Research on friction influence on the working process of agricultural machines for soil tillage

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Abstract. The results presented in this article, refer to a more precise qualitative and quantitative estimation of the friction phenomenon, in the working process of agricultural machines, for soil processing. The positive role of the friction has been taken into consideration, namely to help drive the machinery and to properly disintegrate the soil, as well as the negative role of friction, which generate wear of working tools, high energy consumption and pollution [1, 2]. It is proposed to give a more accurate estimate of the weight of terms expressing the friction, implicitly producing wear, in the formula of the traction force required to pull the agricultural machine. Starting from this information, it is proposed a description of the evolution of wear depending of time, or function of the amount of work performed, as well as criteria for the decision to replace the working tools as worn out. Since 1960, a series of mathematical formulas describing the wear phenomenon have appeared in the literature [1]. The authors [1] identified 182 equations describing the wear phenomenon in its various forms. In this paper we have proposed a mathematical model that is specific to ploughing tools and we attempts to estimate a possible duration of exploitation.

The detailed calculation of the possibility of identifying some mathematical models' constants, using experimental data, shows that structural changes are sometimes required. The structural changes of some formulas, made in accordance with other research results in this field, can highlight components of the traction resistance forces useful in detail calculations of some phenomena that accompany the general process being pursued. The fact that the model for estimating the wear of the working tools of the soil processing machinery can well estimate experimental facts encourages the further development of the model by introducing more parameters defining the geometry of the working tools. This opens the way of optimizing the work tools of the machines that work in and with the soil in general. The mathematical model of plough chisel wear proposed also provides a useful tool for determining the end use at which the work tool must be changed. This value can be, for example, that distance xlim, at which the pointed side of the chisels is completely worn out. For the concrete case under consideration, for example, this value is: xlim = 863 km, working distance.

1. Introduction
Tillage operations consume large amounts of energy and cause significant wear to tillage tools [4]. A major portion of this energy loss and wear can be attributed to the friction between the soil and tool surface [4]. These conclusions are sufficient reasons for the great amount of efforts made by
specialists, materialized in a rich literature and various solutions, each with its advantages and disadvantages. The friction between the tillage tools and the soil, is the main cause of wear. As a result, solutions for reducing tillage tool wear and reducing energy consumption primarily aimed at reducing the friction between tillage tools and soil. Or, as it is said, very synthetically in [6], since the beginning of civilization, man has tried to reduce the amount of energy required to till the soil. Many attempts have been made to reduce the draft necessary to move an implement through the soil. Some of these attempts have sought optimal geometry of tools for soil tillage [1], [2], [9], and [11].

Other attempts sought an optimal position of the tillage tools in the ground [1], [4], and [9]. An important category of authors have sought optimal conditions for soil tillage within the space of the parameters which define the soil state (humidity, compactness, parcel geometry and of working track, etc.). The three categories of solutions refer to the optimization of objective functions such as traction force, friction force or energy consumption. Another category of works has as objective function, the wear (minimization) of the tillage tools. Various types of coatings of soil tillage tools have been tested [6]. Work solutions have been given in the presence of fluid films [5]. For the construction of these tools, composite, ceramic, glass or other materials have been proposed [10]. Work schedules with mechanical vibrations with different frequencies have been proposed [7].

For example [5], says that higher air flow rates may reduce the draft of the tillage tools, but the power required to supply the air becomes so great that the overall power required is greater than that required to operate the smooth tool. The conclusion of study [8], is that the use of an air film between the soil and the surface of tillage tool is not a practical method of reducing the draft or the overall power requirement of tillage tool.

Finally, all these solutions can only be applied after assessing the economic consequences. The costs of coating, using a new material, creating a new geometric shape, making protective films or working vibrations are crucial to switching to serial production. There are also the tests of reliability and maintenance costs of these products.

2. Material and methods

2.1. Traction resistance force, assumption of normal pressure

In the processing experimental data from the soil tillage tools, we have often used successfully the traction resistance (draft force) formula founded by Goreacikin [13]:

\[ F = fG + kab + qabv^2 \]  \hspace{1cm} (1)

Where \( F \) is the draft force, \( f \) is, according to [13], a coefficient analogous to the coefficient of friction. \( G \) is the weight of the soil processing machine, \( k \) is a coefficient that characterizes the specific deformation resistance of the soil, \( a \) and \( b \) are depth and width of work, \( \rho \) is the mass density of the soil, \( v \) is the working speed (assumed constant) and \( \varepsilon \), is a coefficient that depends on the shape of the active surface of the tool body. The values of the parameters \( G, a, b, \rho, v \) and \( F \) were determined for a sufficiently large number of experiences. The experimental data processing used the least squares method to find the average values of coefficients \( f, k \) and \( \varepsilon \).

