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Improvement of Wear Resistance in Toothed Harrows Coated with HVOF and PVD Methods

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ABSTRACT

Surfaces of the toothed harrow were improved by using different coating materials and methods. Four different coating methods and special alloy powders were used as coating materials. TiCN was applied with PVD, and the WC-Ni-Co-Cr-Si-Fe-B powder mixture was applied with HVOF. The coating thicknesses was 2 µm and 5 µm in PVD, 500 µm in the HVOF, and 500+2 µm in the application where HVOF+PVD were used together. The wear trials were carried out in the laboratory, at a 50 km distance, in a double-speed trial pattern that converted circular motion to linear motion. The trial model was used to simulate the wear that occurs under real operating conditions in the soil. As a result of the wear trials carried out under the same operating conditions, a total material loss of 3.99 g occurred in the control (uncoated) harrow, the wear resistance increased, and less material loss was observed in the coated harrows. The sample coated with the PVD method had the lowest value with a material loss of 0.14 g. Material loss for other coated samples PVD-5µ, HVOF-500µ, and PVD-2µ+HVOF-500µ was 0.19, 0.28, and 0.18 g, respectively. When the amount of wear in the uncoated sample was 100%, the proportional loss in PVD-2µ, PVD-5µ, HVOF-500µ, and PVD-2µ+HVOF-500µ coated samples was calculated as 3.41, 4.85, 7.16, and 4.57%, respectively.

Keywords: Agricultural Machinery, Abrasion, Material loss, Coating.

INTRODUCTION

Wear causes malfunctions in machines and is the main cause of material losses, especially in active elements (Bayhan, 2006; Bemporad *et al*., 2008; Bressan *et al*., 2001; Çakmak, 1999; Singh *et al*., 2017). Wear is an increasing process of material loss from the component's surface. Abrasion occurs in many forms such as adhesive wear (oxidative wear, metallic wear, and peel wear), abrasive wear (high-stress grinding wear, low-stress scratch wear and pitting wear), erosion wear (particle impact and cavitation), and frictional wear (Chen *et al*., 2017). Although it is often possible to compensate for the loss of material, it can rarely lead to situations that are very difficult or impossible to recover. Material loss due to use or time causes a decrease in the functionality of the machine even if it does not cause serious malfunctions. Various studies have been carried out to minimize material loss by using rapidly changing and developing technology since the first tools and machines were used (Chen *et al*., 2016; Çiçek, 2018; Dave *et al*., 2016; Dizdar and Maroli, 2016; Ergül, 2015). Improvements in material quality, studies to improve material surface strength (Gupta *et al*., 2004; Kang *et al*., 2012; Jankauskas *et al*., 2015; Kang *et al*., 2017) and tribological properties (Karoonboonyanan *et al*., 2017; Malvarjedi *et al*., 2019a; Marani *et al*., 2019) can be shown as examples. The wear

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resistance of tillage tools can be increased by heat treatments and by applying a hard coating or coating layer on the substrate metal (Nalbant and Palalı, 2011).

The HVOF method to reduce wear in agricultural machinery has been investigated in previous studies (Ergül, 2015; Dizdar and Maroli, 2016; Jegadeeswaran *et al*., 2013; Kang *et al*. , 2017; Güney, 2021). PVD method and double coating processes are used in other sectors (Bressan *et al*., 2001; Bemporad *et al*., 2008; Çiçek, 2018; Dave *et al*., 2015; Malvarjedi *et al*., 2019b).

In this study, comparison of the coating with the HVOF method, which is in the current literature, with the PVD and double coating methods has been made.

MATERIALS AND METHODS

In this study, harrow teeth were coated with different materials and methods. With the coating processes, a hard, low friction coefficient and high wear resistance layer was formed on the harrow teeth. The hard surface layer teeth formed was subjected to an abrasion process and then their wear conditions were examined.

Toothed Harrow Teeth

The teeth of the toothed harrow active element used in the study were made of AISI 1040 steel material. This material is medium carbon steel commonly used in the production of toothed harrow teeth. The chemical content of the AISI 1040 material used is 0.37-0.44% C, 0-0.40% Si, 0.50-0.80% Mn, 0-0.0030% P, and 0-0.035% S.

