Tribological Analysis of Plasma Spray Thermal Deposition on the Active Area of Harrow Discs

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Abstract: *The results of tribological tests of the active area of harrow disks with coatings obtained by the plasma spay thermal method are presented. This study is based on scanning electron microscopy of coated harrow disc samples undergoing standard tribological tests that focuses on the mechanical properties of coatings using tribological methodology. Tribological studies were conducted to determine the following main parameters of the harrow disc material such as: adhesion to the substrate, coefficient of friction, Young's modulus, stiffness and hardness of coated samples and the base material. As the result, improving the mechanical and chemical properties of materials used to manufacture the working bodies of coated harrow discs allows for increased resistance to abrasive wear in modern agricultural machinery.*

KEY WORDS: *TRIBOLOGICAL ANALYSIS, PLASMA SPAY THERMAL METHOD, HARROW, COATED DISC, ACTIVE AREA.*

Introduction

The quality of manufactured tillage agricultural machinery does not allow for prevention severe wear of their working bodies. Increasing the durability of tillage equipment parts, such as harrow discs, is one of the main areas in the design and production of agricultural machinery, the use of which increases productivity, reduces costs and ensures the best results in farming.

Since harrow discs are also subject to severe abrasive wear as a result of soil cultivation, analysis of plasma-thermal spraying on the active part of harrow discs allows to evaluate the resistance to abrasion and corrosion.

A number of scientists has shown that all tillage machines wear out faster as the amount of sand particles in the soil increases, requiring improved mechanical properties of the working surfaces of the working parts [1, 2]. This suggests a relationship between the wear of the active area of the working bodies of the machine and the size of the sand particles and, as a consequence, the optimization of their mechanical properties to increase the wear resistance of the discs is crucial for extending the service life of the active area of the harrow discs [1, 2, 3].

During the soil tillage operation, the harrow disc blades are also subject to significant wear due to abrasive soil particles: sand, small stones and other hard materials accidentally found in the soil. Therefore, the active area of the working elements of these machines must have significant impact resistance [1, 2, 4, 5]. This means using effective methods to improve the required parameters of the active surface of the harrow discs, and subsequently conducting tests of disc harrows in accordance with current standards for testing agricultural machinery.

Plasma spray thermal deposition is one of the effective methods for improving the main parameters of the harrow disc material, considered an advanced method capable of achieving high-quality surface layers [2, 3]. It should be noted that the use of this method is usually limited to very thin coatings - up to 100 µm.

Prerequisites and means for solving the problem

Severe wear conditions require coatings that offer high hardness and durability, such as the often used tungsten carbide (WC) coatings, which consist of WC particles as a hard and resistant phase for wear protection. Once embedded in a metal matrix, the tungsten carbide particles act as a plastic binder, effectively bonding and supporting the carbide grains under severe operating conditions [6].

Carbide degradation, particle ejection, and subsurface crack formation play a significant role in the wear behavior of deposits. The study of erosive and abrasive wear of WC12Co and WC10Co4Cr coatings deposited by the High-Velocity Oxygen Fuel (HVOF) method highlights the fact that wear processes are influenced by the coating microstructure and the testing conditions [7, 8].

Other scientists claim that hot rolled steel plates such as 65Mn and 60Si2Mn coated with WC10Co4Cr showed reduced porosity, denser microstructure, minimal carbon evolution, improved adhesion strength and increased wear resistance [7].

At the same time, it has been established that wear of WC10Co4Cr coatings occurs when the surface of tungsten carbide (WC) particles are destroyed and exfoliated, while the CoCr binder phase undergoes microdestruction, forming grooves and microcracks that propagate until particle exfoliation leads to the formation of pits.

However, researchers such as Cheng et al. found that chromium oxide Cr_2O_3-based coatings with higher titanium oxide TiO_2 concentrations, known for their moderate hardness and good toughness, produced using the athmospheric plasma spray (APS) thermal method exhibit a denser microstructure and improved corrosion resistance in three different solutions such as HCl, NaCl, and NaOH. There is also a risk that ceramic coatings based on pure chromium oxide Cr_2O_3, due to their brittleness, may suffer from poor adhesion, delamination and porosity caused by insufficient particle melting [9, 10, 11, 12]. It has been established that dense TiO_2, which is part of chromium oxide Cr_2O_3, refines the grain size and fills intergranular voids, thus increasing the internal density of the composite coating [13].

