Justification of strengthening of working bodies of forestry machines with self-fluxing alloys during gas-flame spraying

V I Kretinin, A V Teppoev, V A Sokolova*, O A Polyanskaya and S V Alekseeva
Saint-Petersburg State Forest Technical University, 5 Institutskii Lane, St. Petersburg 194021, Russian Federation

*Corresponding email: sokolova_vika@inbox.ru

Abstract. The article deals with the possibility of strengthening the working bodies of tillage machines with self-fluxing alloys by the method of gas-flame sputtering with subsequent melting of the coating. As a result of the research, the analysis of the physical and mechanical properties of the coating made of a self-fluxing alloy and the changes in these properties depending on the technological modes of spraying was carried out. It is established that the structure of self-fluxing alloys depends mainly on the modes of heat treatment (time and temperature of reflow). Metallographic analysis shows, that the self-fluxing alloy PR-N70H17C4R4 forms a pore-free multiphase structure after melting. The presence of components in the structure (borides and carbides) with a hardness of about 11 GPa allows the coating to have significant abrasive wear resistance.

1. Introduction
The working bodies of tillage machines work in the soil, which is a three-phase dispersed medium consisting of solid, liquid and gaseous particles, fragmented and mixed with each other.

The composition, aggregate state and physical and mechanical properties of the soil largely determine its bearing capacity. The greatest influence on the bearing capacity of the soil is its mechanical composition.

The mechanical elements of different soils differ not only in size, percentage content, but also in mineralogical composition, which determines their difference in various properties. The main wear agents of the working bodies are solid (HV 7...11 HPa) mineral particles of quartz and granite, which make up approximately 36.6...70.8% of the soil. Then, according to the degree of distribution, there are feldspar, mica and other minerals (HV 6...7.2 GPa). Most of the particles have a rounded shape, but there are also particles with sharp edges and protrusions that can deform and wear out the contact surfaces of the parts of the working bodies. These minerals, especially quartz, are the main component of most sandy soils, which explains their high bearing capacity. The particles of rocks that form clay soils have a lower hardness, so the wear rate of working bodies on loamy and clay soils is lower than on sandy ones. Due to the significant differences in the bearing capacity of the soils, the wear rate of the parts of the working bodies on different soils will differ significantly. Taking into account also that the soil pressure on different parts of the working surfaces is different, they do not wear out evenly. Depending on the state of the soil, its compaction and clogging with stones and other elements, the loss of working bodies for these reasons reaches from 10 to 40 percent.
2. Methods and Materials

As a rule, the working bodies of tillage machines are made of carbon steel 65G, as well as of steel 30KHGT, St.35. Their hardness after heat treatment does not exceed 7000 MPa. The hardness of the abrasive particles of the soil is much higher and is about 10,000 MPa. For this reason, the actual service life of most machines is 2-4 years (with a designated 7-8 years). In this regard, there is a need to find ways to increase the resource of the working bodies of tillage machines operating under conditions of abrasive wear and shock loads, which is especially characteristic of the soils of the North-Western region. The surfaces of the cutting knives in contact with the abrasive medium should be strengthened with a solid-alloy material, the hardness of which should not be less than 0.8 of the hardness of the abrasive, that is, not less than 8000 MPa.

The most acceptable strengthening materials that provide theoretically justified hardness are pseudo-alloys containing carbides and chromium borides (table 1). However, when these components of the pseudo-alloy are saturated, the resistance of the coating to dynamic action decreases, and the hardened layer is painted and peeled off. Therefore, binding elements are necessary, the role of which is performed by nickel and to a lesser extent-cobalt, molybdenum, etc. Such iron-based materials include:

- mixtures of iron-based powders according to TU 14793-007-51286179-2008 grades FBH-6-2, KBH, containing chromium borides;
- powdered pseudoalloys PS-14-60 according to TU-14-22-28-90 with the addition of 5-7% FBH-1 ligature according to TU-14-5-106-78 containing boron and chromium;
- powdered sormites PG-US25 and PG-S27 according to GOST 28377-89 with the addition of 5-7% FKHB-1 ligature;
- self-fluxing nickel-based alloys.

It should be noted that most iron-based alloys are applied by induction surfacing [1].

| Material                        | Microhardness, MPa |
|---------------------------------|--------------------|
| Quartz                          | 11000 – 11300      |
| Feldspars                       | 6900 – 7200        |
| Granite                         | 8200               |
| Grenades                        | 7500 – 9000        |
| Epilogue                        | 7200               |
| Iron carbides                   | 8000               |
| Molybdenum carbides             | 14900              |
| Chromium carbides               | 15700              |
| Boron carbides                  | 28000 – 35000      |
| Chromium borides                | 15000 – 24000      |
| Tungsten Carbides               | 24000              |
| Manganese carbides              | 7700               |
| Complex iron and chromium carbides | 11000 – 12500     |

The use of self-fluxing alloys in strengthening and restoring the working bodies of tillage machines allows applying coatings by gas-flame method on the surface of a complex configuration with specified physical and mechanical properties, the required thickness and does not require significant costs when introduced into production.