Although, formula (1) is simple and easy to use, language imprecision trades some imperfections that leave room for further research. Thus, the coefficient \( f \) is designated as the analogue of a coefficient of friction, and the coefficient \( \varepsilon \) used in [13] includes, by reference to the unit of measure and additional specification, the soil mass density. For \( f \), the author [13] estimates values around 0.5, and for the product \( \varepsilon \rho \), between 1400 and 2000 Ns²/m⁴.

Sometimes, processing the experimental data according to the least squares method led to values greater than 1 for \( f \). Generally, we are accustomed to using friction coefficients smaller than 1 and very rarely higher, but very little above 1 [14]. For deeper investigations, one can examine the situation by making the difference between the static friction coefficient and the kinetic friction coefficient [14]. If is accepted (a normal hypothesis for the tillage tool-soil interaction process) that \( f \) is a coefficient of
kinetic friction [14], it is possible to use also supra-unit values, even big enough, around 2, 3, as can see from [15]. Accepting the coefficient \( f \) as having the kinetic nature stops the investigations here (from experimental data we obtained 2.753). The explanation is sufficient and also covers cases where the values are less than 1.

In the case when we working with the static friction coefficient, requiring values less than 1 for \( f \), one can imagine an explanation based on an additional normal pressure (see [8]), which is adds to the force \( G \), this acting only on tools that interact in depth with the soil (see figure 1).

Figure 1. Static friction: no, (a) and with additional normal pressure, (b)

For the case in figure 1, (a), the friction force, \( F_f \), is calculated according to the formula:

\[
F_f = \mu G_s = \mu G \cos \alpha
\]  

(2)

Where we noted the coefficient of friction with \( \mu \), and for the case in figure 1, (b), with the formula:

\[
F_f^p = \mu (G_s + p_n S) = \mu (G \cos \alpha + p_n S) = F_f + \mu p_n S
\]  

(3)

Where \( p_n \) is the additional normal pressure, and \( S \) is the contact surface between the two bodies (see figure 1).

Then, if we work with additional normal pressure, the formula (1) can be modified in the next manner:

\[
F = f (G + p_n S) + kab + \alpha p ab\beta
\]  

(4)

In 1987, a formula for friction force, related to wear, gave [16]. The author [16] proposes an additive decomposition of the coefficient of friction in three terms:

\[
f = f_0 + \frac{\tau}{p} + \frac{C_a}{p}
\]  

(5)

Where: \( f_0 \) is the coefficient of friction between soil and steel, \( \tau \) is the shear stress resistance of the soil, \( p \) is the contact pressure of the soil on the tillage tools, \( C_a \) is an abrasive force, and \( P \) is a normal force (on the tillage tools). With these explanations, Goricikin’s equation (1) changes as follows:

\[
F = f_0 G + \frac{\tau}{p} G + \frac{C_a}{P} G + kab + \alpha p ab\beta
\]  

(6)
Where, the normal force is given by the next formula:

\[ P = n a b \tau \sin(\beta) \]  

(7)

The \( \beta \) angle being the angle of the share (the angle between the direction of the share and the direction of movement of the aggregate). Obviously, formulas (6) and (7) are, for the moment, only hypotheses. Compacting the second and third shear terms and shear friction in formula (6), is obtain a simplest formula:

\[ F = f_0 G + C_s \tau + \left(k + \varphi n^2\right) a b \sin(\beta) \]  

(8)

In formula (8) we introduced dependence on soil density, \( \rho \), so that epsilon from (1) or (7) becomes equal to \( \varphi \rho \) product (see [13]) of formula (8). Applying the least squares method for formula (8), we obtain the following values for structure constants of the soil-plug interaction:

\[ f_0 = 0.5, \quad C_s = 0.16 m^2, \quad k = 54995N/m^2, \quad \varepsilon = 1.3 \]  

(9)

Using at an average density of 1500 kg / m\(^3\) and \( \tau = 75 \) kPa. \( C_s \) is a coefficient with signification of area.