In a study of high-temperature oxidation processes in CoCrNi alloys, Park et al. observed significant formation of spinel oxides, $CoCr_2O_4$ and $NiCr_2O_4$, in the outer oxide layer during oxidation.

Solution of the examined problem

To improve the quality of the working bodies of agricultural harrow discs, three types of coatings are applied to the active areas of the discs:

- W_2C/WC12Co (Metco71NS);
- Cr_2O_3-4SiO_2-3TiO (Metco136F);
- Co25.5Cr10.5Ni7.5W0.5C (Metco45CNS).

The experimental coatings were deposited using a Sulzer Metco 9MCE deposition system operating with Ar (5.3 bar, 45 NLPM) and H_2 (3.5 bar, 7.0 NLPM). After mechanical grinding and intensive sandblasting, samples with plasma spray thermal depositions on active areas of harrow discs were tested. Experimental setup includes a rotating support, an automated arm connected to a Sulzer 9MB spray gun, and a sample holder [14].

Powders for spraying the active areas of the harrow discs were produced by company Oerlikon Metco.

Concave and convex parts of harrow discs were coated using the atmospheric plasma spray (APS) thermal deposition method (fig.1).

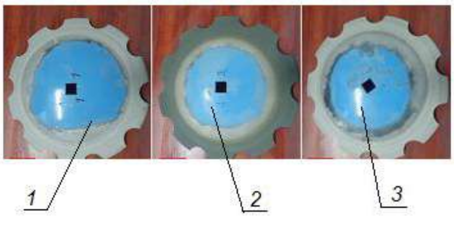


Figure 1. Convex part of experimental discs with coatings:
1 - Sample 1; 2 - Sample 2; 3 - Sample 3.

Before tribological testing, a series of tests were carried out to analyze the surface of the coated samples, using the following equipment [14, 15]:

- scanning electron microscopy (FEG Thermo Fisher - Quattro C, 2024);
- energy-dispersive X-ray spectroscopy (EDX - Bruker, X-Flash detector);
- panalytical equipment X-ray diffraction (XRD-Panalytical equipment).

The tests on the three already mentioned harrow disc samples were carried out using a CETR UMT-2 microtribometer for standard scratch and microhardness testing, connected to a computer (fig.2).

The following requirements apply to sample dimensions:

1) indentation and microscratch tests: 10 mm in width and 20 mm in length;
2) wear and friction tests:
   - for linear table: 10-20 mm in width and 20-30 mm in length,
   - for rotational table: disc with 12 to 65 mm in diameter,
   - pin specimen with 6.35 mm in diameter and 20-30 in length - for upper drive/force sensor.

All samples must have a thickness of maximum 5 mm.

Figure 2. The CETR UMT-2 tribometer for standard scratch and microhardness testing, connected to a computer.

The CETR UMT-2 tribometer (fig.2) was used to analyze and conduct the standard tests of the following tribological processes [14, 15, 16]:

- study of wear processes and determination of friction coefficients at micro and nanometric scales in rotational motion for studied materials;
- study of the microscratch resistance of the material superficial layers;
- microindentation tests to determine the material microhardness and Young modulus.

The values of vertical and friction forces that can be measured between 0.1 mN and 20.0 N and resolution between 1 μN and 1mN, depending on the force sensors. The CETR UMT-2 tribometer (fig.2) covers the following force ranges: 0.1 mN-10 mN, 5 mN-500 mN and 0.2 N-20 N.

Microindentation test methodology. According to ASTM E18-05 standard, for the determination of Rockwell hardness the indentation test consists of 2 main stages [17]:

1) an initial pre-loading stage with a force of up to 10% of the maximum test force;
2) a loading stage with a force of up to 450 N, depending on the force range of the force sensor on which the indentation test is performed.

