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IMPROVING THE RELIABILITY OF TILLAGE MACHINES OPERATIONAL UNITS

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Tillage machines rank high in the structure of the machine and tractor fleet of modern agricultural enterprises. Loss of their working condition during field work can significantly affect crop yields. Element that predominantly limits the durability of the tillage machines is the operational unit. Solution of such a problem as increasing the durability and wear resistance of the tillage machines operational units cannot be based on the use of one of the existing methods (technological, structural and operational), but must be based on a systematic approach using the full range of available methods. It is necessary to consider all significant factors that affect the durability and wear resistance of the operational units, in the process of implementation of the system approach. It was found that the application of a wear-resistant coating makes it possible to increase the durability of the tillage machines operational units: for hardened disc operational units, when used on sandy loam soils, the durability increases by 1.28-1.41 times, on loamy soils – by 1.11-1.24 times, and on clay soils – by 1.07-1.18 times; for reinforced center hoes, when used on sandy loam soils, the durability increases by 1.41-1.53 times, on loamy soils – by 1.48 times and on clay soils – by 1.39-1.44 times; for reinforced plowshares, when used on sandy loam soils, the durability increases by 1.82-2.13 times, on loamy soils – by 1.5-1.85 times and on clay soils – by 1.34-1.52 times. Thus, the application of a wear-resistant coating to the tillage machines operational units is more effective on soils with higher wear capacity (sandy loam and sandy loam). Regularities of the influence of soil and climatic conditions, operating modes, and storage methods on the durability and wear resistance of the tillage machines operational units are revealed. A scientifically based system for the operation of the tillage machines operational units was developed on the basis of experimental data and theoretical research. Basic principles of increasing the durability of the tillage machines operational units by an integrated approach to adapting their wear resistance, considering soil and climatic conditions and operating modes, are formulated. This allow increasing the durability of the tillage machines operational units by 1.84-2.51 times, depending on the type of operational units and soil and climatic conditions.

Key words: *abrasive wear, tillage machines, soil type, operational unit, production, durability, wear resistance.*

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Introduction. In developed countries, losses caused only by the effects of abrasive wear range from 1 to 4% of the gross national product (Tylczak, 1992). In the agro-industrial complex the most abrasive wear and tear are the tillage machines operational units interacting with the soil environment.

Tillage machines rank high in the structure of the machine and tractor fleet of modern agricultural enterprises. Loss of their working condition during field work can significantly affect crop yields. Element that predominantly limits the durability of the tillage machines is the operational unit.

There is a wide variety of types and types of operational units, which are classified according to many features (geometric shape, tillage depth, soil impact, presence or absence of a drive, etc. (Sysolin et al., 2001, Morris et al., 2010, Hevko et al., 2005, Salo et al., 2016, Tesliuk et al., 2016, Borak, 2021). When studying the process of wear of the tillage machines operational units and searching for ways to increase their durability and wear resistance, it is advisable to divide them into the following types: plowshare and disk. It is worth noting that the wear process of active operational units differs significantly from that of inactive operational units. Therefore, it is necessary to devote a separate research to finding ways to increase the durability and wear resistance of active operational units. This paper focuses on three tillage machines operational units (two of them are plowshares and one is a disc): a plowshare, a center hoe, and a cutout disc (Fig. 1).

The ratio between the geometric parameters of the operational units determines their type and field of application. The main geometric parameters of plowshare operational units, not shown in Fig. 1, should also include the thickness and angle of sharpening (Fig. 2).

During the technological operation of tillage, due to abrasive wear, the operational units change their geometric parameters (Fig. 3), which leads to a deterioration in the quality of the technological operation and an increase in the traction resistance of the machine.

In addition to the geometric parameters, the physical and mechanical properties of the material of the tillage machines operational units change during wear.

Over the past 50-60 years, the load on the operational units of tillage and sowing machines has increased by about 4 times (due to the increase in their speed and soil compaction by heavy agricultural machinery) (Borak, 2021). All this leads to a constant increase in the wear rate of operational units and a decrease in their reliability, which is why the issue of solving the scientific and practical problem

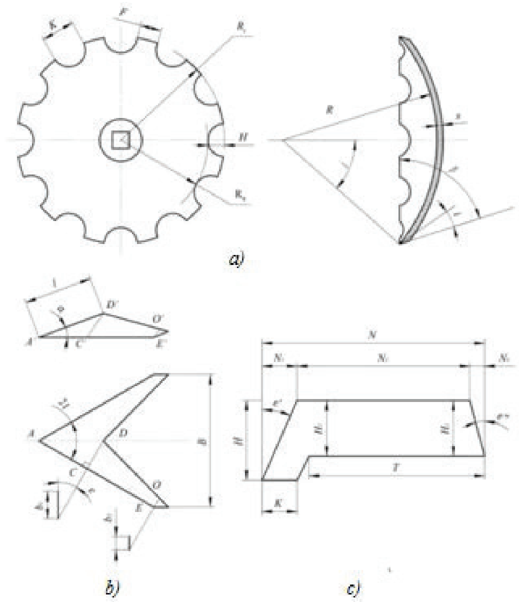


Fig. 1. General view and main geometric parameters of the tillage machines operational units (Sysolin et al., 2001, Morris et al., 2010, Hevko et al., 2005, Salo et al., 2016, Tesliuk et al., 2016, Borak, 2021, Bobrytskyi, 2007) used in the research: a) – cutout disc; b) – center hoe; c) – plowshare; $R_з$ – outer disc diameter; $R_в$ – inner disc diameter; K – groove width; F – tooth width; H – groove depth; s – disc thickness; i – angle of sharpening; j – angle that defines the relationship between the disk diameter and the radius of curvature; R – radius of disc curvature; α – the angle of raising the hoe shin; ε – the angle of the soil pulverization; 2γ – the angle between blades; b_1, b_2 – wing width; B – working width of the hoe; l – plow-point length; N – plowshare length; H – width of the leading edge; H_1 – width of the blade part; H_2 – edge width on the furrow side; ε' – plow-point inclination angle; ε'' – inclination angle of the edge from the furrow side; T – blade length

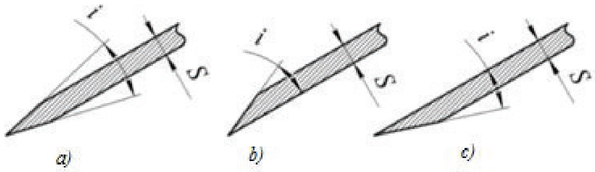


Fig. 2. Scheme of sharpening methods: a), b), c) – two-sided, upper and lower sharpening, respectively; S-thickness of the operational units

