RESEARCH IN RAKE TINES WEAR

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Abstract. Before going of the machine into exploitation, the measurements of the new tines welded to the drum rakes were performed. After collecting rocks from the surfaces of 102 ha and 222 ha, the measurements of the worn tines welded to the drum rakes were performed. Differences in dimensions of the individual tines after wear in two phases were determined. Volumetric and mass wear of the tines were specified. The percentage loss of tine mass due to abrasion was calculated. Mass index of tines wear, expressed in mg·ha^{-1}, taking into account the treated surface, was calculated. Mass index of tine wear, expressed in mg·km^{-1} in terms of the path travelled by tine, was calculated. The degree wear of tines with a thickness of 20 mm depended on the type of steel of which the tines were made. In the long term exploitation, tines made of Hardox steel were characterized by the highest average consumption of 158 mg·km^{-1}, and differences in the consumption of tines made of Hadfield and boron steel were insignificant and amounted to 131 mg·km^{-1} and 130 mg·km^{-1}, respectively. The tines of smaller cross-section (thickness of 16 mm), made of the same boron steel were worn more intensively than the tines of greater thickness (20 mm), and the average values of the indicators were amounted to 152 mg·km^{-1} and 130 mg·km^{-1}, respectively. Tines made of Hardox steel were characterized by the biggest non-uniformity of wear. The standard deviations from the mean value of tine wear after the second stage did not exceed 18.4 % for Hardox steel, 16.0 % for Hadfield steel and 13.0 % for boron steel.

Keywords: volumetric wear, mass wear, wear indicator.

Introduction

The working elements of agricultural tools, moving in the soil, wear out mainly as a result of the impact of hard soil particles on their surfaces (some of the elements are exposed to overload caused by hitting stones) [1]. Miller [2] reported that the presence of stones over 15 mm in diameter in the amount of 0.05 % increased the wear rate by 25 times comparing to clay soils free of stones. Stones with dimensions above 30 mm are usually considered undesirable and eligible to be removed from the fields. However, smaller stones than 20 to 30 mm can also threaten crop machines. The scale of their occurrence and the size of damage caused by them are much smaller than the damage caused by larger stones. The technical possibilities of removing small stones of diameter up to 30 mm are limited, because of the difficulty in separating small stones from the ground [3].

The wear of parts of machines working in soil is not unambiguous, because the values of this parameter depend on the intensity of changes in the geometry of the working elements, and this, in turn, is related to the operating conditions. Elements and tools of these machines are subjected to very high mechanical loads, intensive abrasion caused by hard components of soil (mainly SiO_2), aggressive plant protection agents, natural fertilizers and chemical fertilizers [4].

Therefore, the selection of appropriate construction materials in the construction of agricultural machinery is extremely important, but also very difficult. Among the modern construction materials used for elements of machines and equipment for soil treatment, wear-resistant steels are used; boron steels; multilayer welds overlay based on transition metals and amphoteric elements; sintered carbides [5].

Steels with boron addition (Hardox 450 and boron B27) boride by laser are characterized by greater resistance to friction wear, better cohesion of the coating and less brittleness than diffusive boronizing. Hardox 450 steel due to its chemical composition (lower carbon content) and the condition of the ground (tempered martensite) has more favorable properties than boron steel after laser boronizing: greater micro-hardness and resistance to wear caused by friction [6]. Hadfield steel has an austenitic structure and is characterized by the hardening of its surface during abrasion and crumbling, as well as good ductility parameters, impact resistance and the ability to overcome dynamic loads [7].

The most reliable assessment of the wear of the used working element is obtained in the real conditions that are widely variable. Variable parameters can be: soil parameters, including the soil composition, moisture content, degree of compaction, stones and gravel content, pH and operating parameters, i.e. the working speed and working depth. These factors determine the processes occurring

in the tribological pair of material of the working element and soil, affecting the geometry of wear and thus the durability of the element [8].

The purpose of this work was to determine the wear of tines on the length of the shaft of the stone rake and the degree of tines wear for selected types of abrasion resistant steels (Hardox 450, Hadfield X120Mn12, boron B27).

