Assessment of Tribological Properties of Single- and Double-Layer Pad Coatings Deposited onto Cultivator Points

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ABSTRACT

This paper investigates properties of single- and double-layer pad coatings deposited on cultivator points. The coatings were deposited by manual metal arc welding (MMA) with ESAB OK. 84.58 coated electrodes using an inverter welder, DEDRA DESi201. Tribological properties were determined with a THT 1000 tribometer. A ball-on-disc friction pair was used. Experiments were performed in room temperature, with the sliding speed set equal to 0.3 m/s and two loads: 5 and 20 N. In addition, hardness was measured on the surface and in the cross section of samples by a Rockwell hardness test method (scale C). Surface roughness was measured before and after friction, and post-friction surface topography was examined under microscope. Impact strength tests of the coatings with single- and double layers of pads were performed. The tools and IT algorithms were used to collect and process the results of experimental research.

Keywords: wear, friction, coatings, welding.

INTRODUCTION

Farming machinery elements for soil cultivation are exposed to many external factors that may cause their failure. The surface layer of materials is the most prone to failure because it directly interacts with work environment, i.e. the soil and its components such as stones, gravel, sand, clay, etc. This layer is exposed to operational wear due to friction. The most dominant type of wear in this case is abrasive wear [1]. It consists in separation of small particles of the surface layer of material due to the friction of the above-mentioned work environment factors (that act as abrasive particles and are harder than the surface layer of the material) [2–4]. The wear of surface layers is caused by fundamental processes such as microcutting, scratching, chasing, shearing and the removal of surface microirregularities.

The abrasive wear rate of the surface layer of agricultural machine elements depends on the type of soil, its consistency, structure and humidity [5–6]. Soil is not structurally homogeneous by its very nature, so work conditions can change dynamically [7]. In addition, a mixture of fine particles of soil, stones, gravel, clay, etc. can lead to significant material reduction over a short period of time [9]. This process can also be intensified due to the presence of other substances in the soil, including [10–12]:
- chemically inactive substances (involved in sorption) that reduce mechanical strength of the surface layer of a material,
- corrosion-active substances (electrolytes, salt solutions) that act chemically or electrochemically,
- substances absorbed into the surface layer of a material that reduce its strength

(hydrogen is the main substance absorbed into the surface layer).

The wear of agricultural machine elements also strongly depends on the properties of the surface layer of a material [5, 13]. These properties have a decisive influence on the service life of these products [8]. In order to increase their service life, it is therefore necessary to reduce the wear of materials of frictional pairs [14, 15]. To do so, it is necessary to ensure that the formed surface layer has properties that will significantly increase both tribological wear resistance and service life of construction materials [16]. One of the solutions is to use welding methods (pad welding) that enable modification of the chemical composition of a parent material by introducing various additional components. Pad welding can be used to improve the properties of newly manufactured elements or to regenerate worn parts by coating them with a metal layer of suitable chemical composition and thickness. The purpose of regeneration is to restore the original performance of machine parts [17–20]. Welding consumables are usually in the form of coated electrodes or flux-cored and flux-coated wires.

The most widely used materials are based on Fe, Ti, Co, Ni that are alloyed with different chemical elements such as Cr, B, Ti, Si, Mo, Mn, W, V, Nb. They lead to changes in mechanical, tribological and corrosive properties [21–23]. Due to economic reasons, it is recommended to use Fe-based welding consumables. They include alloys such as Fe-Mn-CB, Fe-C-Cr-B, Fe-C-Cr, Fe-C-Cr-Ti-B, Fe-C-Cr-Ti, Fe-C-Cr-Mn-Ti, Fe-C-Mn-Ti, Fe-C-Cr-WV, Fe-C-Cr-Ni, Fe-Cr-C-Nb [22–25].

In the article [26] is studied experimentally the effect of coating thickness and substrate roughness on the tool wear in turning. TiAlN coating of various thicknesses was applied on tungsten carbide (WC) tool substrate having various surface roughnesses. The tool wear was measured following a fixed cutting distance and speed tests. In general, when plotting the wear vs. coating thickness alone or vs. substrate roughness alone a trend of decreasing wear with either increasing coating thickness or substrate roughness is observed.