The harrow teeth were bought from Hak Çelik Industry and Foreign Trade Inc. in Izmir/Turkey with a material certificate. The harrow teeth used in the study were prepared by cutting from Ø25 mm round solid material to the length used in the manufacture of harrow teeth. After cutting to length, the teeth were milled to 22 mm diameter and 195 mm length with a lathe. Forty mm length M10 thread was milled on one side to provide the assembly. The turning process of harrow teeth was done in Ege University, Faculty of Agriculture, Department of Agricultural Machinery, and Technologies Engineering Departments' Fine Mechanics Workshop. Coated and uncoated harrow teeth used in the trials were produced at one time and using the same quality material.

Coating Materials

Various methods and coatings of different thicknesses and combinations were applied to the harrow teeth used in the study (Table 1). The surface coating methods and application layer thicknesses used for the PVD method were TiCN-2 µm for sample A and TiCN-5 µm for sample B. The surface coating methods and application layer thicknesses used for sample C were HVOF-500 µm. Double-coated harrow teeth (for sample D) were applied with the HVOF method and WC-Co powder mixture at 500 µm in the first coating, and then 2 µm thick TiCN coating material with PVD coating method on the second coating.

The PVD coating was applied in the Uddeholm Turkey Company Bursa plant. The WC-Co powder coating material used in the coating made by the HVOF method was obtained by mixing COLMONOY-6 and

Table 1. Sample coding, Coating Methods, coating material and thickness.

Sample name (Code)	Uncoated Sample (S)	Coating-1 (A)	Coating-2 (B)	Coating-3 (C)	Coating-4 (D)
Coating method	-	PVD	PVD	HVOF	HVOF+PVD
Coating material (Thickness)	-	TiCN (2 µm)	TiCN (5 µm)	WC-Co powder mixture (500 µm)	WC-Co powder mixture (500 µm)+TiCN (2 µm)

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WOKA-3103 powders. This mixture is a WC-Ni-Cr-Co-B-Si-based powder alloy. The COLMONOY-6 powder mixture was prepared at 55% by mass and the WOKA-3103 powder mixture at 45% by mass. The chemical content by mass of the coating mixture used in the HVOF method and defined as WC-Co was 2.76% C, 7.7% Cr, 2.31% Si, 1.65% B, 37.08% W, 7.7% W, 2.29% Fe and 40.81% Ni. The HVOF coating was applied in TESLAB (Thermal Spray Technologies Research and Application Laboratory) located in Sakarya University, Turkey.

Wear Setup

In the study, the coatings used on the harrow teeth made of AISI 1040 steel were worn in an experimental environment to determine the wear resistance and behavior. A linear moving wear pattern was used to perform the wear processes. Wear pattern consisted of an electric motor, gearbox, belt-pulley arrangement, Gal type chain conveyor, and an abrasive bin (Figure 1). The harrow teeth were connected to the connection points on the wear system with the help of detachable fasteners. The harrow teeth were positioned in such a way that the running marks did not overlap each other and were positioned to work at a homogeneous depth in the abrasive material.

The 2.2 kW electric motor (Siemens/Germany), which provided the movement to the wear system, rotateed at 1,400 rpm. The motion taken from the motor is transferred to the gearbox by belt-pulley. The gearbox (Türk Traktör/Turkey) drives the harrow teeth with the help of the second belt-pulley. The gearbox has four-speed stages. However, only two of these four stages are suitable for working with this system. These rotation speeds are 36 rpm for the first stage, 60 rpm for the second stage, respectively. First speed; 3.13 km h^{-1} (0.87 m s^{-1}) and second speed was calculated as 5.22 km h^{-1} (1.45 m s^{-1}) for linear movement. The distance that the harrow teeth travel in a single entrance in the wear pin is 2.9 m. The wear setup was assembled in a laboratory of Ege University, Faculty of Agriculture, Agricultural Machinery and Technologies Engineering Department.

Wear Process and Wear Material

The wear material was predominantly a sandy mixture. To determine the content of the mixture, analysis was made in Ege University, Faculty of Agriculture, Soil Science and Plant Nutrition Department, and the content was determined as 94.4% sand, 4.32% clay, and 1.28% silt, and the constituent class of the wear material was evaluated as sand. Sand and sandy soils are the working environments with high abrasion effects for tillage machines.