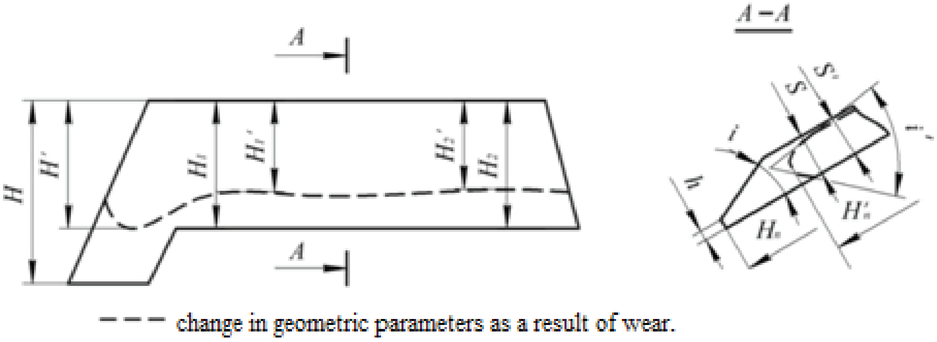


Fig. 3. Changing the shape of the plowshare during tillage operations: H, H_1, H_2, S, i, h – geometric parameters of the new plowshare, H', H_1', H_2', S', i' – geometric parameters of the worn plowshare

of increasing the durability and wear resistance of the tillage machines operational units is acute.

Increasing the durability and wear resistance of the tillage machines operational units is possible only with a comprehensive understanding of the process of their wear. During the operation of tillage machines, the operational units are exposed to wear rate in an aggressive abrasive mass (soil), and, as a result, mechanical, physical and chemical processes take place simultaneously in the contact zone. The ratio between the rate of these processes determines the mechanism and nature of abrasive wear.

Increasing the durability and wear resistance of the tillage machines operational units is one of the main tasks of modern mechanical engineering and enterprises involved in their operation. The urgency of this problem is not only due to the need to reduce material consumption, but also to reduce maintenance costs and reduce equipment downtime due to the need to replace worn-out operational units.

The urgency of this problem is not only due to the need to reduce material consumption, but also to reduce maintenance costs and reduce equipment downtime due to the need to replace worn-out operational units. N. K. Myshkin study emphasizes that the knowledge gained over 50 years in the field of tribology is implemented in industry in the following ratio: 80% design and 20% operation (Borak, 2021). Author refers to a report by P. Jost at a conference in London in 2016, where design is understood as the use of structural and technological methods to increase wear resistance (Borak, 2021). With regard to this distribution for the tillage machines operational units, the role of operational methods will be even less. The solution of such a complex problem as increasing the durability and wear resistance of the tillage machines operational units cannot be based on the use of one of the methods (technological, structural and operational), but must be based on a systematic approach using the full range of available methods.

It is necessary to consider all significant factors that affect the durability and wear resistance of the operational units, in the process of implementation of the system approach.

Two types of the tillage machines operational units were used in the work for research:

a) disc (cutout and solid disc operational unit);
b) plowshares (center hoes and plowshare).

Materials and methods of research. Operational researches of the influence of soil moisture on the wear rate of the tillage machines operational units were performed in agricultural enterprises of the Zhytomyr and Vinnytsia regions during 2016-2018. The average speed of the disk tillage machine was 12 km/h, plow – 10 km/h, cultivator – 11,5 km/h.

Soil moisture content was determined by drying to a constant mass as per DSTU B V.2.1-17:2009.

Research was performed on agricultural machines presented in Table 1.

In all cases, the fields were in post-harvest condition (winter wheat and barley). The speed of the plow varied between 10 and 13 km/h, the cultivator and disk unit – 11 and 15 km/h. To identify the nature of the change in abrasive wear, the change in the linear dimensions of the constituent parts of the tillage machines operational units was monitored. Change in weight and linear dimensions was determined after 10 hectares of production per center hoe, 30 hectares per disk and 5 hectares per plowshare.

Research of the effect of the speed of tillage machines on the wear rate of the operational units was performed as per the current state and industry standards in the conditions of agricultural enterprises of Zhytomyr and Vinnytsia regions on tillage machines presented in Table 2.

The mass wear of the operational units was determined on the laboratory scales CP 34001 S by Sartorius (Germany).

To find out the effect of the geometric shape and chemical composition of the wear-resistant layer on the wear resistance and durability of operational units, three types of the tillage machines operational units were used:

a) spherical cut-out disk operational unit;
b) plowshare;
c) center hoe of the cultivator.

It is necessary to consider all the essential factors that affect the durability and wear resistance of operational units, when implementing a systematic approach.

Works of A. V. Balabukha and H. Wenhua argue that the geometric shape of the wear-resistant coating is crucial for increasing the wear resistance of the tillage machines operational units. To determine the effect of the geometric shape of the wear-resistant coating on the surface of disk operational units, various technological options were proposed (Fig. 4). Wear-resistant coating was applied to the disc operational units made of 65Г steel.

Table 1

Operational units used in the research process

Tillage machine	Soil type	Operational unit	Material of the operational unit
John Deere 2210 cultivator	Sandy loam	Center hoe	Steel 28MnB5 Steel 65Г
	Medium loam		
	Light clay		
ПЛН-3-35	Sandy loam	Plowshare	Steel 65Г Steel Hardox 500
	Medium loam		
	Light clay		
УДА-4.5	Sandy loam	Disk operational unit of the matricary type	Steel 28MnB5 Steel 65Г
	Medium loam		
	Light clay		

Table 2

Operational units used in the research process

Tillage machine	Soil type	Operational unit	Material of the operational unit + applied wear-resistant material
John Deere 2210 cultivator	Sandy loam	Center hoe	28MnB5
	Medium loam		65Г
			65Г+T-620
	Light clay		65Г+T-590
			65Г+M-Fe 6
ПЛН3-35	Sandy loam	Plowshare	65Г
			65Г+T-620
			65Г+T-590
	Medium loam		65Г+M-Fe 6
	Light clay		Hardox 500
			Л53
УДА-4.5	Sandy loam	Disk operational unit of the matricary type	28MnB5
	Medium loam		65Г
			65Г+T-620
			65Г+T-590
	Light clay		65Г+M-Fe 6

1 2 3 4

Fig. 4. Options for applying a wear-resistant coating to disc operational units

Operational units were strengthened with three types of electrodes T-620, T-590, and M-Fe 6, the chemical composition of which is presented in Table 3.

Research of the wear characteristics of the plowshare tillage machines operational units was conducted on three types of soils during 2015-2018 in agricultural enterprises of Zhytomyr and Vinnytsia regions. Tillage machines and operational units used in the research are presented in Table 4.

Research included series-produced plowshares made of Л53 and Nardox 500 steel and center hoes made of 28MnB55 steel (Fig. 5, Fig. 6). Tests were performed without changing the physical and mechanical properties provided by the manufacturers. Operational units, made of 65Г steel, were subjected to bulk hardening at a temperature of 810...830 °C and medium tempering with very precise holding at a temperature of 460...480 °C.