Materials and methods

Research of the degree of tines wear was carried out during the exploitation of the stone rake in light stony soil. The tines wear was determined in 2 stages: after processing the area of 102 and 222 ha. The given working speed during stone collection was 2.5 $km \cdot h^{-1}$. The shaft with tines was positioned at an angle of 63º in relation to the movement direction. The depth of tines work was 70 mm and the width of the rake was 2.5 m. The average soil moisture content in the layer up to 10 cm was 12.6 % and the compactness and volume density were 580 kPa and 1.52 $g \cdot cm^{-3}$, respectively. The stony fields were varied and amounted to $15.3 \pm 4.7 \ t \cdot h^{-1}$.

In the tests of abrasion resistance of elements working in soil, mass wear and linear wear indicators were used [9; 10].

The indicator of mass wear of the stone rake shaft is related to the path travelled by the tine and is expressed in $mg \cdot km^{-1}$. In the literature, it is also given in relation to the treated area in $g \cdot ha^{-1}$. This study investigated the influence of welding places (positioning) of tines for their wear in accordance to Figure 1.
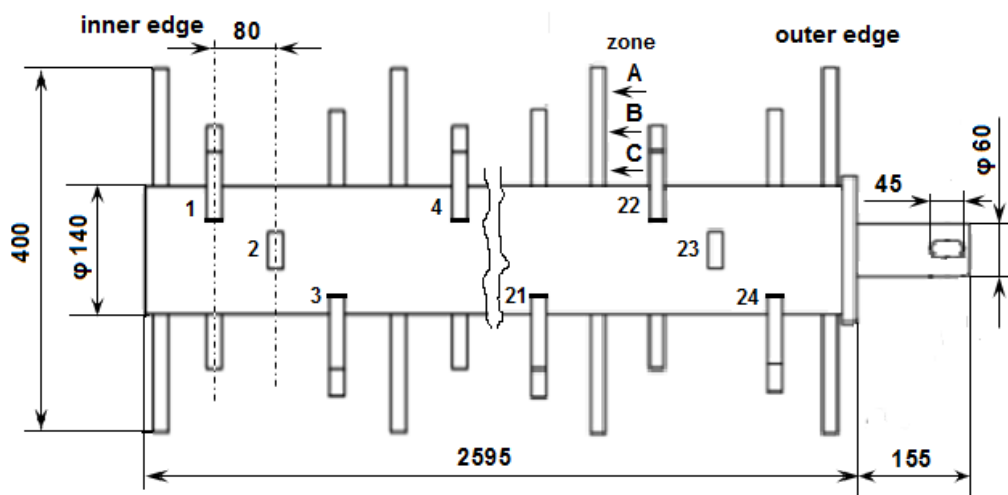

Fig. 1. **Basic dimensions of rake shaft and position of tines**

Tests were carried out for tines made of Hardox 450, Hadfield X120Mn12 and boron B27 steels. The dimensions of tines welded to the shafts worn-up during the machine operation were measured. Tines were numbered from the outer edge of the rotor in the order from 1 to 24 (Fig. 1). The rotor tines from 1 to 9 had a cross-section of 20 mm x 40 mm, while tines from 10 to 24 had a nominal cross-section of 16 mm x 40 mm. The measurements were made on tines mounted in individual rows on the shaft. The height and cross-section measurements were carried out using an electronic caliper MAUa-E2 (Optimum Vis, Poland) with a resolution of ±0.01 mm at three points of the tine cross section: lower A – at the end of the tine, middle B, upper C.

In the next stage volumetric wear was determined using a direct immersion of tines in water (Fig. 2). The buoyant force of the immersed tine was measured in a measuring vessel set to an electronic scale WPS 600/C (Radwag, Poland) in the measuring range of 0.6 kg, with an accuracy of ±0.01 g in three repetitions.