Harrow's teeth were positioned in a pattern prepared for wear, so that the traces of the front teeth did not interfere with the working area of the teeth in the next row. The harrow teeth were randomly placed on the conveyor with 5 samples in the first row and 4 samples in the following row. The study was applied in a randomized block

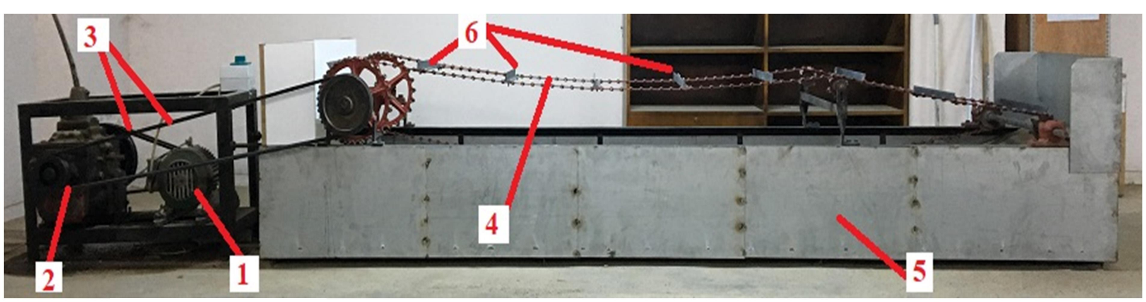

Figure 1. Sample wear pattern: (1) Electric motor, (2) Gear box, (3) Belt-pulley, (4) Gal type chain, (5) Wear bin, (6) Assembly points.

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design with 5 samples (4 coated samples+1 control sample)×2 speeds×3 parallel×2 replicates.

The harrow teeth were connected to the conveyor connected to the chain link in a way that their working directions did not change according to the plan. Harrow teeth with codes A, B, C, D, and S were subjected to wear after their placement was made. The number of laps of the drive sprocket shaft was taken as a basis for measuring the active distance worked in the wear process. The total working distance for each trial was calculated in km, using the number of laps and the active (the distance the tooth enters and leaves the soil) length. To determine the wear amount (teeth weight) of the harrow teeth, the teeth were removed every 5 km at a total working distance of 50 km and weight measurements were made with precision scales. After weighing, the teeth were reattached according to the layout plan so that their directions remained the same.

Microstructural Characterization and Chemical Composition Analysis of Coatings

SEM-EDS and XPS analyzes were performed with Thermo Scientific Apreo S and Thermo Scientific K-Alpha brand devices located in Ege-MATAL (Ege University Center Research and Test Laboratory Application and Research Center, respectively).

RESULTS

Hardness Values of Harrow Teeth

The hardness values of the samples before coating were determined by performing the Brinell Hardness Test. The average hardness values of the teeth made of AISI 1040 steel were found to be 283.38±18.08 HB.

The microhardness test was carried out under a load of 19.614 N for 10 seconds to determine the hardness values of the coatings on the coated harrow teeth. The average microhardness values were 919.50±47.78 HV_2 for sample A, 970.50±125.53 HV_2 for sample B, and 1408.25±191.94 HV_2 for sample D.

For the microhardness test to be applied, the surface to be measured must be parallel to the testing machine's table. As a result of the PVD coating process applied to A, B, and D samples, all surfaces of the samples could be coated. The HVOF coating method was applied for the C sample, and a rotating mechanism was used for the coating process. Due to the setup usage, the coating could only be applied to the round surfaces, and the microhardness test could not be done on the C sample because the surfaces of the harrow teeth were not planar. In samples A, B, and D, the flat surfaces at the tips of the harrow were also covered due to the coating process, so, a parallel surface to the device table was obtained and it was possible to measure.

Wear Results of Harrow Teeth

As expected, because of the wear process, the harrow teeth lost weight due to the wear material. In the first speed of 0.87 m s^{-1}, the highest weight loss was observed in S (uncoated), C, and A coated samples, respectively, while there was no weight loss in B and D coated samples. The effect of coating, forward speed, and wear distance variables on the amount of material loss was found to be statistically significant (95% confidence interval) (Table 2). The coating material, working speed, and working time influence the wear of the teeth. In addition, their interactions were found to be statistically significant.

