Проведено дослідження технологічних процесів відновлення зношених деталей сільськогосподарських машин (плужних лемешів, культиваторних лап), що працюють в умовах підвищеного абразивного зношування. Визначено вплив режимних параметрів технологічного процесу на якість відновленої поверхні ріжучих елементів робочих органів машин в умовах звичайного і вібраційного деформування. Відзначено, що технології відновлення на основі вібраційних коливань дозволяють створювати нові методи обробки, які характеризуються більш високою інтенсивністю: фізико-механічними властивостями матеріалу відновлених деталей, формою і розмірами, режимами обробки. Проведено тензометричні дослідження зміни параметрів ріжучих елементів робочих органів ґрунтообробних машин, що дозволили визначити величину деформацій в процесі обробки деталей. Розроблено математичну модель динаміки абразивного зношування вище зазначених робочих органів, яка дозволила визначити закономірності розподілу інтенсивності зносу ріжучого елемента робочого органу.

На підставі отриманих кривих щільності розподілу величин зносу ріжучих елементів зазначених деталей визначено закон зношування, що дозволило виявити закономірності зміни деформаційно-напруженого стану робочої поверхні ріжучого елемента. Зроблено оцінку впливу основних факторів на процеси, що протікають в матеріалі деталей при експлуатації. Встановлені основні фактори вібраційної обробки робочої поверхні деталей: амплітуда, частота коливань обробного інструменту, час зміцнення. Встановлено критерії граничного стану деталей в умовах абразивного зношування: товщину кромки ріжучого елемента деталей та зміна розміру. Встановлена позитивна роль стискаючих напружень при обробці матеріалу деталей в підвищенні їх зносостійкості. Встановлено залежність величини зносу деталей від наступних основних факторів: матеріалу, способу відновлення, часу роботи. Доведено, що застосування вібраційних коливань обробного робочого органу, знижує інтенсивність зношування деталей ґрунтообробних машин, що є важливим і актуальним для підвищення надійності сільськогосподарських машин

Ключові слова: зміцнююча обробка, пластичне деформування, вібраційне зміцнення, залишкові напруження, шорсткість поверхні, інтенсивність зношування

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SUBSTANTIATION OF PARAMETERS FOR THE TECHNOLOGICAL PROCESS OF RESTORING MACHINE PARTS BY THE METHOD OF PLASTIC DEFORMATION

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1. Introduction

Application of effective technological processes, both in the manufacture of new parts and when restoring the worn-out ones, contributes to improving the strength of their contacting surfaces and, therefore, durability and reliability.

Changes in the qualitative characteristics of technological processes related to the operation of modern machines present challenges to the repair service as they imply improving their resource. A significant share (up to 25 %) all costs associated with the use of machines refer to the cost of repairs and maintenance [1].

Improving the durability of parts is a set of tasks: the use of materials with the required physical and mechanical properties; the use of efficient technologies in manufacture and restoration of parts; optimal operating modes, etc. [2].

The reliability of agricultural machines is typically determined by the durability of pairs at friction. In this regard, it is an important issue to conduct a research aimed at searching for effective technologies of strengthening the surface of layers of parts in contact.

Machining quality issues are very important as they contribute to obtaining the required roughness of surfaces at friction. These requirements are met by the vibration, ultrasonic treatment, as well as methods for thin plastic deformation that provide for the required state of parts' surfaces due to the compaction of their outer layers of material.

Effective restoration technology is such a technology at which total cost of restoration and operation, per unit of output or work produced, would be minimal.

The relevance of this issue is associated with comprehensive studies into the vibration treatment of parts' surfaces that operate in abrasive environment. Specifically, this applies to determining the optimal values for the restoration process parameters: the amplitude and frequency of oscillations in a machining tool and the duration of a part's material treatment.

2. Literature review and problem statement

Resolving a task on improving the reliability of agricultural machinery represents the reserve for productivity and production efficiency, which would make it possible to reduce by 25–30 % those energy resources that are required to deal with failures related to wear of parts [2].

An analysis of paper [3] indicates that a significant part of the worn parts and assembly units has a considerable residual value. During restoration, 20 to 30 times less materials are used than in the manufacture of new parts, but the authors consider this issue only conceptually; consequently, there is a need to examine this issue in greater detail.