Now we have an estimate, still unconfirmed experimentally, only a theoretical estimate of the intensity of the abrasion force exerted on an agricultural machine for soil tillage.

2.2. A mathematical model of wear of tillage tools

In the previous section we showed how to identify terms that give friction that produces significant wear using experimental data and the draft force formulas. Since 1960, a series of mathematical formulas describing the wear phenomenon have appeared in the literature [3]. The authors [3] identified 182 equations describing the wear phenomenon in its various forms. The mathematical model proposed by us is specific to ploughing tools and attempts to estimate a possible duration of exploitation. In 1953, Holm and Archard propose a simple equation for estimating wear, [17]. We will start from a form of the wear equation, established by Archard and Rabinowicz [18], [19]:

\[ V = \frac{K F_n x}{3H} \]  

(10)

Where \( V \) is the volume of lost material, \( F_n \) is the normal surface force, \( x \) is the length of the road in work process (tillage), in friction with the soil, \( H \) is the Brinell hardness.

Figure 2 shows the sketch of principle of the front part of the chisel of a plough. Drawings and photos of the chisel, are shown in figure 3. The new chisel (freshly manufactured) is characterized by the height \( i_0 \) of the front and the length \( l_0 \) of the feather-shaped part. The chisel, which is in some wear condition, but with its feather-shaped in the front part, is characterized by the height \( i = i(x) \) of the front part and the length \( l = l(x) \) of the feather-shaped part. \( I \) is the height of the rear part of the chisel, the long area of constant height. The angle at the top of the chisel is noted \( \alpha \), and with \( b \) is denoted the constant width of the chisel.
We will make the calculation in the simplified hypothesis of a wear that maintains the shape of the tool but not both dimensions. This means that the front part remains rectangular and perpendicular on the base of the chisel body, changing only the height. Starting from the initial dimensions $i_0$ and $b$, it advances to the dimensions $i(x)$ and $b$ and the calculation includes even the wear of the chisel constant section of the chisel with the front of the rectangular shape with the dimensions $I$ and $b$.

Assuming that the wear of the front part of the chisels is given only by shearing friction, the formula (10) can be rewritten as:

$$V = \frac{K \tau i(x)x}{3H}$$  \hspace{1cm} (11)

The normal force being the product of the specific shear strength, $\tau$, with the chisel front part area. On the other hand, the lost volume when the plough with chisels running a distance $x$, results from a simple calculation, using the geometry described in figure 2. The following expression of the lost material volume is obtained:
\[ V(x) = \frac{\{i(x)^2 - i_0^2\} l_0 b}{2(I - i_0)} \]  

(12)

By equating (11) with (12) we get a second degree equation for the function \( i(x) \). By completing the simple form of the lost volume in the chisel constant section, the following formulas are obtained:

\[
\begin{align*}
    i(x) &= \begin{cases} 
      \sqrt{C^2x^2 + 4i_0^2} + Cx, & \text{if } x \leq x_{\text{lim}} \\
      I, & \text{if } x > x_{\text{lim}}
    \end{cases}
\end{align*}
\]

(13)

For function \( i(x) \),

\[
\begin{align*}
    l_{\text{loss}}(x) &= \begin{cases} 
      l_0 - \frac{l_0 I}{I - i_0} \left(1 - \frac{i(x)}{I}\right), & \text{if } x \leq x_{\text{lim}} \\
      l_0 + C_2(x - x_{\text{lim}}), & \text{if } x > x_{\text{lim}}
    \end{cases}
\end{align*}
\]

(14)

For function \( l_{\text{loss}}(x) \), which give the lost chisel length or shortening through wear, and for the for the loss volume through wear

\[
\begin{align*}
    V_{\text{loss}}(x) &= \begin{cases} 
      C_2xbi(x), & \text{if } x \leq x_{\text{lim}} \\
      C_2(x - x_{\text{lim}})bi(x) + C_2x_{\text{lim}}bi(x_{\text{lim}}), & \text{if } x > x_{\text{lim}}
    \end{cases}
\end{align*}
\]

(15)

In the formulas (13) - (15) are used next notation:

\[
\begin{align*}
    C_1 &= \frac{2(I - i_0)}{l_0}, \quad C_2 = \frac{K\tau}{3H}, \quad C = C_1C_2
\end{align*}
\]