Results and discussion. Disc tillage machines are becoming increasingly common in the Ukrainian agricultural sector. In turn, this is due to the need to minimize the impact on the soil, as it not only reduces the economic

Table 3

Chemical composition of the wear-resistant layer on the surface of the tillage machines operational units

Chemical element	Electrode type		
	T-620	**T-590**	**M-Fe 6**
Mn	1…1.5	1…1.5	≤3.0
Si	2...2.5	2…2.5	-
C	2.9...3.5	2.9...3.5	≤2.5
P	≤0.04	≤0.04	≤0.04
S	≤0.035	≤0.035	≤0.04
Cr	22…24	22…27	≤10
Ti	0.5...1.5	-	-
B	0.5...1.5	0.5...1.5	-
Mo	-	-	≤3.0
Nb	-	-	≤10

Table 4

Operational units used in the research process

Tillage machine	Soil type	Operational unit	Material of the operational unit + applied wear-resistant material
John Deere 2210 cultivator	Sandy loam	Center hoe	28MnB5
			65Г
			65Г+T-620
	Medium loam		65Г+T-590
			65Г+M-Fe 6
ПЛН-3-35	Sandy loam	Plowshare	65Г
			65Г+T-620
			65Г+T-590
	Medium loam		65Г+M-Fe 6
	Light clay		Hardox 500
			Л53
Plow “Kverneland”	Sandy loam	Plowshare (with replaceable chisel)	65Г
			Hardox 500
Plow “Diamant 11” manufactured by Lemken	Light clay	Plowshare (with replaceable chisel)	65Г
			Hardox 500
КПС-9 PM Cultivator		Center hoe	28MnB5
			65Г
			65Г+T-620
			65Г+T-590
			65Г+M-Fe 6

a) b)

Fig. 5. General view of the plows used during the research: a – plow “Diamant 11” by Lemken, b – plow “Kverneland”

a) b)

Fig. 6. Plowshares for the ПЛН-3-35 plow: a – experimental plowshare for sandy loam soils; b – series-produced plowshare

costs of growing crops, but also has a positive impact on the environment (reduced impact on the soil from energy vehicles and reduced soil erosion).

Increasing the durability and wear resistance of disk tillage machines operational units has been studied by many researchers (Sysolin et al., 2001, Morris et al., 2010, Hevko et al., 2005, Salo et al., 2016, Tesliuk et al., 2016, Borak, 2021, Bobrytskyi, 2007, Aulin & Tykhyi, 2017). The vast majority of works are devoted to technological methods of increasing wear resistance for certain soil and climatic conditions.

Some studies emphasize that the geometric shape of the wear-resistant coating is crucial for increasing the wear resistance of the tillage machines operational units (Kadenko, 2017). To determine the effect of the geometric shape of the wear-resistant coating on the surface of the operational units of disk tillage machines, various technological options were proposed (Fig. 4). Wear-resistant coating was applied to the disc operational units made of 65Г steel.

It has been proven that the geometric shape of the wear-resistant coating applied to the friction surface is not crucial for increasing the wear resistance of tillage machine disc operational units on all types of soil. The difference lies only within the statistical error (up to 3%) (Fig. 7). Sample 2 (Fig. 7) wears more actively because the volume of the applied wear-resistant coating is much smaller than the volume of the coating applied to other samples of the tillage machines operational units.

After the wear layer of the applied wear-resistant coating was worn off, the wear rate became equal to that of a series-produced operational unit. There is also a noticeable decrease in the wear rate as the disk diameter decreases. This is due to a decrease in pressure on the edge of the operational unit due to a decrease in the working depth.

Application of a wear-resistant coating on the surface of disk operational units increases wear resistance on sandy loam and sandy soils more significantly than on loamy and clay soils (Table 5). This is also due to different mechanisms of abrasive surface wear: on sandy and sandy loam soils, the process of micro-cutting prevails, while on other types of soils, the process of polydeformation destruction of the metal surface prevails.

T-620 electrodes (Table 6) have proven to be the best for increasing the wear resistance of disk operational units, as they are designed for surfacing parts that operate under conditions of abrasive wear with moderate shock loads. Tillage machines operational units hardened with M-Fe 6 electrode had the lowest wear resistance.

It should be emphasized that the use of disc operational units made of expensive 28MnB5 boron-containing steel has a significant effect on increasing wear resistance only on clay and loamy soils. Operation of disk tillage machines on sandy loam and sandy soils using operational units made of 28MnB5 steel does not produce a positive effect.

The area and volume of the applied wear-resistant coating has a significant impact on increasing the durability of the operational units of tillage machines (Fig. 8).

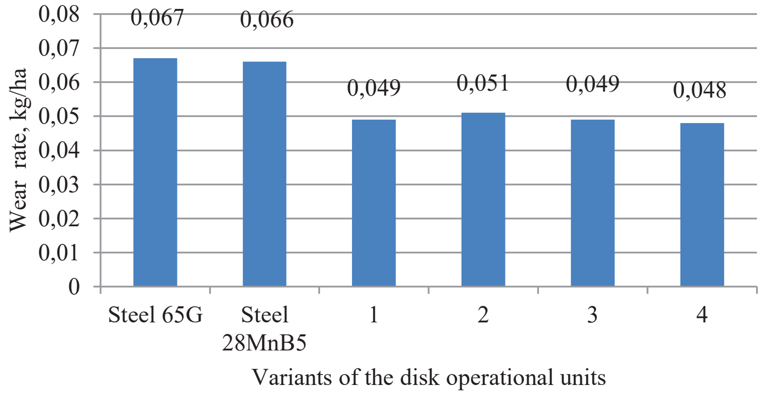
It should be emphasized that as a result of hardening (one layer of wear-resistant coating), the durability of disc operational units increases by 1.28...1.41 times on sandy loam soils, by 1.11...1.24 times on loamy soils, and by 1.07...1.18 times on clay soils.

The second layer of wear-resistant coating increases the durability of the tillage machines operational units:
- by 13.1% when operating on sandy loam soil;
- by 9.3% when operating on medium loam;
- by 7.1% when operating on light clay.

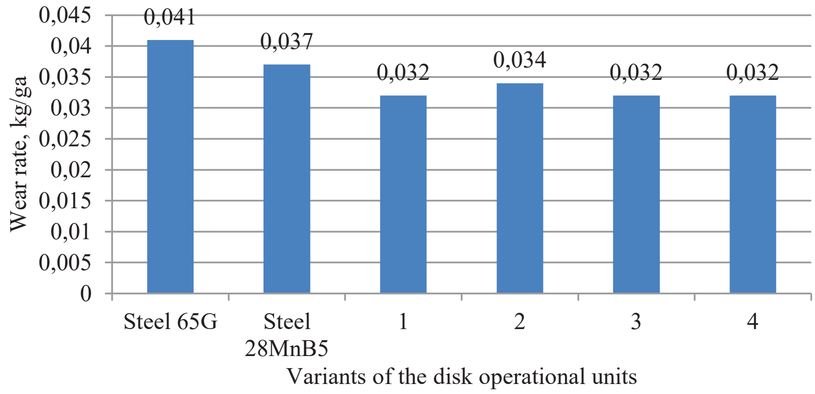
As is well known, two limit states are possible during the operation of disk operational units:
- bluntness of the blade;
- reduction of the outer diameter.