Improved durability of components and assembly units can be achieved by using advanced technologies for improving the properties of materials, including the application of vibration oscillations. Authors of [4] note that this can be achieved by applying different structural schemes in the process of treatment under pressure. However, the scheme proposed in the work does not make it possible to apply it at restoration of components.

Several researchers [5, 6] note that the use of efficient technologies in the manufacture and restoration of parts contributes to the enhancement of fatigue strength and reduces initial roughness of a material. This is due to the presence in a material's surface layer of residual stresses of compression. It should be noted, however, that one of the main challenges in resolving the issue on reliability, durability, and fatigue strength of machine parts is to choose such machining modes that would ensure the presence of residual stresses of compression in the surface layer of a parts' material.

According to [7], the operation of machine parts is often accompanied by the formation in layers adjacent to the surface of a new structure compared to the core. Residual stresses occur in it. However, their influence on the strength characteristics for a material of parts that operate in soil environment has not yet been fully examined given the insufficient research in this area.

As authors of [8] note, maintaining the indicators for durability and strength characteristics of arable surfaces is achieved by forming an optimal structure of surface layers, which partly involves the application of directed oscillations. However, this process has not been fully revealed in the work, which imposes certain limitations on the use of the proposed solutions.

Improvement of durability in the restored (manufactured) parts in most cases can be ensured by giving a material of the surface layer the required physical and mechanical properties under cyclic loading [9]. The surface layer during its deformation exhibits all the characteristics of deformation resistance (limits of durability, fluidity, elasticity, hardness, strength, fatigue, etc.). In this case, plasticity is compromised, that is a metal becomes more fragile.

Among the promising methods for plastic surface deformation is the method of vibration-centrifugal strengthening treatment [10]. As noted in [11], it improves the mechanical properties of a part's working surface. Studying the physical-mechanical properties of a part's surface layer, hardened by this method, indicate its high efficiency: productivity increased by 4...6 times, which confirms its economic effectiveness [2].

In [12], authors point to the increased efficiency of the technological process of parts restoration when applying vibration oscillations. Yet, despite the benefits, the issue of searching for the optimal parameters at plastic deformation remain unresolved.

At vibration machining, there is a periodical detachment of the surface of the tool's working part from the machined workpiece's surface. In this case, there occurs the microprocess of unloading the contacting surfaces of the tool and a workpiece. Dynamic effect increases with an increase in the amplitude and frequency of oscillations of the machining tool [13]. These parameters, as noted by authors of [14], exert a significant impact on the part's surface hardening.

The wear resistance of parts in tillage machines that are exposed to vibration treatment is largely determined by the hardened layer depth. However, paper [15] emphasized a lack of specific recommendations for determining its values in the literature.

In this connection, a comprehensive research is needed into the application of vibration oscillations in the technological processes related to restoring the parts of tillage machines.

3. The aim and objectives of the study

The aim of this study is to improve the reliability of parts in tillage machinery by determining the rational technological parameters at their restoration and strengthening using a method of vibration deformation. To achieve the set aim, the following tasks have been solved:

– to analyze operating conditions of parts in tillage machines in order to restore them using a vibration method;

– to explore and determine technological parameters for the vibration treatment of the specified parts that would make it possible to control the quality of their restoration.

4. Procedure for determining quality indicators

Quality indicators for the strengthening treatment of machine parts at surface plastic deformation of their material include the microhardness of a surface, a strengthened layer thickness, and the degree of strengthening, the roughness of a machined surface, the magnitude of residual stresses, and the character of their distributions.

The choice of technology for parts operating under conditions of abrasive wear (plowshares, cultivator sweeps, etc.) was substantiated by considering the degree of wear, the nature of defects in their cutting elements, material's properties, structural parameters, and machining precision. An analysis of the condition of the restored and new specified parts was performed considering their wear during laboratory and field testing.

A laboratory study into parts strengthening by a vibration deformation method was carried out at the fabricated installation composed of a vibration exciter, a hydraulic system of lifting and lowering, and auxiliary equipment. Deformation rate was adjusted via a V-belt variator of the pump drive.