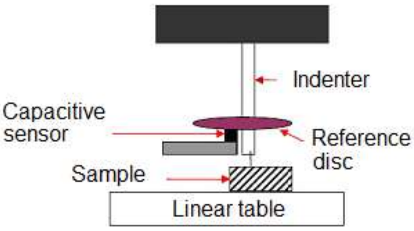


Figure 3. Schematic representation of the positioning of the capacitive sensor under the reference disc

First of all, it is necessary to set up the CETR UMT-2 tribometer to perform the microindentation test. To perform the microindentation test on the tribometer, the linear table is mounted on which the sample and the capacitive sensor support for recording the distance traveled by the indenter in the vertical direction are fixed (fig.3). For that, a two-kilogram force sensor is used, to which the rigid support in which the indenter support system is mounted is fixed by means of two screws.

A metal disk, called a reference disk, is fixed between the indenter support system and the indenter, under which the capacitive sensor is placed to record the vertical displacement of the indenter.

For a correct measurement of the indenter displacement, the capacitive sensor must be positioned as close as possible to the indenter, the entire circumference of the sensor must be covered by the reference disk, and the distance between the upper surface of the capacitive sensor and the reference disk must be 220-230 μm, in order not to exceed the sensor's working range of maximum 254 μm. If the capacitive sensor is positioned too close to the reference disc, there is a risk that the reference disc will hit the sensor (Fig.4).

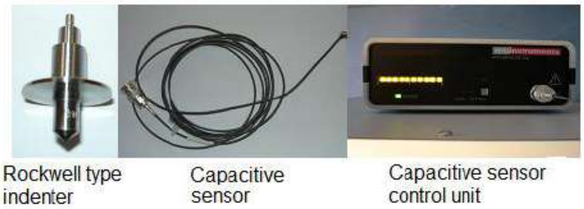


Figure 4. Main elements of the CETR UMT-2 tribometer for microindentation testing

The indenter used for this test has a conical shape at an angle of 120º, with a rounded diamond tip with a radius of 200 μm.

The capacitive sensor is attached to the support system that is mounted on the horizontal table (fig.4) and it is connected to the control unit, which is connected to the CETR tribometer [16].

The hardness measured by the indentation process is defined as the average contact pressure and is given by the relationship:

$$H_{IT} = \frac{F_{\max}}{A_P} \qquad (1)$$

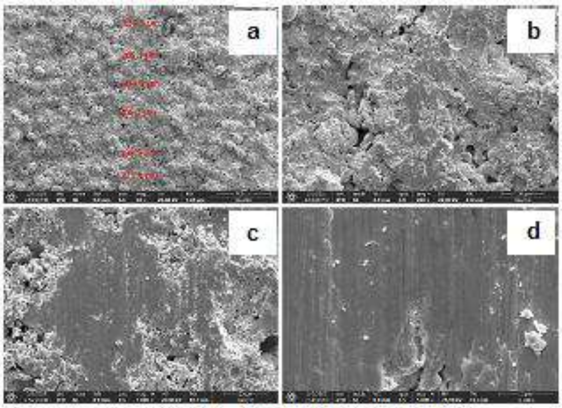
where: F_{max} - the maximum force, N;
A_P - the projection of the contact area at this force, m^2.

Rezults and discussion

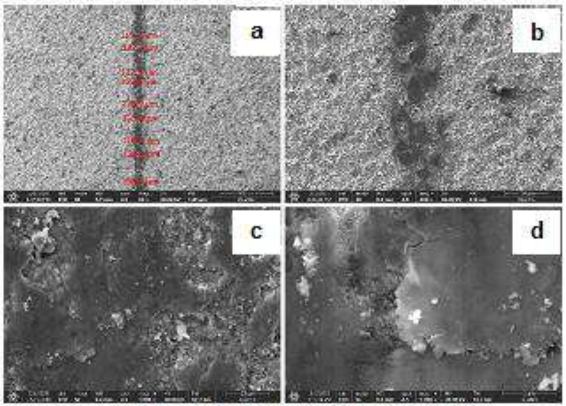
In order to determine the main material parameters such as substrate adhesion, coefficient of friction (COF), Young's modulus (modulus of elasticity), stiffness and hardness a tribological analysis was carried out (fig.5).