In the first case, the operational units are sharpened and continue to be used, and in the second case, they are discarded. The presence of the first limit state leads to equipment downtime and increased maintenance costs. It is necessary to choose the right side and angle of sharpening to avoid the first limit state. As a result of the conducted research, recommendations for sharpening disk operational units were developed (Table 6).

An increase in soil moisture generally leads to an increase in its wear capacity. This phenomenon continues until a critical state is reached, when free water is released on the surface of the operational units. After that, the wear rate of the surface is significantly reduced, as the groundwater will act as a lubricant. It is impossible to cultivate the soil in this condition due to the failure to meet agrotechnical requirements. For all types of soils, the optimal moisture content was determined at which the wear rate on the surfaces of the tillage machines operational units is lowest (Table 7).



a)



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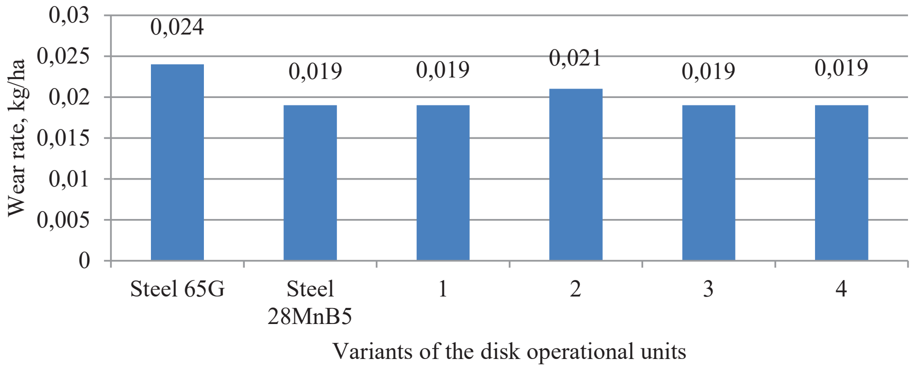

c)

Fig. 7. Wear rate of series-produced and hardened (with T-590 electrode) disc operational units during the cultivation of the first 500 hectares of the field after harvesting corn for silage by the UDA-4.5 unit (variants of wear-resistant coating application 1, 2, 3, 4 are shown in Fig. 1): a – sandy loam soil; b – medium loam; c – light clay (Rogovskii, et al., 2020)

Table 5

Increasing the wear resistance of disk operational units of tillage machine made of 65Г steel

Soil	Electrode type		
	T-620	T-590	M-Fe 6
Sandy loam	1.35...1.42	1.31…1.39	1.32…1.39
Medium loam	1.24...1.35	1.20…1.28	1.19…1.25
Light clay	1.16...1.21	1.14…1.26	1.13...1.21

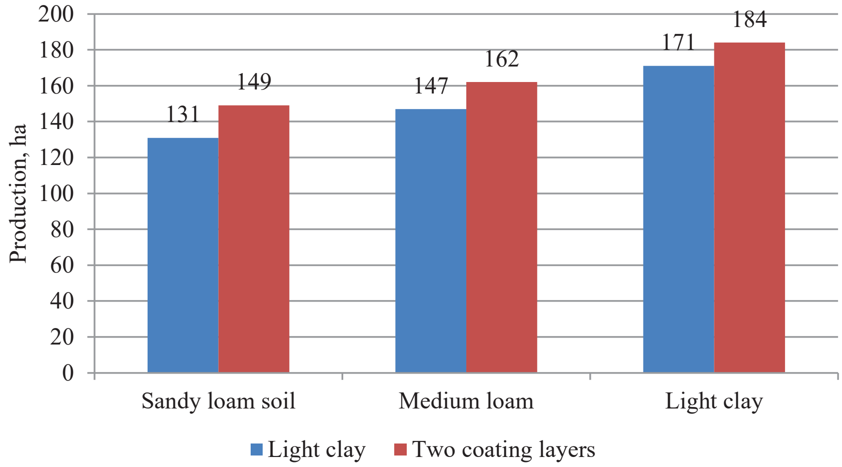

Fig. 8. Production time of the operational units of the УДА-4.5 unit to the limit state (coating scheme No. 4, hardening with T-590 electrode)

Table 6

Necessary geometric parameters of the disk tillage machines operational units to ensure their increased durability

<table>
<tr><th colspan="2">Soil</th><th>Radius of the disk curvature, R</th><th colspan="2">Angle of sharpening</th></tr>
<tr><td rowspan="3">Clay</td><td>Heavy</td><td rowspan="10">$R = (D / 2) sine$</td><td colspan="2" rowspan="3">Outer 10°...20°</td></tr>
<tr><td>Medium</td></tr>
<tr><td>Light</td></tr>
<tr><td rowspan="3">Loam</td><td>Heavy</td><td colspan="2">Outer 10°...20°</td></tr>
<tr><td>Medium</td><td rowspan="6">With hardening, the internal sharpening is 28°...34°</td><td rowspan="6">Outer 10°...20°</td></tr>
<tr><td>Light</td></tr>
<tr><td rowspan="3">Sandy loam and sandy</td><td>Heavy</td></tr>
<tr><td>Sandy loam</td></tr>
<tr><td>Consolidated sand</td></tr>
<tr><td colspan="2">Free sand</td></tr>
</table>

Table 7

Soil moisture that ensures the lowest wear rate

<table>
<tr><th colspan="2">Soil</th><th>Humidity, %</th></tr>
<tr><td rowspan="3">Clay</td><td>Heavy</td><td rowspan="6">13...17</td></tr>
<tr><td>Medium</td></tr>
<tr><td>Light</td></tr>
<tr><td rowspan="3">Loam</td><td>Heavy</td></tr>
<tr><td>Medium</td></tr>
<tr><td>Light</td></tr>
<tr><td rowspan="3">Sandy loam and sandy</td><td>Heavy</td><td>10...11</td></tr>
<tr><td>Sandy loam</td><td rowspan="2">9…10</td></tr>
<tr><td>Consolidated sand</td></tr>
<tr><td colspan="2">Free sand</td><td>7.8</td></tr>
</table>

An increase in the speed of movement of the tillage machines operational units relative to the soil leads to an increase in the wear rate. It is necessary to keep the speed of the machine to a minimum to ensure increased wear resistance. This is impossible in the actual operating conditions of tillage machines, as it can lead to non-compliance with the agrotechnical requirements for the technological operation. Also, reducing the speed will decrease the machine productivity and make it difficult to perform the operation within tight agrotechnical deadlines.

After harvesting crops, nutrient residues remain on the soil surface, which, when interacting with the tillage machines operational units, can release juices that will intensify the process of abrasive wear. Soil cultivation should be performed at the lowest moisture content of nutritious crop residues.