The magnitude of deformation was registered by a pressure gauge and a device to stabilize its readings.

To study the effect of the type of loading (regular and vibrational) on the strength characteristics of machined surface, the study was conducted using the sample models, as well as new disks for diggers, plowshares, and cultivator sweeps. The amplitude of vibrator's oscillations was 0.5–1.0 mm, oscillation frequency of the machining tool was 700–2.100 min^{-1}, treatment duration was 20–40 s.

A study into the structure and properties of the specified parts' material was carried out using the microscope MIM-8, the hardness tester TM-2M, the microhardness tester PMT-3M. The surface roughness of samples was measured at the portable profilometer 253 (No. B-334).

Strain testing was conducted using equipment that included the oscillograph Hitachi V-1565, the 12-channel installation TUP-12. Advance speed of photo paper into the oscillograph was 5 cm/s. The sensors used were the wire strain gauges with a base of 5 mm and a resistance of 100 Ohm. Strain gauges were applied to the samples with the glue BF-88 and were exposed to heat treatment, according to the instructions at the label.

The degree of surface compaction ε_y was determined from the following dependence:

$$\varepsilon_y = \frac{H_y - H_n}{H_n} \cdot 100\,\%, \tag{1}$$

where H_y is the hardened surface microhardness; H_n is the microhardness of the non-hardened (primary) surface.

Evaluation of the surface roughness was conducted according to criteria R_a and R_z.

Samples for a metallographic study were cut out of the specified parts restored in different ways, the size of 30×20×30 mm.

The study has found that a change in the thickness of the cutting edge of a cultivator sweep and a plowshare is distributed in line with the normal law and the following dependence:

$$f(h,t) = \frac{1}{\sqrt{2\pi\sigma_h}} \exp\left\{-\frac{h-\bar{h}(t)^2}{2\sigma_h^2}\right\}, \tag{2}$$

where h is the current value for the thickness of the blade's cutting edge; $\bar{h}(t)$ is the average value for the thickness of a blade's edge; σ_h is the rms deviation at time t.

At plastic deformation of the sample due to a change in its size, the compaction of a material occurs, which contributes to strengthening the machined surface [16].

Degree of compaction (strengthening) η was determined from the following dependence:

$$\eta = \log \varepsilon \frac{\delta_S}{\delta_T}, \tag{3}$$

where ε is the logarithmic degree of deformation; δ_S is the flow stress of a metal; δ_T is the yield strength.

5. Results of research into the strengthening of a material for the working bodies of cultivator sweeps, plowshares, and diggers' disks

5. 1. Modelling the wear dynamics of cutting elements

Construction of a mathematical model of the abrasive wear dynamics of cutting elements in tillage machines included the following stages:

a) processing the acquired data base on existing technical processes related to the restoration processes of specified parts;

b) assessment of the impact of the magnitude of obtained key factors on the processes that occur in the parts' material at operation under conditions of abrasive environment;

c) modelling the dynamics of the course of processes in the surface layers of the specified parts.

Surface wear of the machining working bodies of cultivator sweeps and plowshares can be described by a differential equation:

$$\frac{dJ}{dt} = \varphi(J,t) + \psi(J,t)\cdot\xi(t), \tag{4}$$

where $\varphi(J,t)$ and $\psi(J,t)$ are the functions that characterize the wear intensity; $\xi(t)$ is a random component; t is the wear duration.

Since the process of wear is random, it can be estimated by the probability that satisfies the integral equation by Markov [17]:

$$\frac{d\omega}{dt} = \frac{da(J,t)\omega}{dJ} + \frac{1}{2}\frac{d\mathrm{B}(J,t)\omega}{dJ^2}, \tag{5}$$

where $a(J,t)$ and $\mathrm{B}(J,t)$ are the coefficients that describe, respectively, the mean rate of the random process of wear.

Density of durability distribution is defined by the magnitude of wear of cutting elements:

$$f(t) = \int_0^\infty g(t)\gamma(t-t_0)\mathrm{d}t, \tag{6}$$

where $g(t)$ is the density of distribution of the probability of the analyzed process for the permissible value of wear; $\gamma(t-t_0)$ is the density of distribution of the initial stage in the process of wear:

$$g(t) = \frac{d}{dt}\int_{-\infty}^{t}(J_0, t_0, J, t). \tag{7}$$

Solving equations (5) and (6) in tandem has made it possible to determine the values for the density of distribution of wear of cutting elements (Fig. 1).