Volumetric wear was determined from the difference in the nominal volume of weight of the immersed tine and the mean values of the buoyant forces. To determine the mass wear of individual tines, the same density of steel was assumed for all cases equal to 7.8 $g \cdot cm^{-3}$. The percentage wear was

defined as a ratio of the volume of the worn part of the tine to the volume of the new tine determined from the real dimensions of the tine cross-sections and its length.
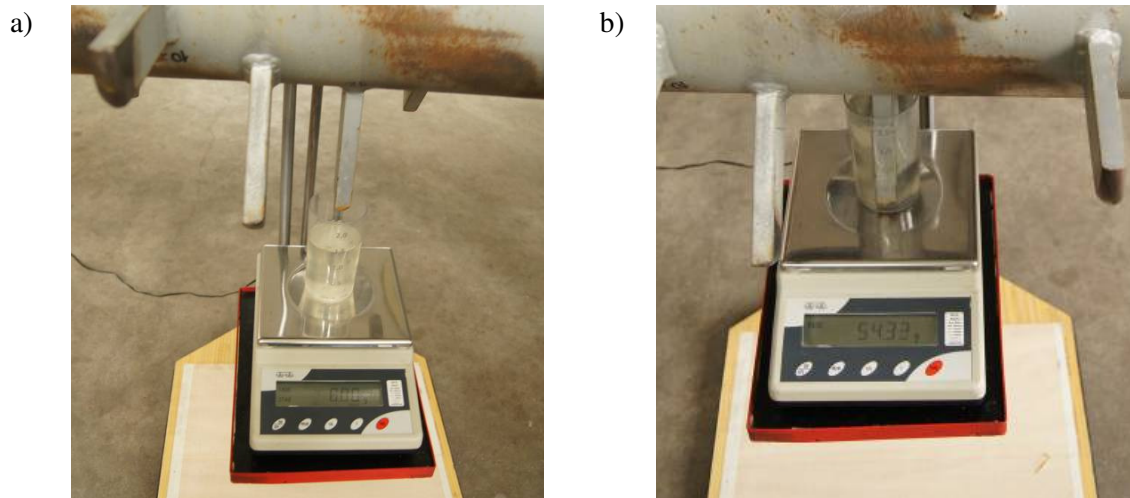

Fig. 2. **Position of measuring vessel, laboratory scale and tine:**
a) before the measurement, b) during the measurement

Results and discussion

During the work, the surfaces of rake tines affect the soil and are subjected to impacts against solids, stones and strong friction, which create areas of high stress on the front and top surfaces and their edges. As a result of this phenomenon, the blades are under a pulse load and are exposed to high abrasion and wear (Fig. 3).
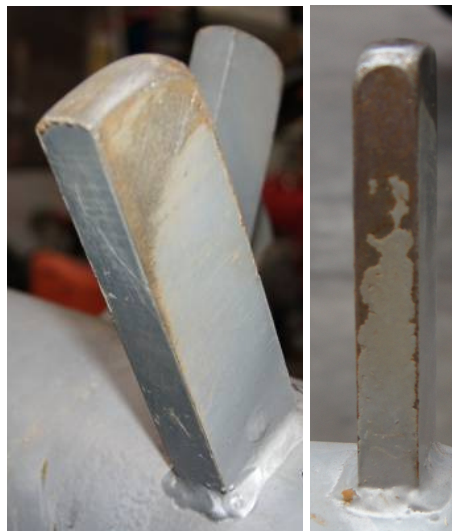

Fig. 3. **View of wear of tine at rake shaft**

Table 1 presents the results of measurements of worn tines. The largest loss of material occurred in the lower (working) zone. The fastest wear was observed on the top surface. Its abrasion was caused by friction against the bottom of the furrow.

At this point, the greatest friction force occurred, which led to "flowing" the material and formation of "lip" on the edge opposite to the tine's forehead. As a result, the length of the tine was shortened. In the central zone, only a few cases noticed a slight reduction in the thickness of the tine, which means that there was no noticeable wear on the side surfaces.

No wear was found in the upper zone, which is confirmed by observations. In the central zone, the effects of wear were visible on the frontal surface ("attack surface") of the tine. In the upper tine zone (cross-section C), slight signs of wear on several tines were observed.