Multifunctional capabilities of the center hoes have led to the development of a large number of their designs that differ in the specifics of wear. Wear process of the cultivator hoes is characterized by high rate due to direct contact with a complex abrasive mass – soil.

The main reason for the loss of the working condition of the center hoes is the wear of the plow-point and wings in width (Fig. 9, a). Other rejected indicators are also possible (wing breakage, wear of the fastening part (Fig. 9, b), cracks, etc.). Despite the fact that the center hoes are symmetrical operational units, uneven wear of the wings is possible (Fig. 9, a) due to improper adjustment of the unit.

The surface wear is not uniform during the cultivating hoes operation. The hoe plow-point is subjected to the greatest load, and therefore the wear rate of the plow-point will be higher than of the other parts of the center hoe. If the cultivator hoes are made of 65Г, 70Г steel with the same physical and mechanical properties of the material throughout the operational unit, the hoe is rejected due to premature plow-point wear. As a result of wear, the thickness of the plow-point decreases and its strength decreases. This leads to bending and breaking of the tip (Fig. 10).

It is well known that three groups of methods can improve the durability and wear resistance of machine parts: structural, technological and operational. As a result of generalizing the information on the problem of increasing the durability of center hoes, it was concluded that more than 90% of the research works are devoted to technological methods of increasing the durability of cultivator center hoes (Kozachenko, 2017), about 8% – to structural and about 2% – to operational methods. The works, devoted to constructive methods, consider them in conjunction with technological methods.

Analysis of research on improving durability and wear resistance showed that all of them are aimed at solving a specific local problem and do not systematically address the issue of improving durability. The problem of increasing the durability of cultivator center hoes shall be solved in a comprehensive manner with the development of technological and design methods. These methods will be based on the soil and climatic conditions of operation, as well as apply scientifically sound operating methods. To implement a comprehensive approach, it is necessary to study the impact of all relevant factors on the durability of cultivator center hoes (material and method of tine reinforcement, soil type and condition, and operating conditions).

Research of the wear characteristics and durability of the center hoes was conducted on three types of soils during 2015-2018. “John Deere 2210” cultivator with a floating hitch was used for this purpose. (Fig. 11).

a)　　　b)

Fig. 9. Reasons for the loss of the working condition of the center hoes: a – plow-point and wing wear in width (on the example of a new and worn hoe); b – wear of the fastening part

Fig. 10. Cultivator plow-point after bending and breaking off

Fig. 11. Used “John Deere 2210” cultivator

Operational units of the cultivator were made of wear-resistant boron-containing steel 28MnB5 and steel 65Г with different hardening options (Table 8). Steel 28MnB5 (analogous to 27MnB5) was chosen for the research because it is used by world leaders in agricultural engineering for the production of arrow tines and has increased resistance to abrasive wear (Kovalchuk et al., 2015).

The center hoes, made of 28MnB5 steel, were operated without changing the physical and mechanical properties provided by the manufacturers. The cultivator's operational units, made of 65Г steel, were subjected to bulk hardening at a temperature of 810...830 °C and medium tempering with very precise holding at a temperature of 460...480 °C. The wear-resistant layer was applied to the front side; its width on the center hoe was 2.5 to 3 times wider than on the wings of the arrowhead. The application was performed by manual arc welding in the conditions of the repair bases of agricultural enterprises as per the scheme presented in (Borak, 2021).

Since the operational units change their length and width in the process of wear in the soil, the rate of massive wear was determined to objectively assess the wear resistance of the hoes at 10 hectares of production per hoe (Fig. 12).

The wear resistance of the cultivator center hoes made of 28MnB5 steel is 18% higher than that of center hoes made of 65Г steel when operating on sandy loam soils, 23% higher when operating on loamy soils, and 57% higher when operating on light clay. Applied protective coatings significantly increase the wear resistance of the cultivator hoes. In particular, as a result of applying a layer with the T-620 electrode, the wear resistance increases by 29...32 %, with the T-590 electrode – by 25...32 % and with M-Fe 6 – by 15...29 %. Due to the wear of the wear-resistant coating, the wear rate was equal to that of a series-produced center hoe.

It should also be noted that the wear rate of the center hoes in the first row is 14.5...21.2 % higher than the wear rate of the center hoes in the second row. This is due to a decrease in the degree of fixation of abrasive particles as a result of partial loosening of the soil layer. An increase in the wear rate by 24.2...38.4% was observed in the center hoes working in the wake of a mobile power vehicle and an agricultural machine. All of these reasons shall be considered when installing center hoes on a cultivator to ensure machine stability.

An increase in the speed of the tillage unit leads to an increase in the wear rate (Borak, 2021). In order to identify the regularity of the influence of the tillage machine speed on the abrasive wear process rate, wear of the center hoes at different machine speeds were researched: 8 km/h, 10 km/h, and 13 km/h (the boundaries of the research are regulated by the technical characteristics of the John Deere 2210 cultivator). The research was performed on sandy loam soils. Production was 10 hectares per hoe. As a result, it was found that there was no effect of changing the speed of the unit on the wear rate. Slight increase in the machine speed is due to the absence of impact.

The tests showed that wing breakage and other mechanical damage occurred only during operation on sandy loam soils in all experimental samples, except for the center hoes made of 28MnB5 steel. Mechanical damage is caused by a large number of stony inclusions in the soil. Damaged center hoes were not considered when calculating their durability (Fig. 13).

Table 8

Operational units used during the research

Tillage machine	Soil type	Operational unit	Material of operational units + wear-resistant coating
John Deere 2210 cultivator	Sandy loam soil	15/5000 center hoe	28MnB5
			65Г
			65Г+T-620
	Medium loam		65Г+T-590
	Light clay		65Г+M-Fe 6

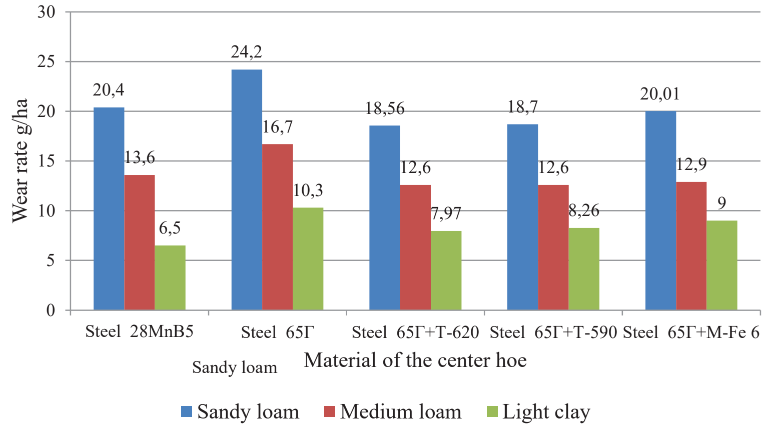

Fig. 12. Wear rate of the John Deere 2210 cultivator center hoes (10 hectares of production per hoe)