Figure 2 shows the amount of material loss occurring in the abrasion tests performed at the first speed and 50 km abrasion distance. Material losses of S samples at first speed were measured as 0.411 g in total at the end of 50 km. Visual changes on teeth are given in Figure 3. The total material loss that occurred in A sample at the first speed was

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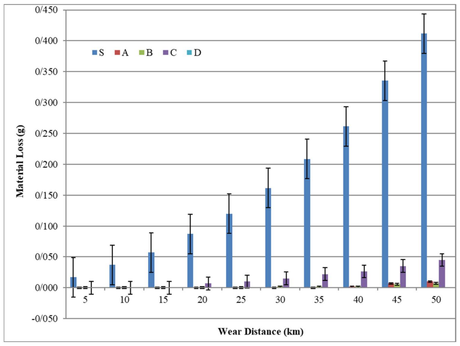

Figure 2. Variation of total material loss in samples at first speed over 50 km distance.

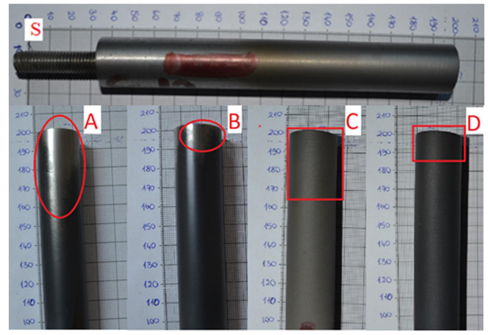

Figure 3. Visual change of teeth after the first speed wear.

Table 2. Statistical evaluation for material loss (ANOVA, α: 0.05).

Material loss					
Sources	Squares total	df	Squares average	F	Level of importance
Coating	3.130	4	0.782	31486.037	0.000
Speed	0.800	1	0.800	32200.024	0.000
Wear distance	0.495	10	0.049	1990.335	0.000
Coating×Speed	1.958	4	0.489	19694.963	0.000
Coating×Wear distance	1.396	40	0.035	1404.742	0.000
Speed×Wear distance	0.313	10	0.031	1259.989	0.000
Total verified	9.039	659			

0.010 g. This loss in B-coated samples was 0.007 g. The material loss that occurs can be interpreted as the removal of the coatings on the samples due to wear. While the coating area lost after abrasion in the A sample was 21.78 mm^2 on average, it was 7.26 mm^2 for the B samples. The wear that occurs in the C samples the loss of material and the removal of the coating from the surface show themselves as a color change. The gray color of the coating acquired a brown-green color with wear. Due to the friction on the tips of the harrow teeth, this color change increased at the tip. The loss of material at the first speed in C samples was 0.045 g. Although there was no weight loss at the first speed in D samples, in all samples, coating removal from the surface due to wear was observed. The removal of the coating from the surface due to the wear in the D samples manifested itself as discoloration and the emergence of the undercoat HVOF coating. The color change concentrated at the ends and was an indication that the abrasion occurred intensively in this area. The visual changes that occurred in the samples that had been coated in the first-speed abrasion condition are given in Figure 4.

It is known that wear increases with increasing forward speed (Dave *et al*, 2016). Accordingly, material losses increased in the second-speed abrasion process. S (Control) samples had the most material loss, while the A and B samples were worn more than the C sample. In addition, while D samples did not lose weight at the first speed, wear occurred with the increase in speed at the second speed.

The amount of material loss that occurred in the wear process at 50 km with the second speed is shown in Figure 4. The material loss at the second speed in the samples without coating was determined as 3.574 g. The material losses of the A samples at the

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second speed were 0.126 g, in the B samples the loss at the second speed was 0.186 g, although there was no material loss at the first speed. Material loss in C samples was 0.238 g, while the material loss for D-coated samples was 0.182 g. In the second speed, the loss of weight in the samples with codes A and B and the areas of removal of the coatings from the surface due to wear increased.

While the separation area formed in the coating in the A sample was 26.62 mm^2 on average, it was 29.04 mm^2 in the B sample. As a result of working at the second speed, the B samples were worn more than the A samples and were exposed to the removal of the coating from the surface in a larger area (Figure 5). The wear of the D samples, the loss of material, and the removal of the coating from the surface are manifested as color change. The gray color of the coating takes on a brown-green color with wear. Due to the friction at the tips of the harrow tooth, this color change increases at the tips that met the soil.

The material loss rate in uncoated (control) samples increased by 8.70 times compared to the first speed (Figure 6). When the increase in material loss due to the working speed of the coated samples was compared, the order was C< A< D< B samples. The increase in wear rates was 5.29, 12.6, 18.2, and 26.57 times, respectively.

