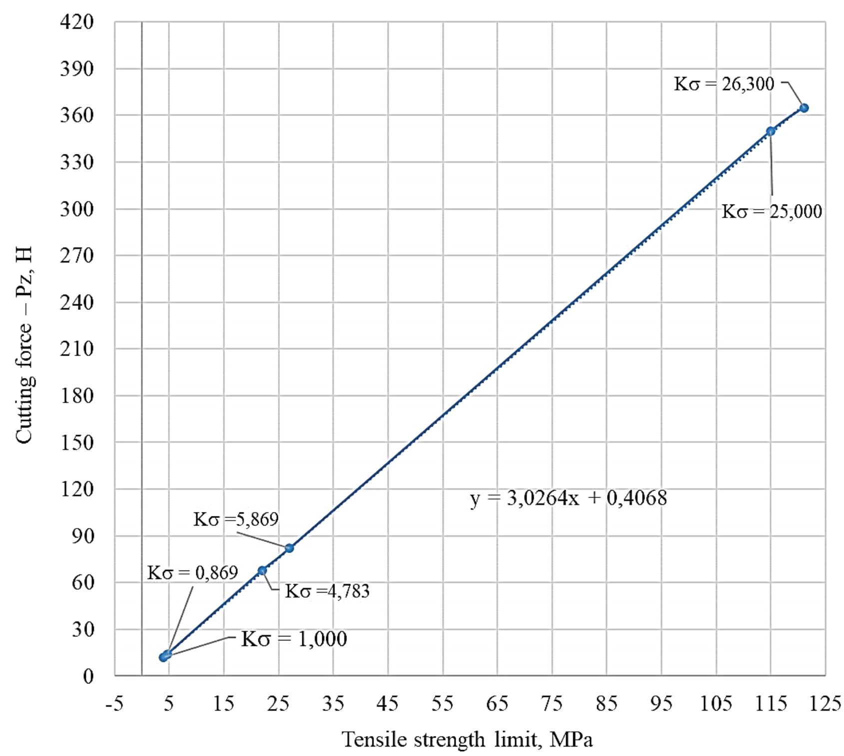

Fig. 7. Chart of dependences of cutting force on tensile strength limit of materials of different tires

Substituting x in equation (10) with the tire material's tensile strength limit σ_{cTire}, we obtained equation of dependences of cutting forces on tensile strength limit of materials of different tires:

$$y = 3.0264 \cdot \sigma_{cTire} + 0.4068. \quad (11)$$

Regression equation (5), taking into consideration the equation of dependences of the cutting force on tensile strength limit of materials of different tires (11), takes the following form:

$$\begin{aligned} P_z &= 0.0000403 \cdot n^2 + 0.0505698 \cdot \varepsilon^2 + 0.0290778 \cdot HRA^2 + \\ &+ 310.072 \cdot S^2 - 0.0400291 \cdot \alpha^2 + 0.2163249 \cdot HRA^2 \cdot \sigma + \\ &+ 2306.7893333 \cdot S^2 \cdot \sigma - 0.2977978 \cdot \alpha^2 \cdot \sigma + \\ &+ 0.3762151 \cdot \sigma \cdot \varepsilon^2 + 0.0003 \cdot \sigma \cdot n^2 - 5.2672918 \cdot HRA - \\ &- 242.3767976 \cdot S + 2.2427734 \cdot \alpha + 3187.482288 \cdot \sigma - \\ &- 6.0076408 \cdot \varepsilon - 0.0362999 \cdot n + 4.036389 \cdot HRA \cdot S + \\ &+ 0.0196499 \cdot HRA \cdot \alpha - 39.1861647 \cdot HRA \cdot \sigma + \\ &+ 0.0092188 \cdot HRA \cdot \varepsilon + 5.0740781 \cdot S \cdot \alpha - \\ &- 1803.168978 \cdot S \cdot \sigma + 3.5178199 \cdot S \cdot \varepsilon + \\ &+ 0.0001407 \cdot HRA \cdot n - 0.2515932 \cdot S \cdot n + \\ &+ 16.6851752 \cdot \alpha \cdot \varepsilon - 44.6940123 \cdot \sigma \cdot \varepsilon - \\ &- 0.0044167 \cdot \alpha \cdot n - 0.2700543 \cdot \sigma \cdot n - 0.0003627 \cdot \varepsilon \cdot n + \\ &+ 37.7487464 \cdot S \cdot \alpha \cdot \sigma - 0.0758154 \cdot S \cdot \alpha \cdot \varepsilon + \\ &+ 26.1709194 \cdot S \cdot \sigma \cdot \varepsilon + 0.0000175 \cdot HRA \cdot \alpha \cdot n + \\ &+ 0.0010464 \cdot HRA \cdot \sigma \cdot n - 0.0000039 \cdot HRA \cdot \varepsilon \cdot n + \\ &+ 0.0164698 \cdot S \cdot \alpha \cdot n - 1.8717344 \cdot S \cdot \sigma \cdot n + \\ &+ 0.0028187 \cdot S \cdot \varepsilon \cdot n + 0.0037561 \cdot \alpha \cdot \sigma \cdot \varepsilon - \\ &- 0.0328581 \cdot \alpha \cdot \sigma \cdot n + 0.0000453 \cdot \alpha \cdot \varepsilon \cdot n - \\ &- 0.002698 \cdot \sigma \cdot \varepsilon \cdot n - 0.2640395 \cdot HRA \cdot S \cdot \alpha + \\ &+ 30.0288288 \cdot HRA \cdot S \cdot \varepsilon + 0.0004061 \cdot HRA \cdot S \cdot n + \\ &+ 0.1461858 \cdot HRA \cdot \alpha \cdot \sigma - 0.0004909 \cdot HRA \cdot \alpha \cdot \varepsilon + \\ &+ 0.0685837 \cdot HRA \cdot \sigma \cdot \varepsilon - 1.964329 \cdot HRA \cdot S \cdot \alpha \cdot \sigma + \\ &+ 0.0037818 \cdot HRA \cdot S \cdot \alpha \cdot \varepsilon - 0.5399703 \cdot HRA \cdot S \cdot \sigma \cdot n - \\ &- 0.0036522 \cdot HRA \cdot \alpha \cdot \sigma \cdot \varepsilon - 0.5640308 \cdot S \cdot \alpha \cdot \sigma \cdot \varepsilon + \\ &+ 0.0001304 \cdot HRA \cdot \alpha \cdot \sigma \cdot n - 0.0000288 \cdot HRA \cdot \sigma \cdot \varepsilon \cdot n + \\ &+ 0.1225278 \cdot S \cdot \alpha \cdot \sigma \cdot n - 0.0002379 \cdot S \cdot \alpha \cdot \varepsilon \cdot n + \\ &+ 0.0209696 \cdot S \cdot \sigma \cdot \varepsilon \cdot n + 0.0003369 \cdot \alpha \cdot \sigma \cdot \varepsilon \cdot n + \\ &+ 0.0281346 \cdot HRA \cdot S \cdot \alpha \cdot \sigma \cdot \varepsilon - \\ &- 0.0017695 \cdot S \cdot \alpha \cdot \sigma \cdot \varepsilon \cdot n + 428.4522187. \end{aligned} \quad (12)$$

To confirm the adequacy of equation (12), we estimated homogeneity of variances of the estimated and experimental values of forces when cutting tires using a statistical Fischer criterion. The analysis was conducted at two points of the plan: K_σ=4.783 (Hankook Ventus Prime 2 K115 195/55R15 – summer), and K_σ=26.300 (Michelin XDW ice grip green 315/70R22.5 – winter); we estimated six values of forces at each point (three experimental, three examined), alternating through one value. Results of calculations are given in Table 10.

Table 10 demonstrates that F at significance α=5 % is lower than the tabular permissible values F_{table}, respectively: $F<F_{table}$; 0.350<0.507, indicating the uniformity of variance estimates and the adequacy of equation (12).

Table 10

Estimation of homogeneity of variances of the estimated and experimental values of forces when cutting tires using a statistical Fischer criterion

No. of experiment	γ_u	y_u, N	$y_{\bar{u}}$, N	S^2_{yu}	F	F_{table} at significance α=5 % [20]
1	1	69	68.7	3.22	1.349	4.280
	2	66	68.7			
	3	69	68.7			
	4	71	68.7			
	5	69	68.7			
	6	68	68.7			
2	1	365	365.7	2.39		
	2	368	365.7			
	3	365	365.7			
	4	364	365.7			
	5	365	365.7			
	6	367	365.7			

6. Discussion of results of studying energy efficiency of the process of cutting worn tires in half when disposing of them

The result of the conducted study is the proposed technique for overcoming the difficulties described in [5], which occur in the technological process of the disposal of worn tires. With this purpose, we obtained a quadratic mathematical model that determines cutting forces in process of shredding worn automobile tires and which consists of two regression equations for calculating forces P_z and P_y.

