BALKANTRIB'O5
5th INTERNATIONAL CONFERENCE ON TRIBOLOGY
JUNE.15-18. 2005
Kragujevac, Serbia and Montenegro

OPTIMAL TRIBOLOGICAL DESIGN OF SOIL PROCESSING TOOLS

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Abstract
Of paramount importance in the performance of agricultural tillage equipment is tillage tool wear, of abrasive nature, resulting in higher energy losses, higher costs and lower rates of work. Tillage quality expressed by a function A=f (t, W) (t: working area or time, W: tillage tool wear land) will be directly affected by the wear law followed. If the latter is known experimentally or theoretically, then an effective (minimum wear) geometric form for the tool is selected. Applying this concept to a straight toothed harrow and regarding the wear resistance of the tool material, the soil texture index and the geometry of the worn surface, the tooth must be of an ''obelisk'' shape with a limiting length corresponding to a final surface area equal to 20% of the limiting worn area, to establish the maximum tooth working time possible for a reliable performance.

Keywords: *soil processing equipment, harrow tooth, abrasive wear, reliability, optimal design*

1. INTRODUCTION

Soil tillage operations consume large amounts of energy and cause significant wear to tillage tools. The latter results in deterioration of the overall performance of the plough i.e. higher energy losses demanding for higher fuel consumption, lower rates of work, decrease in tillage depth, time consuming changeover of the cutting edge and as a consequence, higher operation and product costs [1,2].

This wear process is of a low stress abrasive character due to metal interaction with natural hard and sharp soil particles, as the tool breaks the soil and has to overcome frictional forces. It depends on the characteristics and the working conditions of the tribological system, tillage cutting edge- soil, such as the intrinsic properties of the tool material and the soil conditions.

The mechanisms of this complex phenomenon have been studied, mainly empirically [3-6] and essential influential factors are found to be: tool shape, its hardness and processing method, type of soil and particle hardness, soil water content, the cultivation depth, plough area (or time) and plough speed.

Therefore, there is a need to optimize soil processing equipment for wear reduction and this can be done by tillage tool design, as well as by a proper manipulation of the soil properties and quality [7,8].

The present study proposes a methodology for selecting an optimal shape for the tillage tool, in this case a harrow tooth, involving the wear resistance of the tool material, the soil texture index as the quality criterion and the geometry of the worn tool surface to establish the maximum working time possible for a reliable performance.

2. METHODOLOGY
2.1 General analysis

The working quality and reliability of soil processing machines, such as ploughs, milling machines, weeders, harrows and others can be evaluated using working quality indices, working efficiency coefficients, the draught force of the wearing tillage tool or other energy and economy indices [9], [3].

The variation of quality magnitudes is presented in a qualitative manner in Fig. 1. The association of tillage tool wear with ploughed area **W=f(** τ **)** is presented in Fig. 1.1. In Fig. 1.2 the variation of tillage quality with respect to wear **A=f(W)** is shown and the change in quality against processing time, **A=f(** T_d **)**, is illustrated in Fig. 1.3.

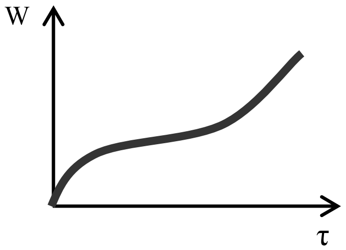

Fig. 1.1

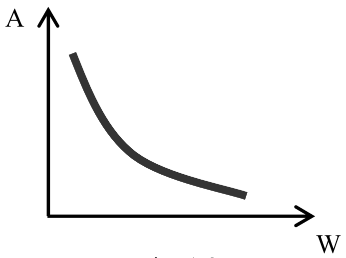

Fig. 1.2

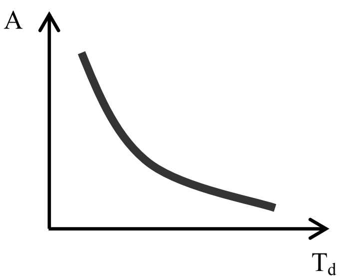

Fig. 1.3

Figure 1: *Variation of quality magnitudes in soil processing [3]*

Regarding the analytical correlation of the aforementioned parameters, the principal relationship combining quality to wear and a work factor like ploughed area or time, is as follows

$$\frac{dA}{d\tau} = \sum_{i=1}^{n} \frac{\partial A}{\partial W_i} \frac{dW_i}{d\tau} \quad , \tag{1}$$

where n is the number of worn elements that affect the working life of the machine part each time considered.