The density of durability distribution of cutting elements is defined by the magnitude of wear in accordance with a homogeneous Markovian process [17].

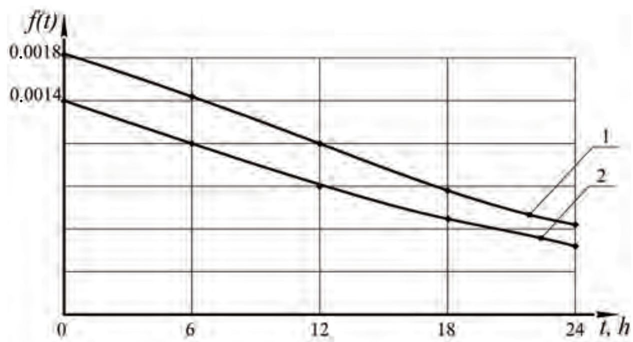

Fig. 1. Density of durability distribution of cutting elements: 1 – plowshare; 2 – cultivator arrow sweep

5. 2. Determining the optimal parameters for strengthening treatment

Experimental research into the process of strengthening the material for parts that operate under conditions of intensive abrasive wear has established criteria for the limit of their state [7].

For plowshares of tillage machines, such criteria are considered to be the magnitude of sock wear Δh and the wall thickness of plowshare Δa; for cultivator arrow sweeps – the wear of a wing width at the blade end Δc and the sock wear Δh.

Results from experimental study into the wear of cultivator sweeps and plowshares are given in Table 1.

Table 1

Results of experimental study into the wear of parts exposed to vibration strengthening

Experiment No.	Oscillation amplitude of machining tool A, mm	Oscillation frequency n, min^{-1}	Duration of strengthening t, s	Wear magnitude	
				Types of sweeps	Types of plowshares
1	0.5	700	20	1.22	1.42
2	0.5	700	30	0.82	1.24
3	0.5	700	40	0.77	1.20
4	0.5	1,400	20	0.91	0.85
5	0.5	1,400	30	0.49	1.47
6	0.5	1,400	40	0.63	1.40
7	0.5	2,100	20	0.97	1.68
8	0.5	2,100	30	0.82	1.46
9	0.5	2,100	40	1.01	1.34
10	0.75	700	20	1.04	1.47
11	0.75	700	30	0.80	1.22
12	0.75	700	40	1.00	1.19
13	0.75	1,400	20	0.64	0.99
14	0.75	1,400	30	0.47	0.95
15	0.75	1,400	40	0.49	0.91
16	0.75	2,100	20	0.78	1.28
17	0.75	2,100	30	0.67	1.24
18	0.75	2,100	40	0.69	1.12
19	1.0	700	20	1.08	1.80
20	1.0	700	30	0.97	1.44
21	1.0	700	40	1.03	1.66
22	1.0	1,400	20	0.94	1.32
23	1.0	1,400	30	0.71	1.11
24	1.0	1,400	40	0.74	1.24
25	1.0	2,100	20	1.10	1.79
26	1.0	2,100	30	0.98	1.10
27	1.0	2,100	40	1.05	1.72

We have experimentally established the following parameters for the vibration strengthening of the specified parts that ensure the technological process of strengthening treatment. When restoring a plowshare, the oscillation amplitude of machining tool: $A=0.5$ mm, treatment time $t=20$ s, oscillation frequency $n=1{,}400$ min^{-1}.

The optimum machining modes for cultivator arrow sweeps are: oscillation amplitude $A=0.75$ mm; oscillation frequency of machining tool $n=1{,}400$ min^{-1}; time of strengthening $t=30$ s.

An analysis of microstructural study has revealed that the vibration treatment produces a more uniform and fine-grained microstructure (Fig. 2, 3), which creates conditions that contribute to strengthening the machined surface.