Table 1

Dimensions of worn tines

Number of tine	Material	Cross-section A		Cross-section B		Cross-section C	
		Tine thickness, mm	Tine width, mm	Tine thickness, mm	Tine width, mm	Tine thickness, mm	Tine width, mm
1	Hardox steel	20.47	40.29	20.62	40.45	20.70	40.86
2	Hadfield steel	20.57	40.40	20.66	40.62	20.78	40.92
3	boron steel	20.10	40.60	20.38	40.71	20.51	40.98
4	Hardox steel	21.09	39.45	21.20	40.54	21.27	41.00
5	Hadfield steel	20.43	40.03	20.70	40.46	20.70	40.60
6	boron steel	20.09	40.32	20.18	40.43	20.28	40.78
7	Hardox steel	20.47	40.28	20.67	40.37	20.72	41.11
8	Hadfield steel	20.33	40.02	20.55	40.59	20.76	40.79
9	boron steel	19.99	40.06	20.24	40.74	20.36	40.96
10	boron steel	15.77	40.03	15.98	40.48	15.99	40.41
11	boron steel	15.62	39.76	15.84	40.23	16.03	40.47
12	boron steel	15.52	39.85	15.95	40.21	15.14	40.64
13	boron steel	15.58	39.51	15.93	40.00	16.25	40.16
14	boron steel	15.82	40.03	16.19	40.34	16.43	40.47
15	boron steel	15.79	40.34	16.23	40.55	16.37	40.84
16	boron steel	16.11	40.20	16.30	40.45	16.64	40.50
17	boron steel	15.93	40.32	16.20	40.64	16.38	40.86
18	boron steel	15.77	40.23	16.30	40.58	16.34	40.89
19	boron steel	15.86	39.89	15.95	40.22	16.14	40.49
20	boron steel	15.91	40.28	16.20	40.73	16.31	40.80
21	boron steel	15.92	40.24	16.22	40.54	16.68	41.22
22	boron steel	15.71	40.54	16.02	40.64	16.34	40.88
23	boron steel	15.99	40.27	16.25	40.73	16.38	40.82
24	boron steel	15.94	40.32	16.12	41.10	16.28	41.38

Table 2 presents the results of volumetric, percentage and mass wear, and mass wear indicator of individual rotor tines. The linear relationship between the degree of mass wear (y) of tines made of boron steel and the place of their welding to the shaft (x) was investigated. To determine the strength of dependence between the location of the tines on the shaft and their wear, the Pearson's linear correlation coefficient was determined [11], in accordance to the formula (1):

$$r_{xy} = \frac{\sum_{j=1}^{n}(x_j - \bar{x})(y_j - \bar{y})}{\sqrt{\left[\sum_{j=1}^{n}(x_j - \bar{x})^2 \sum_{j=1}^{n}(y_j - \bar{y})^2\right]}}. \tag{1}$$

For the assumed degree of significance $\alpha = 0.05$ and the number of degrees of freedom 13, the limiting value of the correlation coefficient r-Pearson = 0.51. The obtained value is equal to 0.81 and is greater than the value of the coefficient for the assumed level of significance, which means a statistically significant correlation. The strength of correlation in the range of 0.7-0.9 indicates a high linear relationship between the location of tines on the shaft and their wear.

The research results show that the tines wear increases proportionally towards the inner edge of the shaft according to the linear regression equation (Fig. 4) at 95 % of confidence level. Because tine

wear increases along the shaft, the cross-section of the tines on the final shaft section was increased and for testing these tines were made of various steel types. The highest average wear in the longer period of use was characterized by tines made of Hardox steel and it was 158 mg·km^{-1}, and the differences in the wear of tines made of Hadfield and boron steel were insignificant and were 131 mg·km^{-1} and 130 mg·km^{-1}, respectively (Tab. 3).

Table 2

Volumetric, percentage, mass wear and mass wear indicator

Number of tine	Volumetric wear, cm^3	Percentage wear, %	Mass wear, g	Mass wear indicator, mg·km^{-1}	Steel
1	8.74	8.40	68.20	184	Hardox
2	5.58	5.37	43.59	117	Hadfield
3	6.35	6.10	49.56	133	boron
4	6.46	6.21	50.41	136	Hardox
5	6.75	6.49	52.66	142	Hadfield
6	7.29	7.01	56.93	153	boron
7	8.24	7.93	64.34	173	Hardox
8	7.91	7.60	61.72	166	Hadfield
9	7.18	6.91	56.07	151	boron
10	8.20	9.85	63.96	172	boron
11	9.26	11.10	72.24	195	boron
12	8.91	10.71	69.54	187	boron
13	8.65	10.40	67.52	182	boron
14	8.00	9.62	62.45	168	boron
15	7.88	9.48	60.52	171	boron
16	7.61	9.14	59.37	160	boron
17	7.69	9.25	60.04	162	boron
18	7.18	8.62	56.00	151	boron
19	8.59	10.32	67.00	181	boron
20	6.77	8.14	52.85	142	boron
21	6.40	7.69	49.92	134	boron
22	7.50	9.02	58.55	158	boron
23	6.84	8.22	53.37	144	boron
24	6.02	7.24	47.02	127	boron