A linear relationship is expected between wear distance and material loss. However, the amount of material loss resulting from the wear processes showed a polynomial trend for each wear distance range. It is seen that there is an increasing relationship between the wear distance and the amount of material loss (Figure 6). Although the same wear distance was applied, the amount of material loss increases for every 5 km traveled. Considering the total working distances, the most abrasion occurred in samples without coating (control-S). The total material loss ranking was realized as A< D< B< C samples. When the total wear amount of the samples coated with uncoated samples was compared, it was determined that there was 29.3 times less material loss in the A sample, 20.6 times in B samples, 14.1 times less in C samples, and 21.9 times less in D samples. As the wear distance and working speed increased, the material loss due to wearing increased.

In Table 3, the amounts of average material loss and total material loss are given in the first and second operating speed conditions after the 50 km wear distance of all samples. In the table, the loss in S (control) samples is accepted as 100. The lowest proportional loss for the first speed value was seen in B samples, then in A and C samples. The sample with the lowest proportional loss rate for the second speed value is the A sample. This sample is followed by the D, B, and C samples.

Different material loss amounts in the samples were measured at the first and second speed values. Comparing these loss

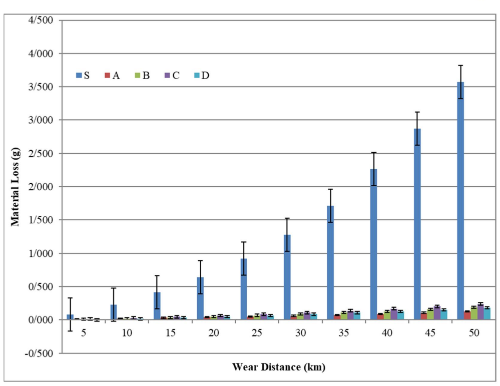

Figure 4. The total amount of material loss in samples at the second speed.

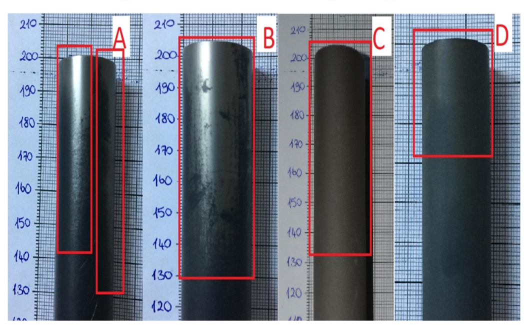

Figure 5. Second-speed wear appearance on coated teeth.

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amounts with the reference value, different proportional losses are calculated in the samples. With the increasing amount of material loss, the proportional losses calculated in A, B, and D samples increased. In sample C, the calculated loss rate is lower for the second speed value. The reason for this is the increase in the amount of material loss measured in the reference sample with an increasing feed rate. When the coated samples are examined in terms of proportional loss, sample C is the sample with the highest value for both speed values.

Microstructural Analysis

XPS Analysis

XPS analysis was performed as spot scanning with the rays emanating from the Al Kα Monochromatic X-ray source at the energy level of 50 eV in the 60×60 mm sampling area. Atomic percentages of the elements in the coatings are given in Table 4 according to the analysis.

According to the data obtained from the XPS analysis, it was determined that most of the composition of the B-coated samples

Table 3. Material loss amounts and rates of samples.

Sample	Speed I		Speed II	
	Material Loss (g)	Proportional loss (%)	Material Loss (g)	Proportional loss (%)
S	0.411	100.00	3.574	100.00
A	0.010	2.43	0.126	3.52
B	0.007	1.70	0.186	5.20
C	0.045	10.95	0.238	6.66
D	0.000	0.00	0.182	5.09