The expression for working life considering quality is deduced from (1) as

$$T_d = \int_{A_o}^{A_d} \frac{dA}{\sum_{i=1}^{n} \frac{\partial A}{\partial W_i} \frac{dW_i}{d\tau}} \quad , \tag{2}$$

where T_d is the working life and A_o, A_d the primary and critical quality values, accordingly.

Any change in the parameters values during the soil process will have an effect on the result of the integral in (2), so we must consider both differentials of (2) separately.

Firstly, $\frac{dW_i}{d\tau}$ expresses the wear rate for, every element and depends on the material wear resistance and may be determined experimentally [3]. Secondly, the partial differential $\frac{\partial A}{\partial W_i}$ may be determined analytically or experimentally on the basis of the quality behaviour against wear; it is generally related to the element geometry and the material wear resistance.

Wear is related to the work factor

$$W = f(\tau) \quad . \tag{3}$$

The wear gradient will be of the form

$$\frac{dW}{d\tau} = \frac{1}{\varphi_{(w)}} \quad . \tag{4}$$

The optimal design of the tool geometrical characteristics in view of wear would allow a reliable use for a longer working time and prolongation of its effective life.

In this way, the following equation must be fulfilled according to the principle of extremes of functions

$$\sum_{i=1}^{n} \frac{\partial A}{\partial W_i} \frac{dW_i}{d\tau} = 0 \quad . \tag{5}$$

This expression denotes the conditions that rule the reliable performance of tillage machinery and considering the equations (2) and

(4), which provide the working time and wear rate, one can control the performance for varying process parameters. Also, it is evident that stabilization of the quality function arises, when the latter is not affected by wear or if wear appears in many elements (surfaces).

2.2 Application to a multi-tooth harrow

The first step to achieve the optimized tool geometrical form, is to describe accurately this form and the next one to introduce it into the equation **A = f(W)**. This problem in the general case could be solved using the variation method. In the simpler case, we must determine the more favourable geometrical form.

The relationship between wear and the geometrical characteristics of the harrow teeth is expressed by

$$F = 4W^2 tg^2 \frac{\omega}{2} \quad , \qquad (6)$$

where F is the worn tooth cross section for an amount of linear wear W (Fig.2) and $\frac{\omega}{2}$ the semi angle of the pyramidal modulation of the tooth. In order to select the optimal form of the engagement part of the tool, the differential $\frac{dW}{d\tau}$ is substituted in (2) with regard to F from data obtained through an extensive research in field [2].

The wear equation based on the experimental findings is given by

$$W = m\tau^{\beta} \quad , \qquad (7)$$

where m expresses the wear resistance of the tool material, which in this study is a steel thermally surface treated and of hardness 55HRC and β is a coefficient dependent on the granular composition of the soil; it takes values around 0.6 for clay soils.

The main features of a straight toothed harrow are: the rectangular cross section bxb (usually 16x16mm^2), the tooth length H usually related to the processing depth a, as H = (2-2.5)a, a is set from 10cm to 15cm. During the ploughing action a conical bulge of condensed soil is formed on the rake face of every tooth. The size of the cone is also influenced by the friction between the tooth and the soil, with tool material playing an important role. Teeth covered by Teflon have shown the best performance.

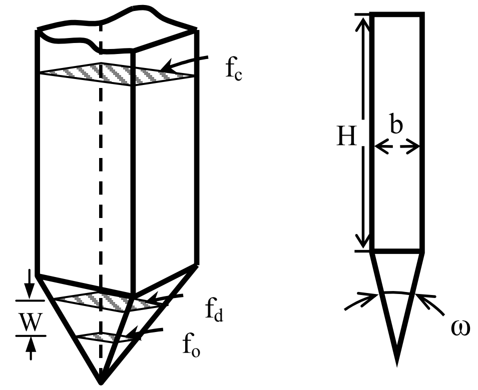

Figure 2: *Harrow tooth modulation – Wear effects*

A harrow tooth ends to a wedge of pyramidal form. Soil particles and remnants of plants are subjected to a normal load N on the tooth and the friction force F. The tracking resistance R_l of the harrow depends on the number of the teeth Z and the tooth specific ploughing resistance K_{1t} (daN/m) and is given by $R_l = K_{1t.} {*} Z$. The working speed is recommended not to exceed 6km/h, as a further increase leads to worsening of the processing quality, reduction in the working depth and increase of the tracking resistance.