It enables substantiated optimization of operational parameters for the process of cutting worn automobile pneumatic tires, specifically, geometrical parameters of the cutting tool. It also makes it possible to choose optimal material of the cutting tool, which ensures minimal energy costs and determine correction factors for regression equations for different types of tires. Specifically, the minimization of cutting forces can be provided, and, consequently, and reduction of energy consumption by technological equipment in the process of shredding worn pneumatic tires. The minimum values of forces Pz are in the range of magnitudes of spindle rotation frequency 900–1,100 rpm at feed of the cutting tool 0.25 mm/rev.

In order to ensure maximal energy efficiency of the process of cutting worn pneumatic tires, it is necessary to apply the cutting tool made of the material of hardness HRA=77 with geometrical parameters: γ=20°, ε=53°, α=68°, spindle rotation frequency n=1.000 rpm, feed of the cutting tool S_p=0.25 mm/rev.

Front angle γ of the cutting tool does not significantly affect the formation of cutting force P_z but ensures its minimal value at γ=20°.

There is a shortcoming in the present work: results of the study match most accurately the tires with a rim diameter from 11 to 22.5 inches. To obtain operational parameters of the process of cutting the tires of larger diameter in half, including very large ones, it is necessary to conduct further studies.

The applied aspect of employing the obtained scientific result is the improvement of a standard technological process to dispose of worn pneumatic tires, which is described in paper [4].

The obtained results allow us to continue theoretical and experimental studies of the process of preliminary shredding of worn tires, specifically, cutting out of bead rings.

7. Conclusions

1. We obtained a quadratic mathematical model for determining cutting forces in the process of cutting the worn automobile tires Bridgestone 7.1/11.0-5 in half, which consists of two regression equations for determining forces P_z and P_y.

2. Correction factors were derived and introduced to the regression equation for determining forces P_z and P_y, which take into consideration strength of the material that the tire is made of, in order to define effective parameters for the process of cutting tires of the types that differ from the tires Bridgestone 7.1/11.0-5.

3. We determined effective operational parameters of the process of cutting worn tires in half, which ensure minimal energy costs: spindle rotation frequency n=1.000 rpm, feed of the cutting tool S_p=0.25 mm/rev.

4. Effective hardness of the cutting tool's material is determined (HRA=77), which is used for cutting worn tires in half and ensures minimal energy costs.

5. Effective geometrical parameters of the cutting tool are determined: front angle γ=20°, angle at the top ε=53°, rear angle α=68°, which ensure minimal energy consumption of the cutting process.

6. In order to ensure maximal energy efficiency of the process of cutting worn pneumatic tires, it is necessary to apply the cutting tool made of the material of hardness HRA=77 with geometrical parameters: γ=20°, ε=53°, α=68°, spindle rotation frequency n=1.000 rpm, feed of the cutting tool S_p=0.25 mm/rev.

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INVESTIGATION OF THE PROCESS OF THREAD EXTRUSION USING THE ULTRASOUND

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Досліджено та змодельовано процес видавлювання різі з накладанням ультразвукових коливань. На основі реологічної моделі деформування ідеального пружно-пластичного тіла розроблені залежності для розрахунку контактних тисків та питомої сили тертя. Змодельовані контактні явища, що проходять в зоні деформації. Визначені оптимальні параметри видавлювання різі. Аналітично визначено діаметр отвору під видавлювання різі з накладанням ультразвукових коливань

Ключові слова: ультразвукове видавлювання різі, частота коливань, амплітуда коливань, контактний тиск

Исследован и смоделирован процесс выдавливания резьбы с наложением ультразвуковых колебаний. На основе реологической модели деформирования идеального упруго-пластического тела выведены зависимости для расчета контактных давлений и удельной силы трения. Смоделированы контактные явления, которые проходят в зоне деформации. Определены оптимальные параметры выдавливания резьбы. Аналитически определен диаметр отверстия под выдавливание резьбы с наложением ультразвуковых колебаний

Ключевые слова: ультразвуковое выдавливания резьбы, частота колебаний, амплитуда колебаний, контактное давление

1. Introduction

Threaded joints are the most common kind of detachable connections in mechanical engineering. An analysis of the existing methods for obtaining internal threads [1, 2] reveals that one of the promising methods of the formation of threaded surfaces is the method of plastic shape-formation (extrusion) of threads by spiral fluted taps. This method possesses