This may indicate that the Hardox steel tines had the hardest surface. However, along with the abrasion of the surface layer, a much faster material wear occurred in the longer period of operation of the rotor than in the case of other steel types. Tines made of Hardox steel were also characterized by the highest unevenness of wear. Deviations in tines wear from the mean value after the second stage did not exceed 18.4 % for Hardox steel, 16 % for Hadfield steel and 13 % for boron steel.

Table 3

Average tines wear made of various types of steel

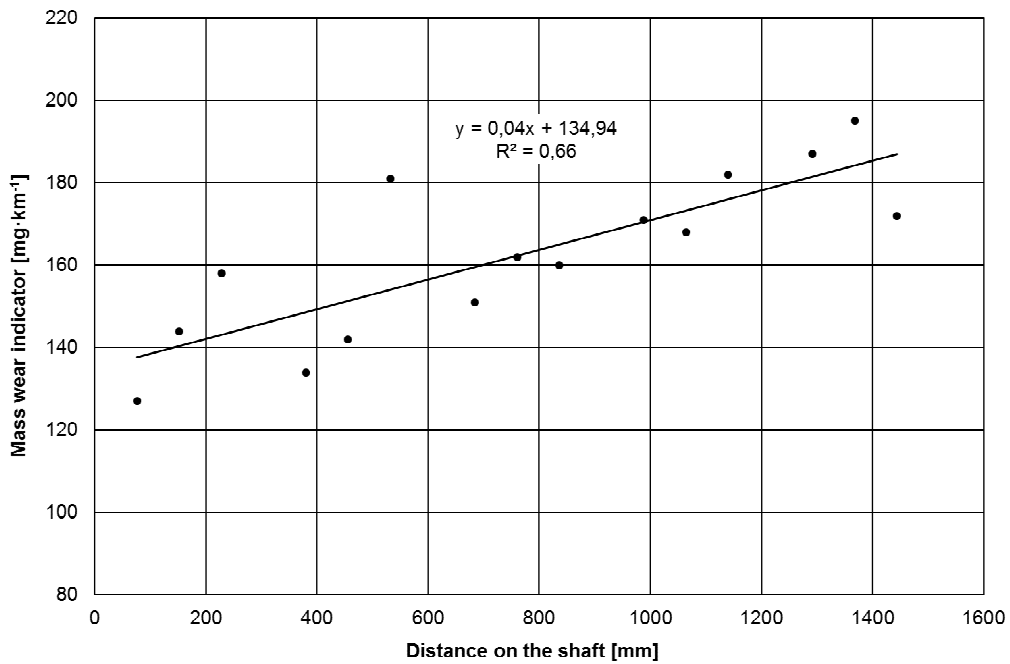| Steel	Volumetric wear, cm^3		Percentage wear, %		Mass wear, g		Mass wear indicator, mg·km^{-1}	
	I stage	II stage	I stage	II stage	I stage	II stage	I stage	II stage
Hardox	0.95	7.49	0.92	7.25	7.42	58.45	44	158
Hadfield	1.42	6.22	1.37	6.01	11.07	48.53	65	131
boron	1.52	6.16	1.46	5.94	11.85	48.07	70	130
boron*	1.86	7.23	2.24	8.70	14.55	56.38	86	152

* tines with a smaller cross-section

Fig. 4. **Influence of tines position (*x*) on rake shaft on mass wear indicator (*y*)**

The results of durability and wear tests of ploughshares made of different steels with boron presented by Konstencki [12] indicate a comparable resistance to abrasive wear covered by material tests. Research in natural soil conditions of modern structural materials made of boron steel, abrasion resistant steel, multicomponent padding weld and tungsten carbide has shown that wear intensities increase linearly with the friction path [13]. The use of these materials significantly increases wear resistance in relation to commonly used steels for elements of machines working in the soil. Many authors indicate that the tool material loss can be observed and can be as much as 10 g per kilometer of tilling.

