Rationale for the choice of wear-resistant coatings in the hardening of tillage working bodies of forestry machines

Yu I Belenkii, V I Kretinin, V A Sokolova and A V Andronov
Saint Petersburg State Forest Technical University, Saint-Petersburg, Russia

E-mail: sokolova_vika@inbox.ru

Abstract. The article deals with the interaction of soil-cutting elements of forestry machines with soil and trees and shrubs. It substantiates the statement that when choosing wear-resistant coatings when hardening tillage working bodies, it is necessary to take into account the composition and physico-mechanical properties of the soil. The method of choosing wear-resistant coatings depending on the hardness of abrasive particles of soil mass is considered. According to the results of experimental studies in the hardening of soil-cutting elements, it is recommended to use flame spraying of wear-resistant coatings from self-fluxing alloys.

1. Introduction
The most important technological operations in the reproduction of forest resources include soil preparation and planting of forest crops. Tillage machines and tools used for these purposes in some cases do not ensure proper quality of work due to the rapid blunting of the cutting elements (shares, paws, discs, knives, etc.). The efficiency of tillage machines is determined by the pre-repair resource of their working bodies. Observations show that the soil-cutting parts are either operated with unsatisfactory performance indicators, or repeatedly subjected to repair and frequent replacement [1]. One of the most effective ways to increase the durability of cutting working bodies of forestry machines interacting with the soil and trees and shrubs, is to use their bimetallic working part, allowing to realize the effect of self-sharpening. Compared with the standard, the resource of such parts increases by 2 - 3 times [2].

2. Methods of research
The aim of the study is to substantiate the choice of coating material when hardening the soil-cutting parts of the working bodies of forestry machines by flame spraying.

Features of the operating conditions of soil-cultivating machines and tools in forestry significantly affect the durability of their main components and parts, especially the life of working bodies (plowshares, knives, disks) and the service life of machines and tools in general. For this reason, the actual service life of most forestry machines is 2–4 years (with a designation of 7–8 years). In this regard, it is necessary to find ways to increase the resource of the working bodies of forestry machines operating under conditions of abrasive wear and impact loads, which is especially characteristic of the soils of the North-West region. Depending on the composition and the physico-mechanical properties of the soil, they have a different wear effect on the details of soil tillage and planting machines (table 1) [3].
In [4] it is noted that on forest soils containing gravelly-stony inclusions, the wear of soil-forming parts increases by more than 3 times, and this, consequently, leads to an increase in the consumption of spare parts.

**Table 1. Soil wear capacity.**

| Soil name by mechanical structure | Content of physical clay (fraction 0.01mm), % | Soils that do not contain stony inclusions | Soils containing small stony inclusions | Stone content up to 20 m³/he | Stone content up to 35 m³/he | Stone content more than 35 m³/he |
|----------------------------------|---------------------------------------------|------------------------------------------|---------------------------------------|-----------------------------|-----------------------------|-----------------------------|
| Clayey                           | 50                                         | 0.32                                     | 1.46                                  | 4.59                        | 5.9                         | 7.44                        |
| Heavy loamy                      | 50 – 40                                     | 0.5                                      | 2.4                                   | 4.4                         | 5.8                         | 7.17                        |
| Medium loamy                     | 40 – 30                                     | 0.82                                     | 2.86                                  | 4.24                        | 5.59                        | 6.95                        |
| Light loamy                      | 30 – 20                                     | 1.53                                     | 4.0                                   | 5.48                        | 6.84                        |                             |
| Loam sandy                       | 20 – 10                                     | 1.86                                     | 3.83                                  | 5.4                         | 6.75                        |                             |
| Sandy                            | 10 – 3                                      | 2.42                                     | 3.38                                  | 5.3                         | 6.69                        |                             |

Observations on the wear of the soil-cutting parts show that their wear occurs as a result of the cutting or sliding action of solid soil particles.

In the study of abrasive wear M M Khrushchev and M A Babichev established the relationship between blade wear width and operating time:

\[ dU = c^*q^*dL \] (1)

where:
- \( U \) - linear wear,
- \( L \) - friction path of the soil over the surface area of the blades,
- \( q \) - normal pressure component,
- \( c \) - wear coefficient depending on soil abrasiveness and wear resistance of the blade material.