Fig. 2. Microstructure of steel 45 surfaced with sormite without strengthening, ×50

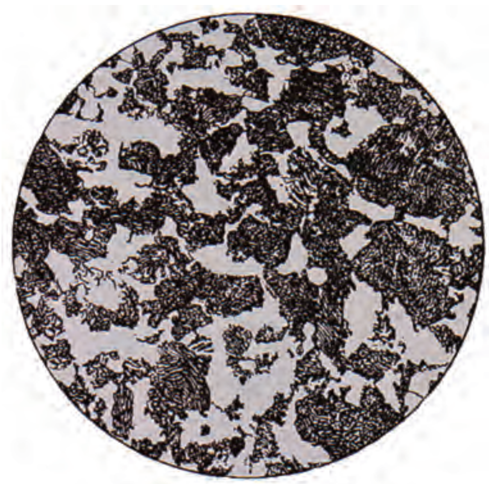

Fig. 3. Microstructure of steel 45 surfaced with sormite and vibration strengthening, ×50

It was revealed that based on the depth of a surfacing material and the base of a cultivator sweep restored by welding a corner plate made from steel 45 surfaced with sormite, the microhardness after vibration strengthening amounted to the following values given in Table 2.

Table 2

Results of change in microhardness

Layer depth, mm	0.5	1.0	1.5	2.0
Surfacing material				
Microhardness, N/mm^2	701	497	388	317
Material of the sweep base				
Microhardness, N/mm^2	609	452	356	302

When restoring parts of tillage machinery, the material of their cutting elements exhibits residual stresses that significantly affect their durability: residual compressive stresses contribute to strength improvement while residual stresses of stretching reduces it.

Based on the acquired strain gauge data, we plotted the curves of residual stresses for the depth of cutting elements (Fig. 4).

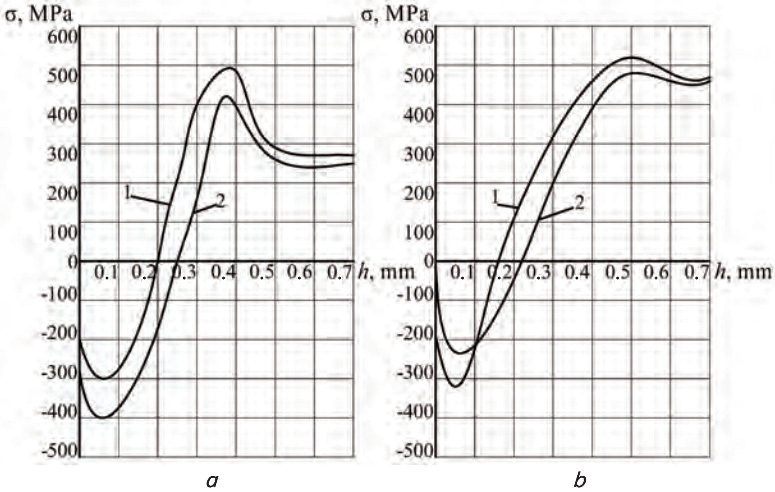

Fig. 4. Distribution of residual stresses depending on the restoration method: *a* — cultivator sweeps: 1 — restored by welding corner plates made from steel 45 followed by surfacing with sormite and vibration strengthening, 2 — new sweeps, strengthened by the vibration method; *b* — plowshares: 1 — restored by welding tires made from steel 45 followed by surfacing with sormite and vibration strengthening, 2 — new plowshares, strengthened by vibration deformation

Table 4

Change in the linear wear of a cutting element depending on the strengthening method and operation duration

Types of parts	Value for wear magnitude, mm			
	6 h	12 h	18 h	24 h
1. A cultivator sweep, restored by welding a corner plate made from steel 45 followed by surfacing with sormite	1.30	2.60	3.92	5.15
2. A cultivator sweep, restored by welding a corner plate made from steel 45 followed by surfacing with sormite and vibration strengthening	1.12	2.28	3.40	4.22
3. A plowshare (new), treated by vibration strengthening	0.28	0.60	0.79	1.14
4. A plowshare, restored by welding the tires made from steel 45 followed by surfacing with sormite and vibration strengthening	0.25	0.52	0.59	0.80

5. 3. Evaluation of wear-resistance of parts in tillage machines

An experimental (bench) study into the wear resistance of a material for the specified parts, restored by different methods, was carried out at a soil channel, provided the similarity between the conditions for their work at the bench and during operation.