(16)

And \( x_{\text{lim}} \) is the length of the path traversed by the plough until the top of the chisel is fully worn:

\[ x_{\text{lim}} = \frac{I^2 - i_0^2}{CI} \]  

(17)

For agricultural soil with \( \tau = 75 \text{ kPa} \), \( H = 200 \) initial geometry parameters: \( I = 0.01 \text{ m} \), \( b = 0.1 \text{ m} \), \( i_0 = 0.001 \text{ m} \), \( l_0 = 0.05 \text{ m} \), plough working width, \( B = 2 \text{ m} \), are obtain the dependences of the function \( i \), \( l_{\text{loss}} \) and \( V_{\text{loss}} \) by the distance \( x \), running the plough in working process, which are given in figure 4, figure 5 and figure 6.

![Figure 4](image_url)

**Figure 4.** Dependence on the working distance of the chisel front height.
Experimentally, for the chisels of a chisel plough with a working width of 2 m, after the ploughing of a 310 ha agricultural area, there was a shortening of 70 mm, i.e. a material loss of 384 g, average values on the chisel.

Estimating the wear of chisels that mounts on the chisel ploughs provides both geometric and dynamic criteria for the service output of these tools. The geometry criterion may refer to the complete wear of the chisel tip or to a limitation in the length of the piece shortening. The dynamic criterion uses the additional force required to drive the plough, due to the shear section increase [20]. From the above calculation, to estimate the increase of the traction force due to the wear of the chisel, the variation of the height of the cutting edge is used, it is multiplied by the width of the chisel and the strength shear limit (multiplied by the number of chisels mounted on the equipment).

3. Results and discussion
The main results of these paper consist in the calculus formulas (5) to (8), for draft force, and (13) to (17) for the wear predict. Also the figure 4 to figure 7 give a graphic image for the dependences of

![Figure 5](image-url)  
**Figure 5.** Dependence on the working distance of the chisel shortening.

![Figure 6](image-url)  
**Figure 6.** Dependence on the working distance of the loss volume.

![Figure 7](image-url)  
**Figure 7.** Dependence on the working distance of the loss mass.
wear estimators by the distance travelled in working process by the plough. We preferred to leave this final formulas of the theoretical calculations in the chapters in which they were deducted, for continuity and ease of comprehension. We specified them clearly so they could be identified.

We just point out that, according to the research objectives, we have sought to identify a crucial component in the wear of the cutting tools in the structure of the draft force. This was the first or the first stage. The second subject capitalized on this component (at least as a size order) in elaborating a formula for estimating the wear of chisel that is mounted on chisel ploughs.

The first topic solves two problems: separating the friction component into a simple, elementary component and a component with local overpressure (on the attack faces of the cutting tools) that give intense wear and identification of the origin of the component that produces this wear.

The second subject takes over the source of wear indicated by the previous study and develops a wear estimation formula for a particular work tool case for which we have had enough experimental data.

4. Conclusions
The detailed calculation of the possibility of identifying some mathematical models' constants, using experimental data, shows that structural changes are sometimes required. The structural changes of some formulas, made in accordance with other research results in this field, can highlight components of the traction resistance forces useful in detail calculations of some phenomena that accompany the general process being pursued.

The fact that the model for estimating the wear of the working tools of the soil processing machinery can well estimate experimental facts, encourages the further development of the model by introducing more parameters defining the geometry of the working tools. This opens the way of optimizing the work tools of the machines that work in and with the soil in general.

The mathematical model of plough chisel wear also provides a useful tool for determining the end use at which the work tool must be changed. This value can be, for example, that distance $x_{lim}$, at which the pointed side of the chisels is completely worn out. For the concrete case under consideration, for example, this value is: $x_{lim} = 863 \text{ km}$, working distance.

For the future, it is intended to use such a model for studying the phenomenon of self-sharpening of the working tool (possibly worn and rebuilt by welding).

The results outlined in this paper need many experimental confirmations before they are used on a regular basis. Also, in this situation are the investigations of new phenomena, which seem to have a random character, for the time being. The ability to see under what conditions the favourable random character turns into a deterministic character is a particularly difficult task for the moment (e.g. the conditions of self-sharpening).

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