Methods for assessing the strength of the blades of soil-cutting parts of forestry machines

V I Kretinin, V A Sokolova, V A Markov and A V Teppoev
Saint Petersburg State Forest Technical University, 5, Institutskiy lane, Saint-Petersburg, 194021, Russia

E-mail: KVI_1960@mail.ru, sokolova_vika@inbox.ru, mactor85@mail.ru, avt01@inbox.ru

Abstract. One way of increasing the wear resistance of working bodies of forestry machines is the use of strengthening technologies. Working tools of tillage machines used in forestry are damaged as a result of edge damage during multiple strike impacts of solid soil inclusions along blade edge. The purpose is to identify the pattern of damage of the blade edge of the soil-cutting parts of forestry machines and theoretically justify the algorithm of strength evaluation in order to determine the rational thickness of the wear-resistant coating during strengthening. Instrumental and analytical studies were carried out on the damage of the reinforced blade edges as a result of multiple impacts on the pendulum copra. Mathematically described is the process of blade edge failure. In the course of multiple strike impacts of soil solid inclusions on the blade edge, there will be accumulation of volumetric damage because of plastic crumpling or chipping. The sharpness of the self-sealing reinforced blade is determined by the thickness of the reinforcing layer and its ability to resist collapse under strike impact size.

1. Introduction
One of the main factors determining the resistance of blade working bodies against damage under dynamic loads, which is typical for tillage forestry tools, is their resistance to plastic crumpling, brittle or fatigue damage. Hard alloys, which strengthen the blades of tillage parts, are more fragile materials than steel, therefore, the blunting of their edges is caused by the formation of cracks, their gradual growth or chipping even from a possible single strike impact of a solid inclusion in the soil.

In the works [1, 2, 3, 4] it is noted that the resistance to edge chipping depends on the impact strength of the hard alloy. The higher the strike impact strength, the higher the edge resistance of the blades. It was found [5,6] that the tendency to brittle damage of the blade is determined by the presence of various stress concentrators in the border zones, primarily microcracks. Along with the usual fragile damage of hard alloys in conditions of cyclic strike impact, fatigue damage also occurs.

2. Research purpose
The purpose is to identify the pattern of damage of the blade edge of forestry machines soil-cutting parts and theoretically justify the algorithm for assessing the strength in order to determine the rational thickness of the wear-resistant coating during hardening.
3. Materials and methods
Changes in the profile during wear are caused by the nature, amount of wear and volume of damage of the cutting edge as a result of the force applied to it by the processed material. The pressure of the soil on the blade is dynamic and can be considered as continuous strike impacts of soil particles and stony inclusions caused by the inertia of the deformed layer. The number and energy of strike impacts depends on the granulometric composition and condition of the soil. Based on the analysis of worn blades, the main regularities of the influence of material properties and geometric parameters of the blade on the radius of rounding are determined [7,8,9,10] as shown in figure 1.

\[ r = l_n \times (\sin i/2)/(1 - \sin i/2), \]

where \( l_n \) is the breaking length,

\[ l_n = 3/2 \times P_b / b \times \sigma_b \times t_q(i/2) \]

where \( P_b \) is the bending force; \( \sigma_b \) is the bending stress; \( i \) is the sharpening angle; \( b \) is the width of the broken edge.

![Blade edge failure diagram](image)

Figure 1. Blade edge failure diagram.

During the movement of the blade, when it meets an elementary particle, the reaction \( \Delta P \) occurs, which can be represented as its constituent forces, normal \( \Delta P_n \) and tangent \( \Delta P_k \). The law of change of these forces depending on the angle \( \theta \) of the meeting of this particle with the blade is as follows:

\[ \Delta P_n = \Delta P \times \sin \theta \quad ; \quad \Delta P_k = \Delta P \times \cos \theta \]

With the decreasing angle \( \theta \) the normal force decreases from the maximum value at \( \theta = 90^\circ \) to \( \Delta P_n = 0 \) at \( \theta =0. \) For soil-cutting working bodies, the blunting of the blade occurs mainly as a result of normal \( P_n \) and tangent \( P_k \) forces that cause brittle discoloration or plastic crumpling of the cutting edge. Under such loading, the radius of rounding is determined by the frequency of strike impact forces applied to the edge, as well as the material's resistance to damage. The edge blunting rate will be a process of summing up the damage:

\[ dL/dt = F(T_\sigma; \sigma; q) \]

where \( dL/dt \) is the damage accumulation rate in the accepted system of units;

\( T_\sigma \) is the tensor of stresses that occur at the edge (in this case, the stress tensor fully characterizes the stress state at the point of loading of the body along three mutually perpendicular platforms); \( \sigma \) is the parameter that characterizes the edge strength of the blade; \( q \) is the number of strokes per unit of time on a given section.