Specifications for the bench that was used during testing are given in Table 3.

Table 3

Characteristics of the testing bench

Bench parameters	Values
1. Bench dimensions, mm:	
length	10,000
width	1,200
height	800
2. Power of electric motor, kW	10
3. Maximal traction effort, N	3,000
4. Speed range, m/s	1–3

To assess the impact of composition of the abrasive mixture in a soil channel on the magnitude of wear of cutting elements in the specified parts, we used the following formulation: 65–70 % of quartz sand and gravel, 30–35 % of clay, cement, and dust [18].

Bench testing has made it possible, in a relatively short time, to evaluate the examined variants of parts restoration and to determine the most effective one.

Research results (Table 4) show that the magnitude of parts wear depends on the following basic factors: their material, treatment technique, and operation time.

Data from Table 4 show that the magnitude of wear of cultivator sweeps, restored by welding the corner plates made from steel 45 surfaced with sormite and exposed to vibration strengthening is 1.22 times less than that at conventional restoration.

The intensity of wear of plowshares, restored by welding the tires made from steel 45 followed by surfacing with sormite and vibration strengthening is 1.42 times lower compared to new plowshares, exposed to vibration strengthening.

Fig. 5 shows the plowshare, restored by welding the tires made from steel 45 followed by surfacing with sormite and vibration strengthening.

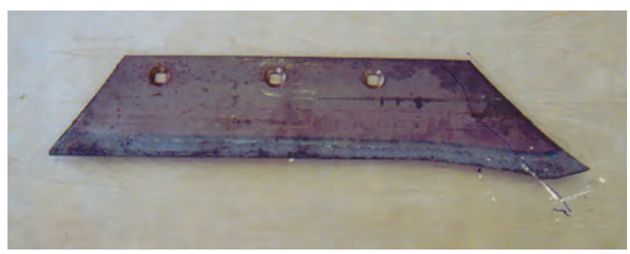

Fig. 5. The plowshare that was restored by welding the tires made from steel 45 followed by surfacing with sormite and vibration strengthening

Operational indicators for the specified variants of plowshares demonstrated their correspondence to bench testing. More reliable (by 31 %) are the plowshares that were restored by welding the tires made from steel 45 followed by the automatic surfacing with sormite and were strengthened by vibration deformation.

6. Discussion of results of studying the improvement of wear resistance of parts in tillage machines through vibration strengthening

Our study has made it possible to develop a technological process for restoring the parts of tillage machinery using a vibration strengthening method. A special feature of this technology is the use of vibration oscillations at plastic deformation to compensate for the worn surfaces of parts. The chosen optimal parameters for the machining tool enabled the reduction in the magnitude of parts' wear. The advantage of this technology is ensuring a greater durability compared with existing methods, by improving the structure of the surface layer. An increase in wear resistance is a consequence of the even distribution of machining effort between the microscopic volumes of machined parts. That ensures a more uniform fine-grained structure of the material.

One should pay attention to several shortcomings, related to increasing the wear depending on the composition and moisture content of tilled soil. This circumstance can be used in the design, as well as in the improvement, of technology for strengthening by pressure in machine engineering and repair operations.

The present study is continuation of earlier research based on the vibration oscillations in technological processes.

7. Conclusions

1. We have studied the influence of operating parameters at vibration plastic deformation. At amplitude A=0.75 mm, frequency n=1,400 min^{-1} of oscillations of the machining tool, and treatment duration t=30 s, the magnitude of wear in cultivator sweeps, restored using the developed technology, is 1.22 times less than that at conventional restoration.

2. The intensity of wear of plowshares, at amplitude A=0.5 mm, frequency n=1,400 min^{-1} of oscillations of the machining tool, and treatment duration t=20 s, restored in line with a given technology, is 1.42 times lower compared to new plowshares.

3. The data acquired from the results of our study, the amplitude, duration, and the number of oscillations of the machining tool, allow their application when developing technological operations aimed at restoring other parts of tillage machinery.

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