Figure 5. Conducting tribological tests in the laboratory of Technical University „Gheorghe Asachi”, Iasi, Romania

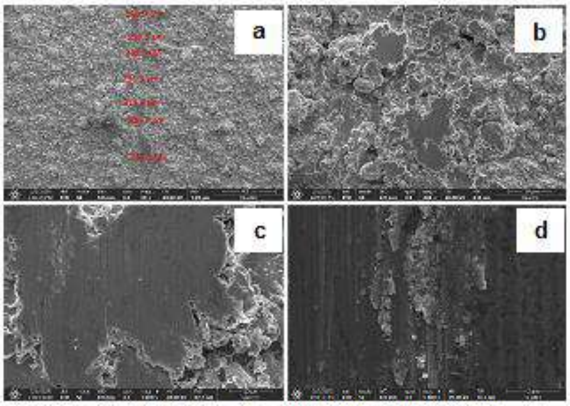
The micro-scratch test was conducted to determine the friction coefficient, calculated as the ratio between the horizontal force F_x(N) and the applied loading force of 10 N, F_z(N) [14, 16].



Sample 1 - W2C/WC12Co (Metco71NS);



Sample 2 - Cr2O3-4SiO2-3TiO (Metco136F);



Sample 3 - Co25.5Cr10.5Ni7.5W0.5C (Metco45C-NS).

Figure 6. *Scratch analysis of the surface of samples: a) 50X; b) 200X; c) 1000X; d) 5000X.*

Figure 6 illustrates the scratch behavior and the size of the marks left by the indenter on the coated surface. In all three cases, the substrate was not reached, however, microcracks and detachment of the superficial surface layer were observed.

Table 1. *Results of tribological tests - scratch analysis*

	Sample	Determined mechanical properties			
		Coefficient of friction (COF)	Young's Modulus, GPa	Stiffness, N/µm	Hardness, GPa
1	*Sample 1* P1 - Metco 71NS	0.4105	23.988	2.482	1.143
2	*Sample 2* P2 - Metco 136F	0.5425	53.102	4.478	1.635
3	*Sample 3* P3 - Metco 45C NS	0.5059	37.679	3.672	1.255
4	Base Material	0.1394	42.964	4.393	1.131

To determine the COF coefficient, which was calculated using formula (1), a micro-scratch test was carried out. As a result, the average scratch width was: for Sample 1 - 227 µm, for Sample 2 - 124 µm, and for Sample 3 - 232 µm.

The values obtained as a result of scratch analysis for all three studied layers and the base material are presented in Table 1. Based on the data presented in Table 1, diagrams of the main material parameters such as the coefficient of friction (CF), Young's modulus, stiffness and hardness for coated samples and the base material were constructed and are presented in figures 7-10.

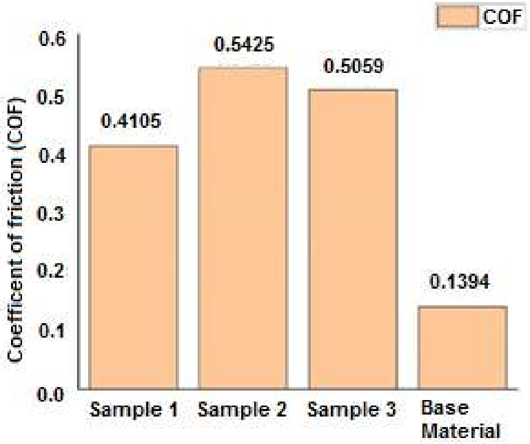


Figure 7. Apparent coefficient of friction (COF) of coated samples and the base material