Tines with smaller cross-sections (16 mm thick), made of the same boron steel, were worn more intensely than the tines with a larger thickness (20 mm), and the average values of the indicators amounted to 152 mg·km^{-1} and 130 mg·km^{-1}, respectively (Fig. 5).

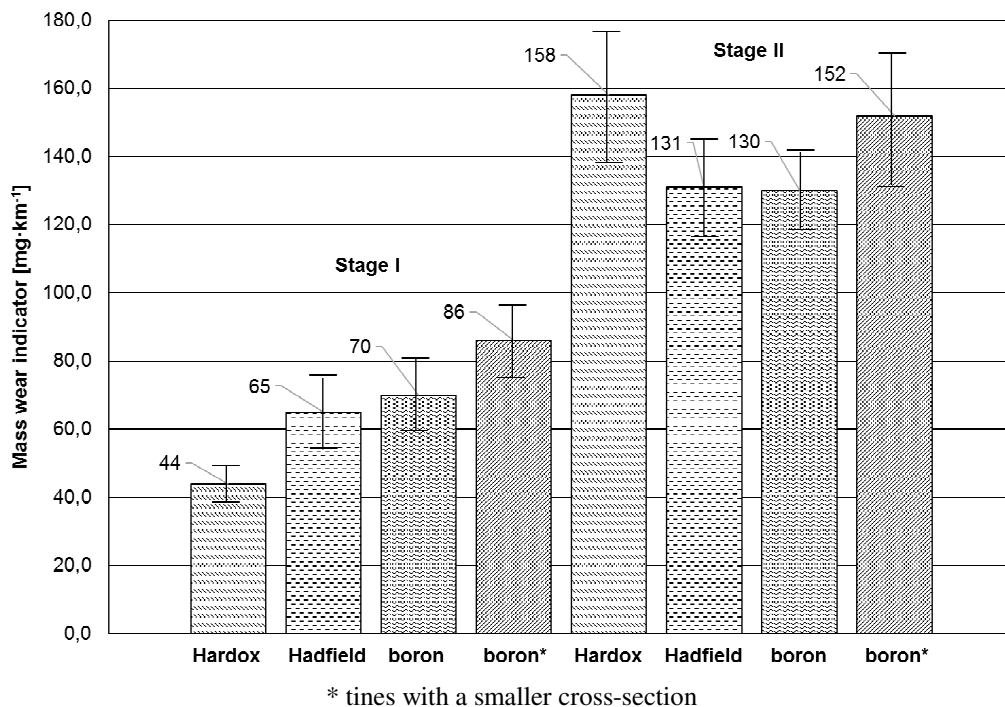* tines with a smaller cross-section

Fig. 5. **Tines wear indicator from different types of steel in the first and second stages**

A study conducted by Tugrul and Icoz [14] found the wear of ploughshare, cultivator and harrows to be 150 g·ha^{-1}, 135 g·ha^{-1} and 90 g·ha^{-1}, respectively. According to Bayhan [15], the wear of the ploughshares is an average of 90 to 210 g·ha^{-1}. This indicates that among these tillage tools the ploughshare experiences the most abrasive wear in soils. For rotary tiller blades, the authors [16] indicate wear of 78 and 158 g after 45 ha cultivated depending on the type of the tiller blades. In our research, the tines wear was 15.24 g·ha^{-1}.

Conclusions

1. The tines wear depends on the place of fixing on the rake shaft and increases linearly in the direction of the stones moving towards the machine throat.
2. The highest unevenness of wear during operation was characterized by the tines made of Hardox steel.
3. Tines made of the same boron steel of smaller cross-sections (thickness of 16 mm) were worn more intensely than the tines of a higher thickness (20 mm).
4. Considering the degree of tines wear, the most favorable solution is to use tines made of Hadfield or boron steel with a thickness of 20 mm.
5. A more detailed assessment of wear of individual tine surfaces can be carried out using 3D scanning and image processing.

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