In recent years, one can observe a growing tendency to develop materials that ensure long service life of machine elements in farming equipment [27] and are cost-effective at the same time. In line with this tendency, this paper investigates tribological properties of single- and double-layer pad coatings deposited (by manual metal arc welding) on cultivator points with Fe-based coated electrodes. The MMA welding method and Fe-based coated electrodes were used in the study due to economic reasons and easy access to welding tools.

MATERIALS AND METHODS

Tests were performed on coatings deposited onto the surface of cultivator points made of 38GSA steel, with dimensions of 210x40mm (Tab. 1). The coatings were deposited by manual metal arc welding using ESAB OK 84.58 coated electrodes with a diameter of 4mm. They are hardfacing electrodes depositing a semi-corrosion-resistant martensitic steel. According to the manufacturer, the peak hardness should be achieved even in the first pass, regardless of the applied cooling rate. These electrodes are specially suitable for hardfacing parts that are exposed to abrasive and impact wear, such as farming equipment, forestry tools, loading machines and mixers. The chemical composition of the electrode is given in Table 1. Welding was performed with an inverter welder (at 150A welding current). Single and double layers of pads were deposited. After that, samples for laboratory tests were prepared; they were shaped as 30 mm diameter and 6 and 20 mm thickness discs and 55×10×10 mm rectangles. Hardness, impact strength and roughness measurements as well as tribological tests and microscopic examination of the friction surface were carried out.

Hardness measurement were made by a Rockwell C scale test using a conical diamond indenter with 120° cone angle. The samples were loaded to a preload of 98N and a total load of 1471N.

Tribological tests were conducted on a high-temperature tribometer, Anton Parr THT 1000, shown in Fig. 1a. The tests were conducted in

Table 1. Chemical composition of 38GSA steel and OK 84.58 electrode

Electrode	Element (wt.%)				
	Mn	C	Cr	Si	Fe
38GSA Steel	0,91	0,35	0,15	0,85	residue
ESAB OK. 84.58	0,7	0,7	10	0,6	residue

accordance with ASTM G133 and G-99. The ball-on-disc configuration was used, Fig. 1b. Samples had the shape of a disc with a diameter of 30 mm and a height of 6 mm. 100Cr6 steel balls with a diameter of 6 mm were used as counter bodies. In the tribological tests, loads of 5 N and 20 N were applied. The loads were selected to simulate light and heavy working conditions of the cultivating unit's coatings. Load 5 N – light working conditions, 20N – hard working conditions. The tests were conducted with a sliding speed of 0.3 m/s and a radius of 4 mm. The total sliding distance was set equal to 200 m. Temperature was measured with a thermocouple at 2 mm from the surface of friction (actual temperature of the interface and the sample could reach higher values). Variations in the coefficient of friction, friction and temperature were measured in the tests. The frequency of data collection was 10 Hz.

Taking into account load and friction path, the wear rate of the frictional pair was determined according to ASTM G133 with Equation (1).

$$w_d = \frac{V_f}{F_n \times l} \tag{1}$$

where: w_d – wear rate,
V_f – volume wear,
F_n – load,
l – friction path (distance).

Sample wear is measured by determining volume wear in the form of a wear trace resulting from interaction with the counterbody. For this purpose, measurements were made in an area perpendicular to the sample wear trace on the circumference of the sample (10 measurement points) with a contact profilometer, Surtronic 3+. The measuring length was set equal to 4 mm.

Volume wear was determined as the product of the average cross-sectional area of the track and the length of the stroke obtained from the ball-on-disc test according to Equation (2).

$$V_f = A \times L \tag{2}$$

where: V_f –volume wear,
A – average cross-sectional area of the track,
L – length of the stroke.

The wear of the counterbody was calculated by measuring the diameters of ball wear with a metallographic microscope, by Equations (3) and (4).

$$V = \frac{\pi h^2}{3}(3r - h) \tag{3}$$

$$h = r - \sqrt{r^2 - \left(\frac{d}{2}\right)^2} \tag{4}$$

where: r – ball radius (3 mm),
h – ball height,
d – ball diameter (experimentally measured).