Another interesting fact is that particles of varying size are mixed up and removed at different depths, when teeth are worn and become wider. The meaning of this is that a kind of separation in size of soil components occurs, resulting in unsatisfactory germination because rhizomata and big stones tend to go up on the surface at the sowing zone [10].

3. RESULTS AND DISCUSSION

From experiments carried out in clay soils and for 20% soil moisture content [2] the corresponding results are tabulated in Table 1. The geometry of the harrow teeth used was: orthogonal cross section 16x16mm^2, tool length H=20cm, edge length l=10mm and approach angle $\varpi = 80^0$

Table1: Data from in field measurements

	Test measurements				
	Ploughed area τ (ha)	Wear W(mm)	Working time T_d (h)	k_t or A	Tooth area F (mm^2)
1	8.0	2.30	4.2	0.38	14.8 (F_0)
2	22.5	3.90	11.7	0.34	42.6
3	32.4	6.05	16.9	0.26	102.5
4	52.4	6.76	30.6	0.21	128.0 (F_d)
5	58.0	8.10	26.1	0.18	183.7
6	73.8	9.52	43.8	0.15	253.8

Plough quality A is represented by the soil texture index k_t ($k_t = W_{(\leq 10 - \geq 0,25)} / W_{(\geq 10, \leq 0,25)}$), [2] which was determined before and after processing. It indicates how well the seed bed is prepared. The initial process was a plough in two passes by a double stroke discus harrow. The working speed was 6km/h and the working width was 3.2m. The results listed in Table 1 correspond to trials performed by three harrows with 20 teeth each and are the average values from 60 teeth wear measurements under identical working conditions.

On the basis of these results statistical regression models are formulated and listed in Table 2.

Table 2: Regression models developed for the factors of Table 1

	Models	Correlation coefficient R
1	$W = 0.714\tau^{0,.59}$	R= 0.98
2	$A = 0.64W^{-0.56}$	R = 0.94
3	$W = 1.06T_d^{0.59}$	R = 0.97
4	$A = 0.99F^{0.77}$	R = 0.99
5	$A = 0.86\tau^{-0.37}$	R = 0.97
6	$F = 2.38W^{2.06}$	R = 0.99
7	$W = 1.07A^{-1.16}$	R = 0.97
8	$A = 0.67T_d^{-0.36}$	R = 0.92
9	$\tau = 1.39F^{0.71}$	R = 0.98

By analyzing (7) we draw the conclusion that the wear rate is inversely proportional to the worn surface area, which is involved in (8) $\frac{dW}{d\tau} = \beta m \tau^{\beta-1}$.

Table 2 provides $\tau = 1,39F^{0,71}$ and substituting in the above equation we take $\frac{dW}{d\tau} = \beta m\left[1,39F^{0,71}\right]^{\beta-1} =$

$$\beta m\left[1,39F^{0,718}\right]^{0,59-1} =$$

$$= \frac{\beta m}{\left[1,39F^{0,718}\right]^{0,41}}$$

$$\frac{dW}{d\tau} = \frac{\beta m}{1,14F^{0,3}} \quad . \tag{8}$$

This is the final relationship we arrive at in the present study.

In view of literature [9] a relevant model has been proposed

$$\frac{dW}{d\tau} = \frac{a_n c}{k_a F^{0,33}} \quad , \tag{9}$$

where a_n is wear coefficient for the soil type considered, c is soil resistance coefficient and k_a is tooth wear resistance coefficient.

By comparing the two equations and equalizing the corresponding coefficients: the ratio $a_n c = \beta / 1,14$ is dependent on the particular soil and the working depth and $m = \frac{1}{k_a}$ are wear coefficients dependent on tool material.