For pure metals and annealed steels, the dependence of wear rate on hardness is as follows:

\[ \frac{dU}{dL} = \frac{c^*q}{H_m^*} \] (2)

where \( H_m \) - material hardness.

For heat-treated steels (normal hardening and tempering):

\[ \frac{dU}{dL} = \frac{c^*q}{(1-\beta)H_0+\beta H_m^*} \] (3)

where:
- \( H_0 \) - hardness of annealed steel,
- \( \beta \) - dimensionless coefficient depending on the composition of the steel and having a value from 0 to 1.0.

Abrasive wear of metals largely depends on the nature of the abrasive particles and the conditions of their impact with the metal surface.

In the general case, wear is caused by hyperbolic dependence with the hardness of the material (figure 1) [5, 6]. However, in the presence of dynamic loads, this dependence may be violated, since with increasing hardness, the brittleness of the alloy increases.
Depending on the conditions of interaction of the part with abrasive particles, the destruction of the metal can occur by micro-cutting, multiple plastic deformation of the friction surface and corrosion-mechanical wear. It was established experimentally that the mechanism of abrasive wear is mainly determined by the ratio of the hardness of the material $H_m$ and the hardness $H_a$ of abrasive particles [7]. At $H_m \ll H_a$, microcutting and severe plastic deformation of friction surfaces are observed. With a higher hardness of the alloy, the process of destruction proceeds mainly due to corrosion-mechanical abrasion or brittle fracture. In real conditions of work of soil-cutting parts, all types of wear to some extent appear simultaneously. However, wear resistance is determined by any one type of wear, dominant in specific working conditions.

The dependence of wear resistance on the hardness of the material is generally determined by the following mathematical expression:

$$\varepsilon = b \cdot H^n,$$

where: $\varepsilon$ - relative wear resistance of the material,
$b$ - coefficient depending on the intensity of wear,
$H$ - material hardness,
$n$ - exponent depending on the ratio of the hardness of the abrasive particles and the material.

At small values of material hardness ($H_a \gg H_m$), micro-cutting takes place, and wear resistance is proportional to the first degree of hardness ($n = 1$), for large values of material hardness ($H_a \geq H_m$), when the depth of abrasive particles is less, plastic extrusion or corrosion-mechanical abrasion ($n > 1$) can occur.

3. Results of research
When choosing wear-resistant coatings for hardening and restoration in relation to the operating conditions of the working bodies of forestry machines, it is necessary to take into account the dynamic loads and strength of the alloy. In this case, the mathematical expression of the optimum hardness of the alloy takes the following form:

$$H_{opt} = 0.8H_a \cdot k_d \cdot k_s,$$

where: $H_a$ - hardness of abrasive particles, $k_d$ - coefficient of dynamic loading (for soils of medium hardness, not containing stony inclusions $k_d = 1$), $k_s$ - alloy strength factor.

Taking into account the dynamism of the load, the dependence of wear resistance of a material on hardness can have four main varieties (figure 2).
Figure 2. The dependence of the wear-resistance of the material on its hardness.

a) When $H_a > H_m, n = 1$. In this case, the dependence has the form established by M M Khrushchev and M A Babichev [6].

b) When $H_a \geq H_m, n > 1$. The curve only on plot A is straightforward. The power type curve of section B is caused by a change in the mechanism of metal destruction, which corresponds to corrosion-mechanical phenomena.

c) When $H_a \geq H_m, n > 1, k_0 < 1$. A feature of this relationship is at first smooth, and then abrupt increase in wear resistance, followed by a steep decline. This is due to the fact that with an increase in the hardness of the alloy comes its brittle destruction.

d) When $H_a \geq H_m, n = 1, k_0 \ll 1$. In this case, the straight part of the curve at certain values of the hardness of the alloy turns into a steep drop-down line, due to the brittle fracture of the alloy.

Based on the provisions considered, the optimum hardness of the alloys depends on the conditions of wear. When abrading alloys in an abrasive medium ($k_0 = 1$), their hardness can be limited only by technological factors. If the item does not experience significant loads, then usually the higher the hardness, the more carbides in the alloy, the more durable the material.