Following the tribological tests, surface wear was measured. In order to analyse obtained results, surfaces of the samples and counter bodies were examined. First, surface roughness parameters were examined; they were measured before and after the tribological tests using a Surtronic 3+ roughness gauge. After that, microscopic examination was performed. A scanning electron microscope, FEI Quanta 3D, was used to examine the friction surface topography. Wear trace images were recorded in a High Vacuum mode (pressure <6·10⁻⁴ Pa) with 10 kV.
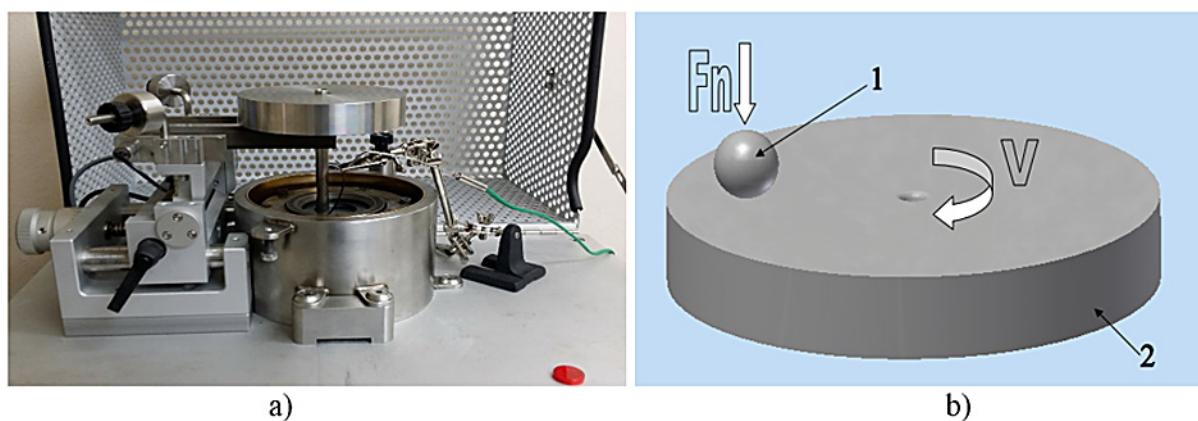

Fig. 1. Schematic set-up of tribological tests, THT 1000 tribometer (a), ball-on-disc friction pair (b); 1 – counterbody; 2 – sample

RESULTS AND DISCUSSION

Hardness tests were carried out on the surface and in the cross-section of the samples. Performed by the Rockwell C scale method, the measurements of hardness in the cross-section led to determination of changes in the deposited coating, interface and substrate.

The samples with two layers of padding have a hardness of 58 HRC, those with a single-layer pad – 56 HRC, while the hardness of the sample without padding is 51 HRC. The hardness of the cross-section of the coatings, the weld interface and the substrate before the tribological tests is shown in Fig. 2. The figure also shows hardness measurement points. The hardness of the coatings with two layers of padding varies between 55 and 56 HRC, that of the weld interface from 20 to 24 HRC, and that of the substrate from 31 to 32 HRC. One can observe that the substrate hardness decreases after welding from 51 HRC to 32 HRC (prior to welding, the surface hardness of the cultivator point is 51 HRC). This can be advantageous, since the entire surface has a hard outer layer and a soft substrate. Under dynamic loads, this combination of properties produces higher service life and impact load resistance.

Impact tests results demonstrate that the samples have high impact strengths. The impact strength of the coating with one layer of padding is 135 J / cm^2, while that of the coating with two layers is 147 J / cm^2. Analysis of the fractured samples demonstrates that the coating with two layers of padding (Fig. 3 a) has higher impact strength and ductility than the single-layer pad coating Fig. 3b).

The process of material wear depends on many factors such as friction pair material, contact temperature, roughness, surface hardness, load and slipping speed. The tribological tests were carried out on samples with one and two layers of padding. The objective of the tests was to determine properties of the coatings depending on impact loads, without a lubricant in room temperature. Two loads were applied: 5 and 20 N. Volume wear was determined with Equation (2).