4. Results and discussion
At cutting the soil the bending forces occur at the edge of the blade, resulting in the tip of the blade breaking off. After breaking off under the action of the \( P_n \) forces directed along the bisector of the
sharpening angle \( i \) dynamic stresses \( \sigma_q \) arise and the process of damage accumulation continues. According to figure 1 the thickness of the blade after breaking the edge is defined as:

\[
h = 2 \cdot l_n \cdot t_q (i/2),
\]

(5)

If damaged, the height of the hole increases by \( \Delta h \), and the depth by \( \Delta l_n \).

Then the dynamic stress \( \sigma_q \) at the point of strike impact is determined from the expression adopted in the works of I. A. Birger and R. R. Mavlyutov:

\[
\sigma_q = \frac{P_n \cdot b \cdot \Delta h}{2 \cdot \Delta l_n \cdot t_q (i/2)},
\]

(6)

From this expression one can determine the increment of the damage depth per unit of time:

\[
\frac{dl_n}{dt} = \frac{P_n \cdot q}{2 \cdot b \cdot \sigma_q \cdot t_q (i/2)},
\]

(7)

where \( \frac{dl_n}{dt} \) is the speed of increasing the damage depth; \( P_n \) is the normal component of the strike impact force spent on damage edge; \( b \) is the damage width; \( i \) is the sharpening angle; \( q \) is the number of strokes per unit of time on a given section.

To determine the extent of damage to the edge of the blade from the first strike impact, we assume and consider the blade as a beam, rigidly fixed at one end, on the free end of which the load falls.

The potential energy \( U_p \) when bending the beam is determined by the formula:

\[
U_p = \frac{M^2 e}{2 \cdot E \cdot I},
\]

(8)

where \( M \) is the bending moment; \( I \) is the beam length; \( E \) is the modulus of material elasticity; \( I \) is the axial moment of inertia.

Then

\[
\sigma_b = \frac{M \cdot h}{2 \cdot I},
\]

(9)

According to expression (9), the normal stress \( \sigma_b \) at any section point is directly proportional to \( M \) and the distance of the point from the neutral axis and inversely proportional to the moment of inertia of the section relative to the neutral axis. In our case, \( h \) is the thickness of the blade at the distance \( l_n \) from the edge.

Equating the potential and kinetic energy, we get:

\[
U_p = T_k = \frac{(2 \cdot I \cdot \sigma_b / h)^2 \cdot l_n}{2 \cdot E \cdot I},
\]

(10)

Converting expression (10), we get:

\[
\frac{b \cdot h \cdot l_n}{2} = \frac{3 \cdot T_k \cdot E}{\sigma_b^2},
\]

(11)

where \( b \) and \( h \) are the width and height of the damaged area of the blade at a distance \( l_n \) from the edge.

The left side of equation (11) is nothing more than the volume of blade damage from the bending force.

Further accumulation of damage occurs under the influence of multiple emerging complex stress state at the contact point of the striking bodies, called the stress state tensor, which is formed from three vector quantities:

1) the compressive stresses \( \sigma_c \) directed along the bisector of the sharpening angle,
2) the tangential stresses $\tau_k$ directed perpendicular to the bisector of the sharpening angle and the edge line of the blade,

3) the tangent stresses $\tau_{k1}$ directed along the edge line of the blade.

If the edge of the blade is perpendicular to the direction of the strike impact, the stresses $\tau_{k1}$ can be ignored.

The potential energy $U_p$ accumulated per unit volume at dynamic stresses $\sigma_d$ can be defined as follows:

$$U_p = V_d * \sigma_d^2 / 2 * E,$$ (12)

where $V_d$ is some volume of damage; $E$ is the modulus of material elasticity.

By equating the potential energy $U_p$ of the edge deformation and the kinetic impact energy directed along the bisector of the sharpening angle and performing a number of transformations, we determine the volume of damage of the edge of the blade per unit of time:

$$dV_d / dt = (2 * E * T_k) / \sigma_d^2 * q,$$ (13)

where $dV_d / dt$ is the speed of increasing the volume of edge damage; $T_k$ is the normal component of the strike impact energy spent on edge damage; $q$ is the number of strokes per unit of time on this section.

One of the most important parameters of the working bodies of forestry machines is sharpness of their blades, depending on the radius of the blade edge and the sharpening angle.

The dependence of the radius of blunting the blade edge on the thickness $h_a$ of the reinforcing layer is determined with the following expression:

$$r = 0.5 * h_a,$$ (14)

The relationship expressed by dependency (14) determines the need to assign 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 not due to wear, but to the damage of the edge. In this regard, studies have been conducted to assess the impact strength of the edge of the blade reinforced with the PR-N70H17C4R4 alloy by gas-flame spraying. The impact strength of the blade edge was estimated using a pendulum coper (figure 2). The sample blade of the working body was installed in the groove of the anvil and secured. The pendulum with the load was deflected at a given angle, which determines the impact energy. The results of the impact on the blade were observed and measured using the Brinell MPB-2 magnifier, 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 VK2 with the diameter of 6 mm. The angle of deflection of the pendulum is measured with an error of up to 2°.