A tool form that could be regarded optimal for given tooth material and wear resistance should allow maximum soil removal for the area F_d . The working part of the tooth is described by a parabola. For any section, the relationship between the worn area F and the linear wear W is the following

$$F = F_d\left[x^{\frac{1}{n}} + \frac{W}{H}\left(y^{\frac{1}{n}} - x^{\frac{1}{n}}\right)\right]^n \quad , \tag{10}$$

where $x = \frac{F_0}{F_d}$ = (0.1, 0.2 - ..0.5), $y = \frac{F_e}{F_d} =$ (2- 4), F_0 is the smallest obelisk surface, F_d is the limiting allowable tooth working surface area, F_c is the tooth body cross section (16mm*16mm = 256 mm^2), n = (0.5-2.5), W is the allowable tooth length regarding wear and H the tool length.

After substituting (8) into (2) and after differentiation and integration, the working time relationship takes the form

$$T_d = 0{,}6 \frac{Hk_u F_d^{0{,}33}}{a_n c y^{0{,}5}} R_1 \quad , \tag{11}$$

where R_1 is a function of the tooth geometrical form

$$R_1 = 1{,}67 \frac{y^{0{,}5}}{1+0{,}33^n} \frac{1-x^{\frac{1}{n}+0{,}33}}{y^{\frac{1}{n}} - x^{\frac{1}{n}}} \quad . \tag{12}$$

It is observed that the tooth working time is directly related to the material wear resistance k_a and the height H of the allowable working part of the tooth. For favourable values of n and x a chart is formed [9] for R_1 versus x and y for two typical values of the latter resulting in good tooth performance. It is obvious that for $2 \le y \le 4$ the maximum deposit for tooth widening is achieved for n>2, which stands for a concave form of the working part and is unsuitable regarding mechanical strength. For $0.15 \le x \le 0.25$ a remarkable reduction in linear wear is achieved with regard to the maximum available material for re-sharpenings. According to this concept, to establish the maximum tooth working time possible for a reliable performance, the tooth must be of an ''obelisk'' shape with a limiting length corresponding to a final surface area equal to 20% of the limiting worn area.

4. CONCLUSIONS

From the foregoing discussion, the application of optimized structural parameters of tillage tools enables the prolongation of their reliable working duration.

This methodology of wear protection by design can be expanded to other soil processing tools.

5. REFERENCES

[1] Kushwaha, R. L., Chi, L. and Roy, C., "Investigation of agricultural tools with plasma-sprayed coatings'', *Trib. Int.*, 23 (5) (1990), 297-300.

[2] Natsis, A., Papadakis, G. and Pitsilis, J., ''The influence of soil type, soil water and share sharpness of a mouldboard plough on energy consumption, rate of work and tillage quality'', *J. agric. Engng Res.*, 72 (1999), 171-176.

[3] Natsis, A., ''The effect of soil type and soil conditions on the wear of the plough and effect of the latter on energy consumption, rate of the work and tillage quality'', PhD thesis, University of Tirana, 1988 (in Albanian).

[4] Kufel, K., Wierzcholski, K., "The wear of the shares of plough bodies with rigid and elastic connections to the frame, *Wear*, 162-164 (2) (1993), 1002-1003.

[5] Fielke, J. M., " Interaction of the cutting edge of tillage implements with soil'', *J. agric. Engng Res.,* 63 (1) (1996), 61 – 72.

[6] Ferguson, S. A., Fielke, J. M. and Riley, T. W., ''Wear of cultivator shares in abrasive South Australian soils'', *J. agric. Engng Res.*, 69 (1998), 99-105.

[7] Weise, G., Eichhorn, H,'' The application of Mohr-Coulomb mechanics to the design of winged shares'', *J. agric. Engng Res.*, 67 (3) (1997), 235-247.

[8] Bhakat, A. K., Mishra, A. K., Mishra, N. S. and Jha, S.," Metallurgical life cycle assessment through prediction of wear for agricultural grade steel'', *Wear*, 257 (2004), 338-346.

[9] Rozenbaum, A. N and Tenebaum, M.M.,"Optimizacija parametri konstruktiv iznosi details selskogo hosjastvija mashini'', Tractori iselhozmashini 7. (1973), 37-42.

[10] Kouwenhoven J.K., Tepstra R., ''Sorting of Tines-like tools in field'', *J. agric. Engng. Res.*, 24(1)(1979),95-113.