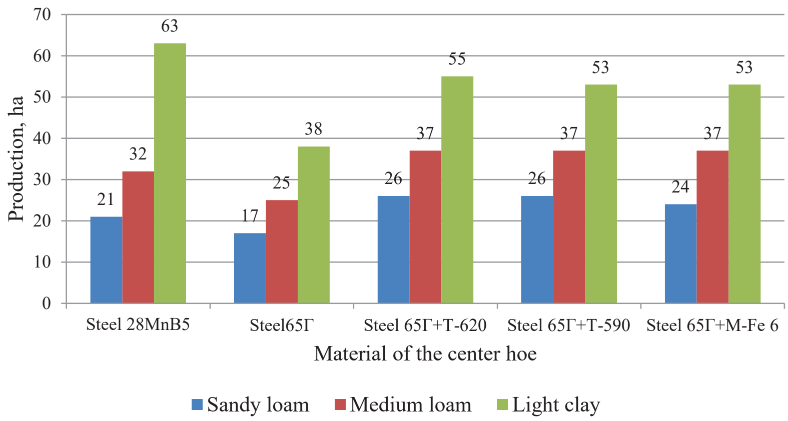

Fig. 13. Durability of the center hoes

The use of a center hoe made of high-quality 28MnB5 boron-containing steel has increased its durability compared to a center hoe made of 65Г steel by 24% when operating on sandy loam soils, 28% on medium loam, and 66% on light clay.

It should be noted that the durability of cultivator hoes made of 28MnB5 steel is higher than the durability of reinforced cultivator hoes during operation on clay soils. When using cultivator tines on sandy loam and medium loamy soils, the hardened hoes have a higher durability compared to tines made of 28MnB5 steel.

Some researches have noted that applying a layer on the back side promotes self-sharpening and increases the service life of the center hoe by 18% compared to applying a wear-resistant layer on the front side. Tests have shown that the durability of cultivator hoes with a wear-resistant layer applied on the back side is higher than the durability of cultivator hoes with a wear-resistant layer on the front side, during operation on clay soils only. This increase was within the statistical margin of error and amounted to 2.8%. When operating such hoes on sandy loam and loamy soils, as a result of rapid wear of the base material, we observed the protrusion of the hardened layer, which broke off during interaction with hard soil elements. The durability of such hoes turned out to be 1.6...1.9 times less than the durability of series-produced hoes.

The ratio of the geometric parameters of the wear-resistant layer applied to the plowpoint and wings of the center hoe should be based on the ratio of the wear rate of these parts. The ratio of wear rate of the plow-point and wings of the center hoe was determined on a series-produced hoe made of 65Г steel (Table 9).

The results of Table 10 make it possible to determine the scheme for applying wear-resistant coatings to the center hoes, considering the soil conditions of their operation. During the operation of the hoes on clay and medium loamy soils, the wear-resistant layer should be 2.5 times wider and thicker than the layer applied to the hoe wings. On sandy loam soils, the geometric dimensions of the wear layer on the plow-point and wings should have a ratio of 1.25/1. Such ratios can be achieved not only by applying wear-resistant coatings, but also by installing a removable tip on the plow-point of the center hoe.

The degree of abrasive particle adhesion in the soil significantly affects the ratio of wear rate of the plow-point and wings of the center hoe. Research of the influence of the fixation degree of abrasive particles in the soil on the wear rate of the plow-point and wings was performed on sandy loam soils with different fixation degrees of abrasive particles: a plot after harvesting winter wheat; a plot after harvesting winter wheat and plowing (the day after plowing); a plot after harvesting winter wheat and plowing (48 days after plowing).

Table 9

Ratio of plow-point and wing wear rate of cultivator hoes (production per hoe – 10 ha, field after rape)

Place of measurements	Wear rate mm/ha		
	Sandy loam	Medium loam	Light clay
Plow-point	0.85	0.57	0.37
Wings	0.68	0.23	0.15
Correlation between plow-point and wing wear rates			
Plow-point/wings	1.25	2.48	2.46

Table 10

Correlation of wear intensity of the plow-point and wings of the center hoe in sandy soil conditions with different degrees of abrasive particle fixation

Research conditions	Correlation between plow-point and blade wear rates
Plot after harvesting winter wheat	1.28
Plot after harvesting winter wheat and plowing (the day after plowing)	1.08
Plot after harvesting winter wheat and plowing (48 days after plowing)	1.21

The research results are presented in Table 10.

If cultivators are used only for secondary tillage (after plowing), the wear rate of the plow-point and wings will differ by only 8%, which must be considered when strengthening the center hoes.

During operation, it is important that the center hoes are self-sharpening to ensure that the cultivation operation is performed efficiently. The ratio of the thickness of the wear-resistant coating and the base metal can be determined using the results presented above and the methodology developed by A. S. Rabinovich.

Wear characteristics and proposed ways to increase the durability and wear resistance of plowshares were researched on three types of soils during 2015-2018 at agricultural enterprises in Zhytomyr and Vinnytsia regions. The tillage machines and operational units, used in the research, are presented in Table 11.

Research involved series-produced plowshares made of Л53 and Nardox 500 steel. Tests were conducted without changing the physical and mechanical properties provided by the manufacturers. Plows, made of 65Г steel, were subjected to bulk hardening at a temperature of 810...830 °C and medium tempering with very precise holding at a temperature of 460...480 °C.

The scheme of applying a wear-resistant coating for plowshares, during operation on different types of soils, should differ significantly based on the ratio of wear resistance of the blade and nose parts of the plow (Fig. 6, a), in contrast to series-produced plowshares, where the reinforcement is performed along the entire length with the same thickness (Fig. 6, b). Previous researches have shown that the hardening of series-produced plowshares leads to rapid wear of the plow-point and loss of the ability to penetrate the soil, and therefore it is replaced with an unused blade part (Borak, 2020).

The results of wear resistance researches of series-produced and hardened plowshares are shown in Fig. 14.

It was found that the use of Nardox 500 steel for the manufacture of tine and plowshare operational units is more efficient when operating on clay soils. The wear resistance of plowshares made of this steel is higher than the wear resistance of plowshares made of 65Г steel, by 26% during operation in sandy loam soil, by 43% during operation in loamy soil, and by 82% during operation in light clay (Fig. 16).