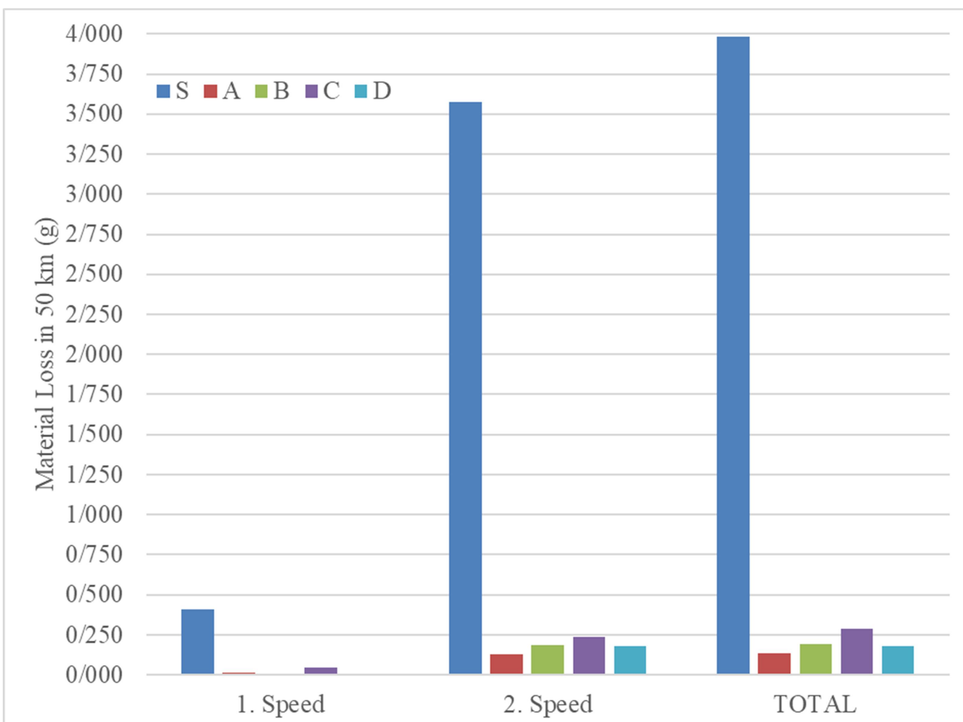

Figure 6. Material losses change in samples after 50 km wear distance for speed I, speed II, and total material loss of the samples per 50 km wear distance.

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Table 4. XPS Patterns of coatings.

A - B		C		D	
Element	Atomic %	Element	Atomic %	Element	Atomic %
C	74.78	W	0.4	W	0.2
N	4.69	Si	3.21	S	2.62
Ti	0.88	B	1.84	B	2.18
O	17.24	C	69.96	C	52.27
		N	5.05	N	6.32
		O	16.17	Ti	1.13
		Co	0.66	O	20.59
		Ni	0.46	Fe	0.56
				Co	0.37
				Cr	0.76

consisted of Ti_2X, Fe_2X, and C_1X compounds. The compounds formed in the C-coated samples were determined as Fe_2X, Si_2X, Cr_2X, W_4X, Ni_2X, Co_2X, C_1X, B_1X, and N_1X. D-coated samples were determined to consist of Co_2X, Ti_2X, Fe_2X, W_4X, Ni_2X, C_1X, B_1X, N_1X, and S_2X compounds.

SEM and EDS Analysis

The 5000X magnified images of the B-C-D coated sample taken from the SEM analyzer are given in Figure 7. The coated material and crystal grains formed by the coating are visible in the figure. It is seen that the coating provides good adhesion to the surface with the help of the layers formed due to the surface roughness and the indentations and protrusions formed during processing. The granular structure and crystals formed by the WC-Co elements in the powder mixture sprayed with the HVOF coating the granular structure formed by the HVOF coating and the large-sized WC crystals, and the small-sized Ti crystals formed in the cavities are seen in the C samples (Figure 7).

EDS analysis was performed for each sample to determine the elements forming the coating. EDS analysis was performed at 5000X magnification. For EDS analysis, a certain area was determined on the sample and the mass and atomic percentage values of the elements were found in this area. Table 5 shows levels of the chemical composition of the B, C, and D samples by % mass.

DISCUSSION

After contact with abrasive materials in the soil, abrasion occurs on the harrow teeth over time. To prevent abrasion, harrow teeth exposed to abrasion are coated with WC (Tungsten Carbide) based powder alloys and TiCN (Titanium Carbonitride) based materials. When the wear mechanisms are examined, it can be said that the abrasion on the hard surface is less compared to the soft surface. However, since the work can be done in two directions in toothed harrows and the active element coated surfaces are round, all surfaces are coated. Ergül (2015) emphasized that WC-based materials have good abrasion resistance. Kang *et al*. (2017) coated the soil tillage cutting blades with the thermal spray method using different coating materials. They reported that the WC-Co-Cr coating powder showed better wear resistance than other coating powders. In this study, which was carried out to prevent the abrasion that occurs on the harrow teeth, it was determined that the wear on the teeth that were not coated at the end of the abrasion processes lost more material compared to the WC-based coated teeth.