The volume wear of the samples with one layer of padding under a load of 5 N is 0.018 mm^3. In turn, the volume wear of the samples with a double-layer pad is 0.045 mm^3. A similar observation can be made for the samples after friction under a load of 20 N. The volume wear of the single-layer pad samples is 0.012 mm^3, while that of the samples with two layers of padding increases to 0.055 mm^3. The volume wear of the counter bodies under a load of 5 N is 0.011 mm^3 for the samples with one and two layers of padding alike. On the other hand, the volume wear of the single-layer pad samples under a load of 20 N
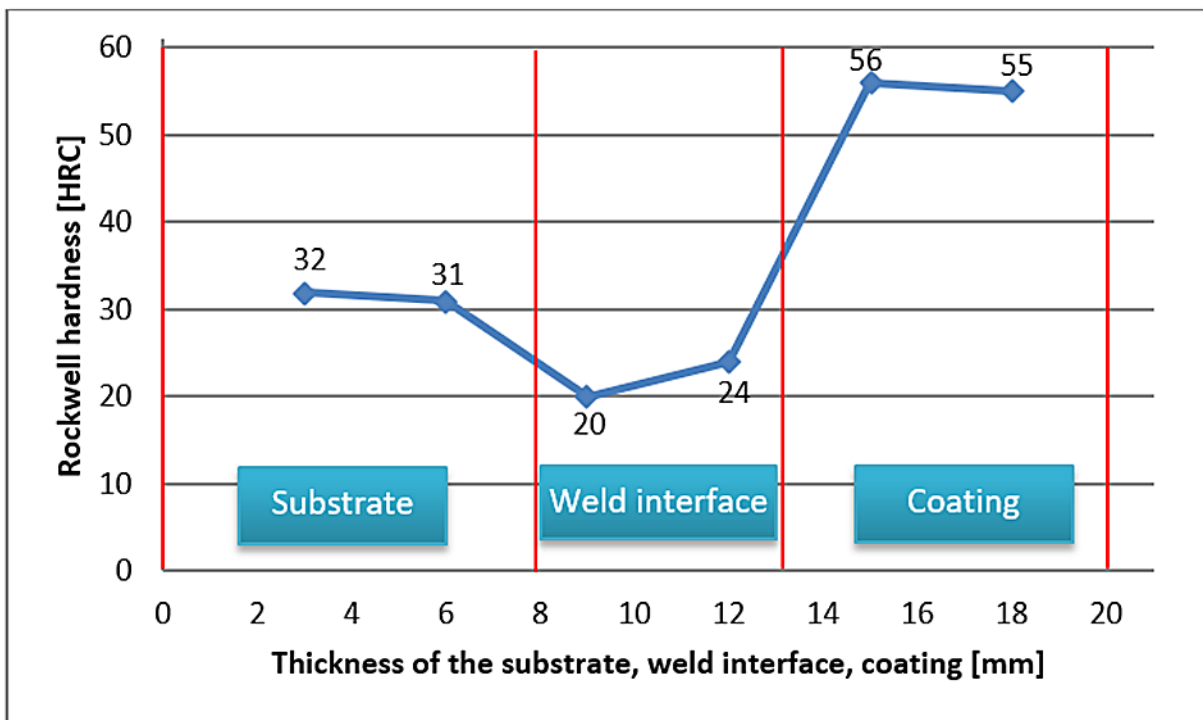
Fig. 2. Hardness in the cross section of coatings, weld interface and substrate

Fig. 3. Fracture of the sample with a) double-layer pad, b) single-layer pad

load is 0.029 mm³. For the counterbodies of the samples with two layers of padding it increases to 0.034 mm³. Analysing volume wear results of the samples and the counterbodies, one can observe that the volume wear of the samples (single-layer pad coatings) and their counterbodies under 5 and 20 N loads is lower than that of the double-layer pad samples and their counterbodies. This confirms the recommendations of the electrode manufacturer that optimum properties of the coatings can be achieved even in the first pass, irrespective of applied the cooling rate. It is also worth noting that the volume wear of the samples loaded with 20 N is lower by 0.006 mm³ for the samples with one layer of padding and by 0.010 mm³ for the samples with two layers of padding. The increase in load to 20 N does not cause a sudden increase in the wear volume. Obtained results are similar.