Table 11

Operational units of plows used in the research

Tillage machine	Soil type	Operational unit	Material of the operational unit + applied wear-resistant material
ПЛН-3-35	1. Sandy loam 2. Medium loam 3. Light clay	Plowshare	65Г
			65Г+Т-620
			65Г+Т-590
			65Г+М-Fe 6
			Hardox 500
			Л53
Plow “Kverneland”		Plowshare (with replaceable chisel)	65Г
			Hardox 500
Plow “Diamant 11” manufactured by Lemken		Plowshare (with replaceable chisel)	65Г
			Hardox 500

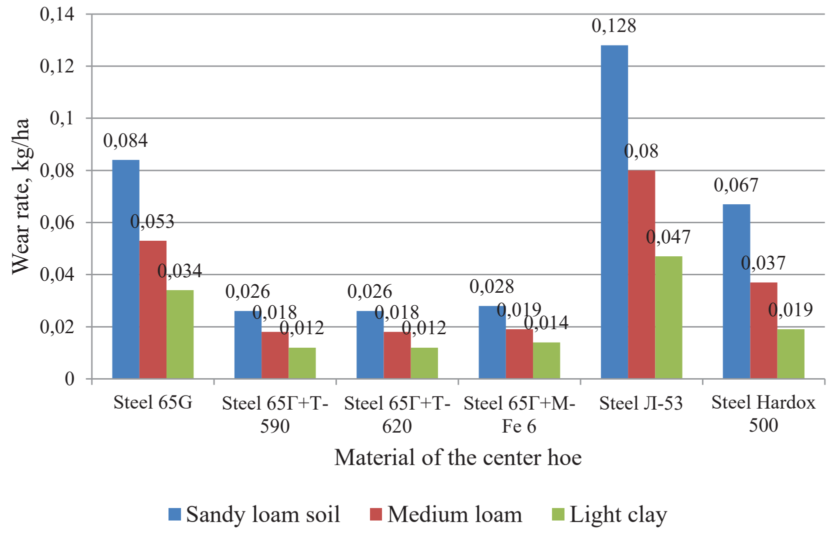

Fig. 14. Wear resistance of ПЛН-3.35 plow plowshares (production of 4 hectares per operational unit)

High efficiency in plowing sandy loam and loamy soils is provided by plowshares with a wear-resistant coating applied by manual arc surfacing with T-620 and T-590 electrodes (Table 12).

Despite such a significant increase in the wear resistance of arc hardened plowshares at the initial stages of operation, their durability does not increase significantly (Fig. 15). This is primarily due to the intensification of abrasive wear on the surface of the operational units after the wear-resistant coating is worn off.

The use of series-produced plowshares made of Nardox 500 steel allows to increase the durability by 1.31...1.49 times compared to series-produced plowshares made of 65Г steel, and by 2...2.14 times compared to plowshares made of L53 steel. A more significant increase in the durability of plowshares made of Nardox 500 steel was observed during operation on light clay compared to operation on sandy loam and loamy soils. It should be noted that the durability of plowshares made of Nardox 500 steel is higher than that of hardened plowshares when working on clay soils, and vice

Table 12

Increasing the wear resistance of plowshares made of 65Г steel (ПЛН-3-35 plow, production is 4 hectares per one plowshare)

Soil	Electrode type		
	T-620	T-590	M-Fe 6
Sandy loam	3.20...3.33	3.21...3.32	2.95...3.07
Medium loam	2.85...2.87	2.84…2.85	2.64...2.71
Light clay	2.77…2.82	2.78…2.83	2.41...2.50

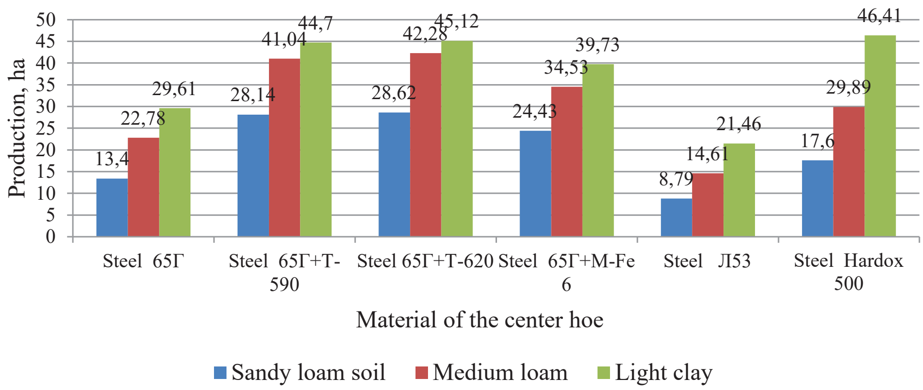

Fig. 15. The average service life of the plowshares ПЛН-3.35

versa on sandy and sandy loam soils. This, in turn, is due to the different ratio of the wear rate of the plow-point and the plow blade during operation on different soil types (Table 13).

The data in Table 14 make it possible to determine the scheme of applying a wear-resistant coating for plowshares, considering the soil and climatic conditions of their operation. Applying a wear-resistant coating only to the toe of the plowshare will significantly increase its durability during operation of plowshares in loamy and clay soils. On sandy soils, it was found that it is necessary to change the plow-point and blade at the same time.

The results of theoretical researches confirm that the degree of abrasive particles fixation in the soil can significantly affect the ratio of the wear rate of the blade and the plow-point of the plowshare. To confirm or refute this statement, researches were conducted on sandy loam soil with three different degrees of abrasive particle consolidation:

1) Plot after winter wheat;
2) Plot after winter wheat, repeated plowing on the 7th day after the first cultivation;
3) Plot after winter wheat, repeated plowing on the 74th day after the first cultivation.

The research results are given in Table 14.

The change in the ratio of the wear rate of the blade and the plow-point of the plowshares is due to the fact that the blade will interact with the landside in all processing options and the degree of fixation of abrasive particles will not change, unlike the abrasive particles with which the plow-point of the plowshares interacts. An increase in the wear rate of the blade part of the plowshare was observed on all types of soils. It is necessary to strengthen the blade part primarily to increase its durability when processing loose soils of all types.

The ratio of the thickness of the wear-resistant and bearing layers should ensure self-sharpening conditions with no possibility of a hard layer protrusion. Protrusion of the hard layer will cause it to break off. Thickness of the wear-resistant layer should be calculated as per the method proposed in (Borak, 2021).

The use of plowshares with replaceable chisel significantly increases their durability by replacing the chisel during operation. During the period of operation of such plowshares, from 2 to 4 chisel replacements can occur, as the wear rate of the plowshare nose significantly exceeds the wear rate of the blade. In addition, it should be noted that in case of mechanical damage to the plow-point section, only the chisel is replaced. The use of plowshares with replaceable chisels can increase the durability of the plow by 2.3....4.4 times. A special feature is that the chisel protects the plow-point of the plowshare from wear not only along the length but also along the width of the plow-point (Fig. 16).

For plowshares with a replaceable chisel, the thickness change is wavy due to the formation of a wave of abrasive particles by the chisel as it breaks up the soil.

During the operation of plowshare operational units, unlike disc ones, no intensification of the abrasive wear process was detected in the presence of plant residues on the soil surface. Research works have shown that the difference in the wear rate of plowshares and center hoes in the presence and absence of plant residues is within the statistical error (± 3%).

An increase in the speed of the tillage machine leads to an increase in the wear rate of the operational units. It is necessary to keep the speed of the machine as low as possible to ensure increased wear resistance. This is not possible in the actual operation of tillage machines, as the productivity of the machine reduces with decreasing speed. This can lead to a failure in performing a quality operation within tight agrotechnical deadlines.