The wear resistance of materials under abrasive wear is determined by the amount and hardness of carbides in its structure [2]. The structure of self-fluxing alloys under gas-flame sputtering with subsequent reflow is related to the coating technology and depends mainly on the heat treatment modes [3]. In order to determine the effect of the thermodeformation cycle of reflow on the area of the coating junction with the base metal, a metallographic analysis of the coating quality was performed.
The microstructures of the sprayed and fused powder coatings were studied on marginal and oblique sections made according to the standard method.

### 3. Results and Discussion

The quality of the coating-base connection and the microstructure were studied using a MIM-8M microscope at ×100, ×200 magnification. The photos were taken at ×100 magnification. The microhardness was measured on the PMT-3 device according to GOST R ISO 7507-1-2007. The hardness was determined on a Rockwell TC-2 hardness tester in accordance with GOST 9013-59. Analysis of the state diagrams of Ni – Cr – B and Ni – Cr – B – Si and measurement of microhardness-structural components, proves that the structure of the heat-treated coating can be decomposed into a solid solution based on nickel (350...450 HV 0.05), nickel eutectic (600...800 HV 0.05) and crystal formations of various shapes and sizes (1000...3600 HV 0.05). The latter include chromium carbides (1080...1400 HV 0.05), chromium borides (CrB) and nickel borides (Ni2B) (1500...2400 HV 0.05). In addition, data on the formation of nickel silicides (Ni3Si) and borosilicides in the coating structure are presented. Nickel-based solid solution, nickel eutectic, and boride compounds are detected in the structure by etching the microplate with ferric chloride, and carbide compounds are detected by etching with Murakami reagent. The total hardness of the melted layer is: for the coating of PR-H73X16C3P3-47...60 HRCE, for PR-H70X17C4P4-56...59 HRCE. The microstructure of the dusted and fused coating of PR-N70X17X4P4 on a steel base 35 is shown in figure 1, and the distribution of microhardness on the base and coating is shown in figure 2. From the presented figures 1 and 2, it can be seen: the melting led to the formation of a solid, monolithic and uniform microstructure layer. In the transition zone, a solid solution based on nickel is observed, depleted of boron and carbon and enriched with iron diffused into it. The fusion line can be traced quite clearly, mixing of the main and melted coating is not observed. The coating layer adjacent to the base metal with a thickness of 20...40 microns practically does not contain chromium carbides. This circumstance is important, since the absence of carbides significantly increases the plasticity of the transition layer. In the zone of temperature influence in the steel at the melting boundary, there is a noticeable change in the structure. On the side of the base metal, areas with an increased content of perlite, 50...70 microns deep, are adjacent to the reflow line, due to the activation of diffusion processes in the solid state in the border zone heated to high temperatures (1310...1330 °C). Next, there are pearlite-ferritic areas with a microhardness of 170...206 HV.

![Figure 1](image.png)

**Figure 1.** Connection area of the PR-N70H17X4R4 coating with the base metal.
In previous studies, it is noted that exposure to melting (temperature $1310\ldots1330^\circ C$) for 1 min leads to a decrease in the hardness of the coating by $6\ldots8$ units of HRC. As a result, studies were conducted on the distribution of microhardness over the coating cross-section, depending on the holding time at the heat treatment temperature. Metallographic studies carried out (figure 3) confirm the decrease in microhardness that occurs in the iron diffusion zone and ends in the base metal. Graph analysis (figure 3) shows that the boundary of the decrease in microhardness with increasing exposure moves towards the surface of the coating with a simultaneous change in the structure—there is an increase in solid crystal formations. In general, we can say that the influence of the thermal deformation cycle on the base metal during the melting of coatings made of self-fluxing alloys is insignificant in comparison with surfacing (table 2).
Table 2. Chemical composition of raw and melted materials.

| Alloy grade   | Condition  | Content of elements, % | Cr  | B  | Si  | C   | Fe  | Ni  |
|---------------|------------|------------------------|-----|----|-----|-----|-----|-----|
| PR-N70H17X4R4 | The original | 14.23 2.29 3.01 0.61 2.47 | -   |    |     |     |     |     |
|               | Fused      | 13.96 2.03 2.74 0.39 1.98 | -   |    |     |     |     |     |
| PR-N73H16S3R3 | The original | 15.38 2.81 3.37 0.67 3.84 | -   |    |     |     |     |     |
|               | Fused      | 15.02 2.58 3.16 0.52 3.42 | -   |    |     |     |     |     |