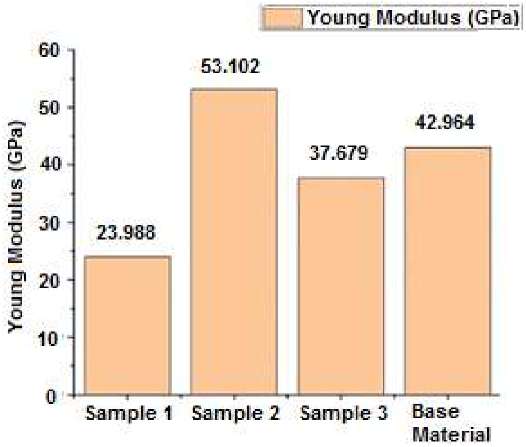


Figure 8. Young's modulus of coated samples and the base material

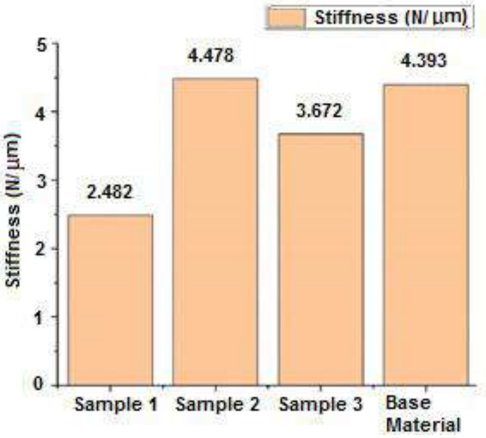


Figure 9. Stiffness of coated samples and the base material

Analysis of the tribological test results presented in figures 7–10 for all three categories of tested samples coated by plasma spray thermal method and the base material shows that the deposition of

Sample 2, which contains ceramic compounds of chromium, silicon and titanium oxides (Cr_2O_3-$4SiO_2$-3TiO), led to a higher coefficient of friction, Young's modulus, stiffness and hardness, compared to the other two coatings.

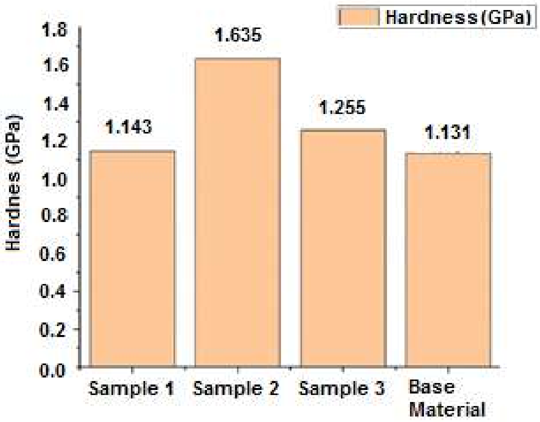


Figure 10. Hardness of coated samples and the base material

It is necessary to mention that in the case of stiffness, the highest and closest results were obtained for Sample 2 and the Base Material, the results being within the limits of the admissible error. Sample 1 recorded poor results for Young's modulus, stiffness and hardness, but for the coefficient of friction the result was better compared to the base material.

Conclusions

1. The morphological analysis revealed a rough and porous surface with some unmelted particles and small cracks of the coatings of the following samples (Sample 1 - W_2C/WC12Co (Metco71NS), Sample 2 - Cr_2O_3-$4SiO_2$-3TiO (Metco136F) and Sample 3 - Co25.5Cr10.5Ni7.5W0.5C (Metco45C-NS)) deposited on the active area of the harrow discs using atmospheric plasma spray thermal deposition. Tribological analysis of the coated samples was followed by Scratch analysis of the surface of samples.

2. To determine the coefficient of friction (COF), a micro-scratch test was performed, as a result of which the average scratch width was: for Sample 1 - 227 µm, for Sample 2 - 124 µm and for Sample 3 - 232 µm.

3. The scratch behavior, as well as the size of the indentation marks on the coated surface in all three cases, showed that the substrate was intact, but microcracks and delamination of the superficial layer were observed.

4. Sample 2, with Cr_2O_3-$4SiO_2$-3TiO (Metco136F) coatings deposited on the active area of the harrow discs using the atmospheric plasma spray thermal deposition showed the highest values among all studied coatings for coefficient of friction, Young's modulus, stiffness and hardness.

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