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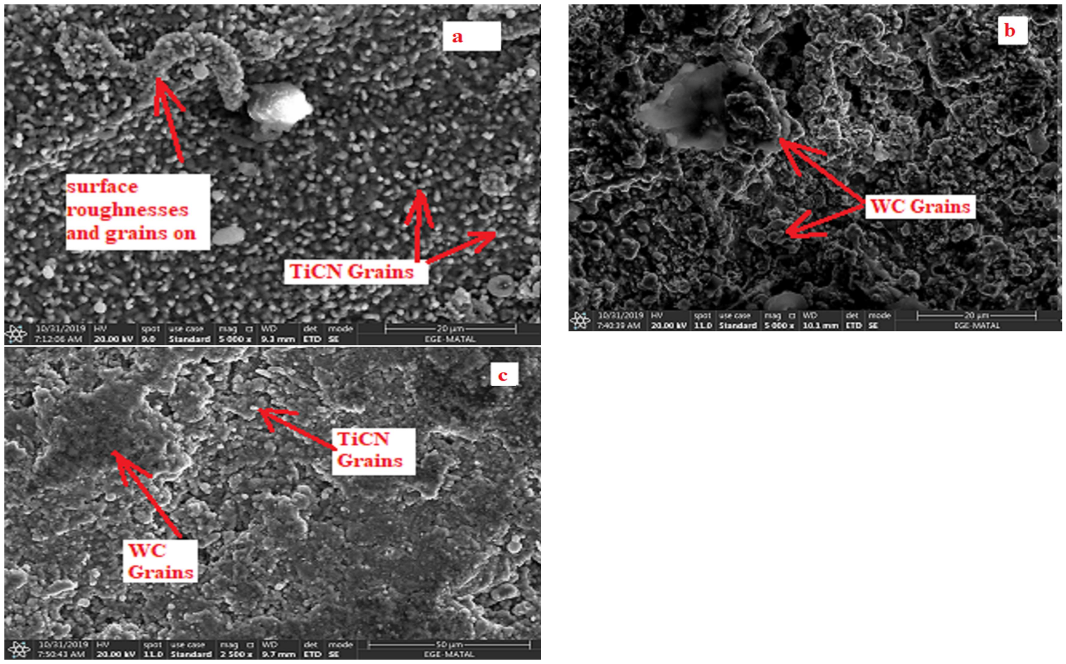

Figure 7. SEM micrographs of coatings (top view).

Table 5. EDS chemical compositions of the coating materials.[a]

B		C		D	
Element	By mass %	Element	By mass %	Element	By mass %
C	13,12	B	3,13	C	13,06
N	22,19	C	25,36	N	21,62
O	6,93	Si	1,64	O	9,37
Ti	29,3	Cr	1,77	Ti	**29,54**
Fe	4,55	Fe	3,39	Cr	0,16
		Co	11,38	Fe	0,89
		Ni	1,09	Ni	0,11
		W	**52,24**	W	2,15

[a] B: PVD– 5 μ; C: HVOF– 500 μ, D: HVOF– 500 μ+PVD–2 μ.

Singh *et al*. (2021) applied different coatings in their study to determine the wear characteristics of plow end irons manufactured from EN-42 steel material and conducted field trials in different conditions. They obtained different surface hardnesses with the coatings they applied on the end irons. They reported that there were differences in wear rates with the change in the hardness values. In this study, different coatings were applied to harrow teeth and different hardness values were obtained. For this reason, the wear behavior of the harrow teeth has become different.

Nalbant and Palalı (2011) investigated the wear conditions of the different surface coating layers applied to the plowshare during soil cultivation. They reported that the coating made with the PVD method showed the longest wear resistance

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compared to other coating methods and had the least material loss. Malvajerdi *et al*. (2019) coated the active elements of the soil cultivation machines made of Ck45 material with the PVD method and reported that the friction coefficient in the samples decreased, the draft force decreased, and the working life increased. In this study, PVD-coated harrow teeth had the least material loss.

Picas *et al*. (2017) reported that the double-coated samples showed longer wear resistance and the friction coefficients could be reduced to very low values. The results of this study show that the material loss of the double-coated samples was more than PVD-coated samples. The first coating layer applied with HVOF appeared to increase the friction coefficient, therefore the material loss values were higher.

According to the findings obtained in the study, it was determined that TiCN-based (PVD) coatings had less material loss than uncoated and WC-based (HVOF) coatings. In this study, a tough and partially hard base-first coating layer and a hard second coating layer were obtained in double-coated samples. In the abrasion tests, it was determined that the double-coated samples were in the second place in terms of material loss due to wearing.