Figure 2. Pendulum coper.
The kinetic energy of the pendulum is defined as follows:

\[ Tk = \frac{mv^2}{2} = 2mgL\sin^2 \varphi/2 \quad (15) \]

Where \( K = mgL \) is the pendulum characteristic.

The impact energy changed due to the pendulum deflection angle, which was determined by the expression:

\[ \varphi = 2\arcsin \left( \frac{Tk}{2K} \right)^{1/2} \quad (16) \]

When solid inclusions of soil collide with the blade, the energy of their collision will fluctuate in some range, so the characteristic of the pendulum for such studies can be assumed constant, and the amount of energy can be changed only by the angle of deviation \( \varphi \). In our case when studying the strength properties of the blade edges the pendulum characteristic was equal to \( K = 13.15 \) H*m.

Thus, the angle of the pendulum deflection when the impact energy of 0.06 H*m was equal to 5°, and when the impact energy of 0.1 H*m – 7°. As a result of strike impacts the depth of the damage hole after application was determined 5; 10; 20; 40; 80; 200; 300; 400; 500 strikes. The required number of strikes was determined by the condition of stabilization of the damage growth rate, which remained constant in the future. A sufficient number of strikes was taken by 500, since with a further increase in the number of strikes, the increase in the damage depth was not observed.

During the tests, the depth of the damage hole to the blade edge after wear on the HF installation was measured.

On a certain depth, the volume of damage is equal to:

\[ V_d = \frac{2}{3}l_n^{3.4} \pi R^{0.6} \tan \iota \quad (17) \]

where \( l_n \) is the damage depth, mm; \( R \) is the radius of the striker; \( \iota \) is the sharpening angle, degrees.

The criterion for evaluating the impact strength of the edge of a hardened blade is the volume of the damage hole after 500 strikes, and the specific energy index \( \sigma_b \), which is characterized by the total value of the energy required for the damage of 1 mm\(^3\), the dimension of which (H*m/mm\(^3\)).

Figure 3 shows the dependence of the damage depth of the blade on the number of strikes with different coating thickness (base material is the 65G steel).

\[ \text{Number of strikes: 1) } h_a = 0.5 \text{ mm, 2) } h_a = 1.0 \text{ mm, 3) } h_a = 1.4 \text{ mm} \]

**Figure 3.** The dependence of the damage depth of on the number of strikes.

The regression analysis based on the test results allowed obtaining a correlation between the damage depth and the number of strikes, which is approximated by an empirical equation of the form:
\[ l_n = b \cdot N^n, \]  
\[ (18) \]

where \( l_n \) is the depth of the hole damage, \( N \) is the number of strikes, \( b, n \) are accordingly, the coefficients and indicators of the degree which depend on the properties and geometric features of the colliding bodies in the contact zone.

The parameters of the empirical dependence were determined using the least squares method. Checking for the accordance of the calculated values to the results of tests on the Fischer F-criterion showed their adequacy.

Table 1 shows the impact strength of the blade edge and the dependence parameters. Analysis of the research results showed that with increasing coating thickness, the intensity of growth in the depth of the hole increases (figure 4). It was found that the damage of the blade edge occurs as a result of plastic displacement of the metal towards the main layer. Peeling and brittle resulting in chipping of the coating was found, which indicates a sufficiently high resistance to strike impacts.

**Table 1.** The influence of coating thickness on impact strength.

| coating thickness, mm | base material | the 65G steel | the St3 steel |
|-----------------------|---------------|---------------|---------------|
|                       | \( b \)       | \( n \)       | \( \sigma_b \) | \( b \)       | \( n \)       | \( \sigma_b \) |
| 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           |

Figure 4. The effect of coating thickness on the intensity of growing depth of the hole at an impact energy of 0.05 H*m: 1) the St3 steel; 2) the 65G steel.

Analysis of the obtained test results (table 1) [7] allows to conclude that with increasing thickness of the coating the impact strength of the edge of bimetallic blades decreases. This makes it necessary to assign a small (0.5...1.5 mm) thickness of the reinforcing layer. The studies have shown that the value of the blunting radius, determined by the damage depth \( l_n \) at \( h_a = 1.4 \) mm does not exceed 0.5 mm, which ensures the performance of soil-cutting elements.

**5. Conclusion**

Thus, during the repeated strike impacts of soil solid inclusions of on the blade edge, there will be an accumulation of volumetric damage, as a result of plastic crumpling or chipping. The damage of the blade edge leads to blunting of soil-cutting parts, which affects their performance. Therefore, the sharpness of a self-sharpening hardened blade will be determined by the thickness of the reinforcing layer and its ability to resist damage under strike impacts.

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