In the presence of shock loads, the optimum hardness is limited by the strength of the material. Under these conditions, it is necessary to increase the viscosity of the alloy. Details of tillage machines are made of carbon steels with a carbon content of 0.4 - 0.7% or of steel 60G, 65G and their hardness after heat treatment does not exceed 7000 MPa. The hardness of the abrasive particles of the soil is much higher and amounts to 11000 MPa (table 2). Therefore, the surface of the soil-cutting parts in contact with the abrasive medium, it is necessary to strengthen the solid-alloyed material, the hardness of which should be not less than 0.8 hardness of the abrasive, that is, not less than 8800 MPa.

| Metal           | Microhardness, MPa | Metal           | Microhardness, MPa |
|-----------------|--------------------|-----------------|--------------------|
| Quartz          | 11000 – 11300      | Chromium carbide| 15700              |
| Feldspar        | 6900 – 7200        | Boron carbides  | 28000 – 35000      |
| Granite         | 8200               | Chromium borides| 15000 – 24000      |
| Grenades        | 7500 – 9000        | Tungsten carbide| 24000              |
| Epilot          | 7200               | Manganese carbides| 7700              |
| Iron carbides   | 8000               | Complex iron and| 11000 – 12500      |
| Molybdenum carbides | 14900            | chromium carbides|                    |
Nickel-based self-fluxing alloys have such characteristics. Conducted research [8] and metallographic analysis show that the self-fluxing alloy PR-H70X17C4P4, after reflowing, forms a practically non-porous multiphase structure. The presence in the structure of components (borides and carbides) with a hardness of about 11 GPa allows the coating to have significant abrasive wear resistance.

4. Conclusions
When choosing a wear-resistant coating and method of hardening soil-cultivating working bodies of forestry machines, many factors must be taken into account. The most significant ones include:

- working conditions of the part (pressure on the working surface, shock loads, etc.);
- material details, chemical composition and physico-mechanical properties;
- geometrical dimensions and configuration of the working surface;
- the possibility of excluding machining;
- the possibility of obtaining a metal coating with the specified service properties, ease of technology and cost-effective work.

The use of self-fluxing alloys during the hardening of the working bodies of forestry machines makes it possible to apply coatings in a gas-flame method on the surface of a complex configuration with desired physicomechanical properties, of the required thickness and does not require significant costs during implementation.

References
[1] 1989 Mechanization - the decisive element of the concept of forestry development Forestry 8 15-9
[2] Kalinichenko N P, Silaev G V and Shapkin O M 1986 Organization and technology of forestry work (Moscow: Agropromizdat)
[3] Kornienko P P, Serikov Yu M et al 1987 Mechanization of tillage for forest crops (Moscow: Agropromizdat)
[4] Bykov V F 1976 The effect of soil saturation and stonyness on the wear of the working bodies of forest cultivators Proceedings of MLTI 88 108-1
[5] Kleis I R 1980 Fundamentals of choice of materials for work in the conditions of gas abrasive wear Friction and wear 2 263-77
[6] Khrushchov M M, Babichev M A et al 1971 Wear resistance and structure of hard surfaced (Moscow: Mechanical Engineering)
[7] Dobrovolsky A G and Kosshelenko P I 1989 Abrasive wear resistance of materials (K.: Technique)
[8] Kretinin V I 1990 Increasing the durability of the working bodies of tree-planting machines by flame spraying during repairs (Leningrad)
[9] Kretinin V I, Markov V A, Sokolova V A and Markov A N 2017 Theoretical background of increasing the durability of soil-cutting parts during hardening Proceedings of the St. Petersburg Forestry Academy 219 156-60
[10] Lazarenko G P 1984 Predicting the conditions for spraying gas-thermal coatings with a given thickness and waviness Izvestiya of universities. Engineering 7 102-8
[11] Borisov Yu S, Kharlamov Yu A, Sidorenko S L and Ardatovskaya E N 1987 Thermal coatings of powder materials (Kiev: Naukova Dumka)
[12] Linnik V A and Pekshev P Yu 1985 Modern technology of thermal spray coating (Moscow: Mashinostroenie)
[13] Ged'o V M, Markov V A, Sokolova V A, Parfenopolo G K and Chernyh L G 2018 IOP Conf. Ser.: Mater. Sci. Eng. 386 012023