One of the most important parameters of the working bodies of forestry machines is the sharpness of their blades, which depends on the radius of the edge of the blade and the angle of sharpening. In [3, 4], the dependence of the blunt radius of the blade edge on the thickness $h_a$ of the reinforcing layer is noted:

$$r = 0.5 \star h_a.$$  \hspace{1cm} (1)

The relationship expressed by the dependence (1) determines the need to assign a small (0.5 - 1.5 mm) thickness of the reinforcing layer, but its wear resistance is limited. The formation of a radius on the cutting edges is mainly due to the destruction of the edge, not to wear. In this regard, studies were conducted to assess the impact strength of the edge of the blade reinforced with the PR-N70H17X4R4 alloy by the method of flame spraying. The impact strength of the blade edge was evaluated using a pendulum copra, figure 4. The sample blade of the working body was installed in the groove of the anvil and fixed. The pendulum with the load was deflected by a given angle, which determines the impact energy. The results of the impact on the blade were observed and measured using a Brinell magnifier BCH-2, with an accuracy of 0.05 mm. The impact on the edge of the blade was carried out sideways with an inserted cylinder made of hard alloy BK2 with a diameter of 6 mm. The angle of deflection of the pendulum was measured with an error of up to 2.

![Figure 4. Pendulum copra.](image)

The potential energy of the pendulum is determined by the angle of its deflection-$\varphi$. The velocity of the center of mass reduction can be defined as:

$$v = 2 \star \sin \frac{\varphi}{2} \sqrt{gL},$$  \hspace{1cm} (2)

where, $L$ – pendulum length, $\varphi$ – the angle of deflection of the pendulum, $g$ – the acceleration of free fall.

Then the kinetic energy of the pendulum is determined as follows:

$$T = \frac{mv^2}{2} = 2mgL \star \sin^2 \frac{\varphi}{2} = K \star \sin^2 \frac{\varphi}{2},$$  \hspace{1cm} (3)

where, $K = mgL$ – characteristics of the pendulum.
The impact energy was changed due to the angle of deflection of the pendulum, which was determined by the expression:

\[ \varphi = 2 \text{arcsin} \left( \frac{T}{2K} \right), \]  

(4)

When solid soil inclusions collide with the blade, the energy of their collision will fluctuate in a certain range, so the characteristic of the pendulum for such studies can be assumed constant, and the energy value can be changed only due to the angle of deviation \( \varphi \). In our case, when studying the strength properties of the edges of the blades, the characteristic of the pendulum is \( K = 13.15 \text{ N*m} \). Thus, the angle of deflection of the pendulum at the impact energy of 0.06 N*m was equal to -5°, and at the impact energy of 0.1 N*m – 7°. As a result of impact impacts, the depth of the damage hole was determined after applying 5; 10; 20; 40; 80; 120; 200; 300; 400; 500 blows. The required number of blows was determined by the condition of stabilization of the damage growth rate, which remained constant in the future. A sufficient number of blows was taken 500, since with a further increase in the number of blows, the increase in the depth of damage was not observed. In [5], we also note the completion of the 500-stroke inflection of the graph expressing the dependence of the length of samples from various grades of steel and deposited metal on the number of impacts experienced by contact-impact loading.

The accuracy of the described method for determining the parameters of the edge strength of the blades was evaluated by a set of statistical data on the depth of 30 damage holes on steel heat-strengthened blades up to 55 – 58 HRC with a sharpening angle of 40°. The repetition of the impact with an energy of 0.05 N*m was 500 (for one hole). The average depth of the holes and their statistical indicators are given in table 3.

| Material | Unit of measurement | Statistical data (n = 30) of damage depth |
|----------|---------------------|----------------------------------------|
| Steel 65G | mm | l | \( \sigma_e \) | \( \nu, \% \) |
| Steel 65G | mm | 0.3897 | 0.0066 | 1.7 |

The repetition of experiments with a confidence probability of 0.9 and a marginal error of \( \Delta = \pm 3\delta = \pm 0.019 \) according to the table of VI Romanovsky was equal to two. For a certain depth of the volume of damage, the repetition of experiments with a confidence probability of 0.9 and a marginal error of \( \Delta = \pm 3\delta = \pm 0.019 \) according to the table of VI Romanovsky was equal to two. For a certain depth, the damage volume is equal to:

\[ V_p = \frac{2}{3} l_p^2 R^{0.6} \cdot \tan i, \]  

(5)

where, \( l_p \) – damage depth, mm; \( R \) – striker radius; \( i \) – the angle of sharpening, deg.