The contacts stresses of the samples with one and two layers of padding under a load of 5 N are 1.091 GPa. However, under a load of 20 N – they are 1.732 GPa. Fig. 4 shows the wear volume of the samples with one and two layers of padding and of the counterbodies in room temperature, under two loads: 5 and 20 N.

Load and friction path are important factors that must be taken into account when calculating and describing the rate of wear. Considering both load and friction path, the wear rate of the friction pair was calculated according to Equation 1. The wear rate and the friction coefficient determined in the tribological tests under 5 and 20 N loads are given in Figs. 5 a and b. Analysing obtained wear rates in terms of the number of pad layers, it can be observed that the wear rate of the samples with two layers of padding increases under both 5 and 20 N load. Under a load of 5 N, the wear rate of the samples with one layer of padding is equal to 1.84×10^{-5} $mm^3N^{-1}m^{-1}$, while that of the samples with two layers of padding increases to 4.50×10^{-5} $mm^3N^{-1}m^{-1}$. On the other hand, under a load of 20 N, the wear rate of the single-layer pad coatings is 0.30×10^{-5} $mm^3N^{-1}m^{-1}$, and that of the double-layer pad coatings is 1.38×10^{-5} $mm^3N^{-1}m^{-1}$. Under a load of 20 N, the wear rate of the counterbodies of the samples with one layer of padding is equal to 0.72×10^{-5} $mm^3N^{-1}m^{-1}$, while that of the counterbodies of the samples with two layers of padding increases to 0.85×10^{-5} $mm^3N^{-1}m^{-1}$. The mean coefficient of friction under a load of 20 N for the samples with one layer of padding is 0.51 and for the samples with
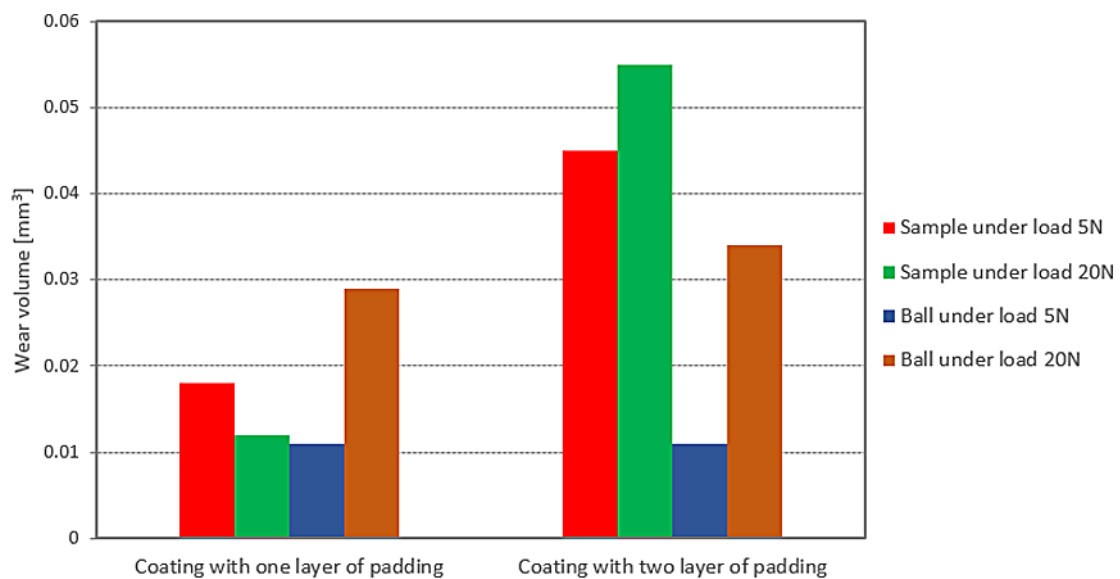

Fig. 4. Wear volume of single- and double-layer pad samples and counterbodies

two layers of padding – 0.57. On the other hand, the maximum coefficient of friction is 0.58 and 0.72, respectively. The mean coefficient of friction determined in the tribological tests for a load of 5 N is the same in both cases and amounts to 0.47. On the other hand, the maximum friction coefficient for the combination with one layer of padding is 0.68, and for two layers of padding – it is 0.66.