CONCLUSIONS

This study aimed to improve the wear resistance of harrow teeth by using different surface coating methods. To prevent/reduce wear, the harrow teeth exposed to wear coated with WC (Tungsten carbide) based and TiCN (Titanium Carbonitride) based materials. According to the findings, it was determined that coatings made with the TiCN-based (PVD) method had less material loss and relative wear resistance improved compared to uncoated and WC-based (HVOF) samples. It can be said that the formation of a first coating layer and a hard second coating layer on a tough and partially hard substrate in double-coated samples partially improves the material wear resistance and is the second-best coating in this regard.

In the study, it was determined that the coated harrow teeth provides a much better wear resistance than the control (S) samples.

When the coated samples (A-B-C-D) are compared, they are the C-coated (HVOF-WC powder alloy) samples that suffered the most weight loss at both speeds. During this coating process, it is thought that the roughness value of the powder mixture sprayed on the surface is relatively high at a visually detectable level, resulting in a higher friction coefficient compared to other coated samples. While B and D coated samples did not lose weight compared to the first-speed etching tests, A coated samples lost weight. While there was no weight loss in the B-coated samples at the first speed, shedding was observed in the coating on the coated surface.

In the second speed trial, weight loss was observed in all samples. It is seen that B samples lost the most material among the coated samples. The weight loss in D samples was expected to be less due to the double coating formed with a less hard layer on the backing material and a harder second layer with a low friction coefficient. However, with the erosion of the second coating layer, wear was observed in the lower coating layer. Sample A, on the other hand, showed the best performance and gave the best result at both speed levels.

According to the result of this study, the average weight loss of the coated samples was 21.5 times less compared to the samples without coating. Although the cost for the coating processes was 17 times higher than the cost of uncoated samples, it seems more profitable to use coated samples when looking at the weight loss. The usage of coated material appears to be more profitable, with the coating processes getting cheaper. Among the coatings, for agricultural machinery active elements, the PVD method is seen as a more effective coating method than the HVOF that were used in the studied soil conditions.

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بهبود مقاومت به سایش در چنگه‌های دندانه دار(Toothed Harrows) پوشش داده شده با روش های HVOF و PVD

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چکیده

سطوح چنگه دندانه دار با استفاده از مواد و روش های مختلف پوشش بهبود داده شد. چهار روش پوشش-دهی مختلف و پودرهای آلیاژی خاص به عنوان مواد پوشش استفاده شد. TiCN با PVD اعمال شد، و مخلوط پودر WC-Ni-Co-Cr-Si-Fe-B با HVOF به کار برده شد. ضخامت پوشش در PVD ۲میکرومتر و۵ میکرومتر، در HVOF برابر 500میکرومتر ، و در کاربردهایی که HVOF + PVD با هم استفاده می‌شد،۲+ ۵۰۰ میکرومتر بود. آزمایش‌های سایش در آزمایشگاه، در یک مسیر ۵۰ کیلومتری، در یک

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الگوی آزمایشی با سرعت دوگانه که حرکت دایره‌ای را به حرکت خطی تبدیل می‌کرد، انجام شد.مدل آزمایشی برای شبیه سازی سایشی که در شرایط عملیاتی واقعی در خاک رخ می دهد استفاده شد. در نتیجه آزمایش‌های سایش انجام شده در شرایط عملیاتی یکسان، اتلاف کل مواد برابر ۳.۹۹ گرم در چنگه شاهد (بدون پوشش) رخ داد، مقاومت به سایش افزایش یافت و تلفات مواد کمتری در چنگه های پوشش‌دار مشاهده شد. نمونه پوشش داده شده با روش PVD با اتلاف ۰.۱۴ گرم کمترین مقدار را داشت. از دست دادن مواد در دیگر نمونه های پوشش داده شده PVD-5µ، HVOF-500µ، و PVD-2µ+ HVOF-500µ به ترتیب برابر ۰.۱۹، ۰.۲۸ و ۰.۱۸ گرم بود. هنگامی که میزان سایش در نمونه بدون پوشش ۱۰۰% بود، افت متناسب در نمونه های پوشش داده شده PVD-2µ، PVD-5µ، HVOF-500، PVD-2µ+HVOF-500µبه ترتیب برابر۳.۴۱%، ۴.۸۵%، ۷.۱۶% و ۴.۵۷% محاسبه شد.

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