The criterion for assessing the impact strength of the edge of a hardened blade is the volume of the damage hole after 500 blows, and the specific energy index \( \sigma_{\text{specific}} \) which is characterized by the total value of the energy required for the formation of damage with a volume of 1 mm³, the dimension of which is (H*m/mm³). Asa result of repeated impact impacts on the edge of the blade, data on changes in these indicators are obtained. It was found that the increase in the depth of the hole from the number of strokes in the semi-logarithmic coordinate system occurs according to a linear law and stops after 500 strokes.

The conducted regression analysis based on the test results allowed us to obtain a correlation dependence of the damage depth on the number of impacts, which is approximated by the empirical equation of the form:

\[ l_n = b^* N^n, \]  

(6)

where, \( l_n \) – depth of the damage hole, \( N \) – number of strokes, \( b, n \) – respectively, the coefficients and exponents that depend on the properties and geometric features of the colliding bodies in the contact zone.
The parameters of the empirical dependence were determined by the least squares method. Checking for the agreement of the calculated values with the results of the tests according to the Fischer F-test showed their adequacy.

Table 4 shows the impact strength of the edge of the blades and the parameters of the dependence. The analysis of the research results shows that with the increase in the thickness of the coating, the intensity of the growth of the depth of the well increases. It was found that the destruction of the edge of the blade occurs as a result of plastic displacement of the metal towards the base layer. Peeling and brittle chipping of the coatings were not detected, which indicates a sufficiently high resistance to their impact effects [6].

Table 4. Effect of coating thickness on impact strength.

| Coating thickness, mm | Material | Steel 65G | SteelSt.3 |
|-----------------------|----------|-----------|-----------|
|                       |          | $b$       | $n$       | $\sigma_{specific}$ | $H \ast m$ | $b$ | $n$ | $\sigma_{specific}$ | $H \ast m$ |
| 0.5                   |          | 0.07      | 0.265     | 309.02       | 0.137   | 0.209 | 154.32 |
| 1.0                   |          | 0.105     | 0.236     | 163.4        | 0.189   | 0.18  | 98.8   |
| 1.4                   |          | 0.154     | 0.207     | 105.04       | 0.29    | 0.132 | 73.1   |

4. Conclusion
The chemical composition of the melted coating practically does not differ from the initial state (Table 2), which is confirmed by the chemical analysis. Metallographic analysis shows that the self-fluxing alloy PR-N70H17C4P4 forms an almost nonporous multiphase structure after melting. The presence of components in the structure (borides and carbides) with a hardness of about 11 GPa allows the coating to have significant abrasive wear resistance. It should be noted that the bluntness of the blade as a result of damage occurs by destroying the material of a brittle or plastic nature. The presence of nickel in self-fluxing alloys allows us to recommend them for strengthening the soil-cutting parts of forestry machines operating under shock conditions. The rational thickness of the coating, which provides the required wear resistance of the blade, with a given impact strength of the material is 1.2...1.4 mm. As shown by the conducted studies [4, 5], the GPN of coatings made of self-fluxing alloys can be successfully used to strengthen the working bodies of forestry machines during their restoration.

References
[1] Panteleenko F I, Lyalyakin V P, Ivanov V P and Konstantinov V M 2003 Restoration of machine parts: Reference book ed V P Ivanov (Moscow: Machinostroenie), p 672
[2] Evgrafov V A and Orlov B N 2004 Influence of surface layer hardness on abrasive wear of working bodies of tillage machines Repair, restoration, modernization No 23p 21
[3] Baldaev L H 2009 Gas-thermal spraying of powder materials for obtaining protective coatings with specified properties: Doctoral thesis of technical sciences. Kursk, p 317
[4] Kretinin V I, Markov V A, Sokolova V A and Markov A N 2017 Theoretical prerequisites for increasing the durability of soil-cutting parts during hardening News of the St. Petersburg Forestry Academy Issue 219 pp 156-160
[5] Vojnash S A, Birman A R, Krivonogova A S, Sokolova V A and Markov V A 2017 On the question of assessing the stability of a tracked sortimentovoz Forests of Russia: politics, industry, science, education: Materials of the second international scientific and technical conference (St. Petersburg: SPbGLTU), p 24-27
[6] Markov V A, Sokolova V A and Kretinin V I Assessing the Impact Strength of Blade Edges of Forestry Machinery Operating Components Lecture Notes in Mechanical Engineering, Proceedings of the 4th International Conference on Industrial Engineering ICEI2018, pp 837-844