Findings. Research of the wear characteristics and operational tests of plowshare operational units allows us to draw the following conclusions:

– The nature and mechanism of abrasive wear depends on the type of soil, its aggregate state and operating conditions;

Table 13

Ratio of wear rate of the blade and nose parts for different soil types (series-produced plowshares, steel Л53, production is 4 ha per one plowshare, fields are in a post-harvest condition, after harvesting corn for silage)

Place of measurements	Wear rate, mm/ha		
	Sandy loam soil	Medium loam	Light clay
Plow-point (plow-point length)	8.42	7.31	4.27
Blade (blade width)	5.38	3.12	1.78
Correlation between wear rate of plow-point and plowshare blade	1.56	2.3	2.39

Table 14

Ratio of wear rate of the blade and plow-point parts in sandy soil conditions with different degrees of abrasive particle fixation (processing depth in all cases – 220 mm)

Research conditions	Correlation between plow-point and blade wear rates
Plot after winter wheat	1.49
Plot after winter wheat, repeated plowing on the 7th day after the first cultivation	0.68
Plot after winter wheat, repeated plowing on the 74th day after the first cultivation	0.89

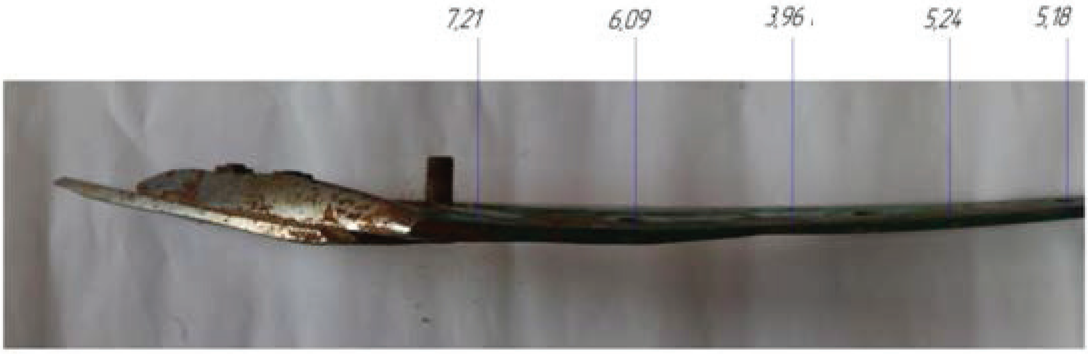

Fig. 16. Changes in the thickness of a plowshare with a replaceable chisel during operation on sandy loam soils (the plowshare has exhausted its service life)

– Application of a wear-resistant coating leads to an increase in wear resistance on all types of soils, but this is most pronounced on soils with a higher wear capacity;

– It is necessary to use plowshares with a wear-resistant coating, and on clay soils – plowshares made of high-quality wear-resistant steels on sandy and sandy loamy soils in order to increase durability;

– the presence of plant residues on the soil surface does not significantly change the abrasive wear rate of plowshare operational units (unlike disk ones);

– The ratio of the geometric parameters of the wear-resistant coating should be based on the conditions and operating modes of the plowshare operational units;

– Increasing the durability and wear resistance of the tillage machines operational units should be based on an integrated approach. This approach should use a range of technological and design methods, considering soil and climatic conditions, and implement scientifically sound operating methods.

Wear of the disk tillage machines operational units is complex (different mechanism and nature of abrasive wear on the surface of the operational units, the occurrence of related wear processes and the possibility of switching to impact abrasive wear of the surface). Problem of increasing the wear resistance and durability of the tillage machines operational units that interact with the soil environment cannot be solved by just using technological methods to increase wear resistance and durability. To achieve this goal, it is necessary to apply an integrated approach, that includes the development of technological and design methods to increase wear resistance and durability, considering soil and climatic conditions, and the introduction of scientifically sound methods of tillage machinery operation.

As per the wear characteristics of plowshare and disk operational units, schemes of wear-resistant coating application have been developed to increase their durability and wear resistance, considering the operating conditions and modes of operation. It has been established that the application of a wear-resistant coating is more effective during the operation of operational units on soils with a higher wear capacity (sandy and sandy loam soils).

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Підвищення надійності робочих органів ґрунтообробних машин

Ґрунтообробні машини займають одне з провідних місць у структурі машинно-тракторного парку сучасних аграрних підприємств. Утрата їх працездатного стану під час проведення польових робіт може суттєво вплинути на урожайність сільськогосподарських культур. У ґрунтообробних машинах елементом, який переважно лімітує довговічність машин, є робочий орган. Вирішення проблеми підвищення довговічності та зносостійкості робочих органів ґрунтообробних машин не може базуватися на використанні одного з наявних методів (технологічного, конструктивного та експлуатаційного), а повинно ґрунтуватися на системному підході з використанням усього спектру доступних методів. У процесі реалізації системного підходу необхідно врахувати всі істотні чинники, які впливають на довговічність і зносостійкість робочих органів. В роботі встановлено, що нанесення зносостійкого покриття дає можливість підвищити довговічність робочих органів ґрунтообробних машин: для зміцнених дискових робочих органів при експлуатації їх на супіщаних ґрунтах довговічність підвищується в 1,28–1,41 рази, на суглинках – в 1,11–1,24 рази та на глинистих ґрунтах – в 1,07–1,18 рази; для зміцнених стрілчастих лап при експлуатації їх на супіщаних ґрунтах довговічність підвищується в 1,41–1,53 рази, на суглинках – в 1,48 рази та на глинистих ґрунтах – в 1,39–1,44 рази; для зміцнених лемешів при експлуатації їх на супіщаних ґрунтах довговічність підвищується в 1,82–2,13 рази, на суглинках – в 1,5–1,85 рази та на глинистих ґрунтах – в 1,34–1,52 рази. Отже, нанесення зносостійкого покриття на робочі органи ґрунтообробних машин більш ефективне на ґрунтах, які мають вищу зношувальну здатність (супіщані та піщані). Виявлено закономірності впливу ґрунтово-кліматичних умов, режимів експлуатації та способів зберігання на довговічність і зносостійкість робочих органів ґрунтообробних машин. На основі експериментальних даних та теоретичних досліджень розроблено науково обґрунтовану систему експлуатації робочих органів ґрунтообробних машин. Сформульовано основні принципи підвищення довговічності робочих органів ґрунтообробних машин комплексним підходом адаптації їх зносостійкості з урахуванням ґрунтово-кліматичних умов та режимів експлуатації, які дозволяють підвищити довговічність робочих органів ґрунтообробних машин в 1,84–2,51 рази в залежності від типу робочих органів та ґрунтово-кліматичних умов.

Ключові слова: *абразивний знос, ґрунтообробні машини, тип ґрунту, експлуатаційний агрегат, виробництво, довговічність, зносостійкість.*