In the tribological tests, the friction coefficient was measured on a continuous basis for two combinations: counterbody–single-layer pad coating and counterbody–double-layer pad coating. Fig. 6a shows variations in the friction coefficient under a load of 5 N, while Fig. 6b shows the behaviour of this parameter under a load of 20 N, measured over a distance of 200 m.

As shown in Fig. 6a, under a load of 5 N, the friction coefficient of the two tested combinations (counterbody–single-layer pad coating and counterbody–double-layer pad coating) becomes stable only after a distance of 60 m. Once stable, the coefficient of friction varies in a similar range for both cases. On the other hand, in both cases, under a load of 20 N, the coefficient of friction becomes stable much faster after exceeding a 30 m friction path. In the tests, the friction coefficient is higher for the counterbody–double-layer pad coating combination than for the combination with a single layer of padding.

Results of the surface roughness measurements before and after friction, under loads of 5 N and 20 N, for the single- and double-layer pad coatings are shown in Fig. 7. The results led to determination of the effect of the number of pad layers and load values on the *Ra* parameter of the friction pairs used in the tribological tests.

Before friction the roughness parameters *Ra* of the coatings with single- and double-layer pad are similar – 0.371 μm and 0.367 μm, respectively. Under a load of 5 N, the friction surface roughness increases to 0.421 μm for the coating with one layer of padding and to 1.01 μm for the coating with two layers of padding. On the other hand, under a load of 20 N, the surface roughness decreases compared to its value before friction and is equal to 0.266. The results show that the friction surface roughness of the coating with two layers of padding increases to 0.792 μm.

Microscopic examination led to identification of phenomena and wear mechanism in the material. Fig. 8 shows the SEM images (different enlargements) of wear tracks on the surface of single- and double-layer pad coatings under loads of 5 N and 20 N. The friction surface has a flake-layered structure. There are differences in the shape and size of layers and flakes. Individual layers and flakes are located on different levels, and they overlap. They also show the presence of plastic strains that are more visible under a load of 20 N for both types of tested coatings (Figs. 8 e-h).

Flake-layered structures are formed as a result of plasticization of the surface layers. This occurs when the properties of a material in thin surface layers are conducive (low yield point or the deposition of wear products onto friction surface). The flake-layered structure of the friction surface is characterized by minimal wear because the thin layers are easily renewed.

CONCLUSIONS

This paper investigated the properties of single- and double-layer pad coatings deposited on the working surface of cultivator points. The deposition of coatings by welding methods increases the properties of consumables. The tools and IT algorithms were used to collect and process the results of experimental research. Based on the results, the following conclusions can be formulated:

1. After welding, the hardness of the single- and double-layer pad coatings is similar, respectively 56 HRC and 58 HRC. On the other hand, the hardness of the substrate decreases after welding from 51 HRC to 32 HRC.
2. The coatings with two layers of padding have higher impact strength and ductility (147 J/cm^2) than the coatings with one layer of padding (135 J/cm^2).
3. The coatings with one layer of padding have a lower wear rate than those with two layers of padding. It has been found that their wear rate is the lowest under a load of 20 N. The volume wear of the samples (single-layer pad) and their counterbodies under 5 and 20 N loads is several times lower than that of the coating with two layers of padding and their counterbodies.
4. Analysing the dependence between wear rate and the number of pad layers, it can be observed that the wear rate increases for the coatings with two layers of padding under 5 and 20 N loads alike.
5. The roughness *Ra* of friction surface of the coating with one layer of padding decreases under a load of 20 N, when compared to its initial roughness. Prior to friction, the roughness *Ra* is 0.371 μm while after friction – 0.266 μm. On the other hand, under a load of 5 N, the roughness
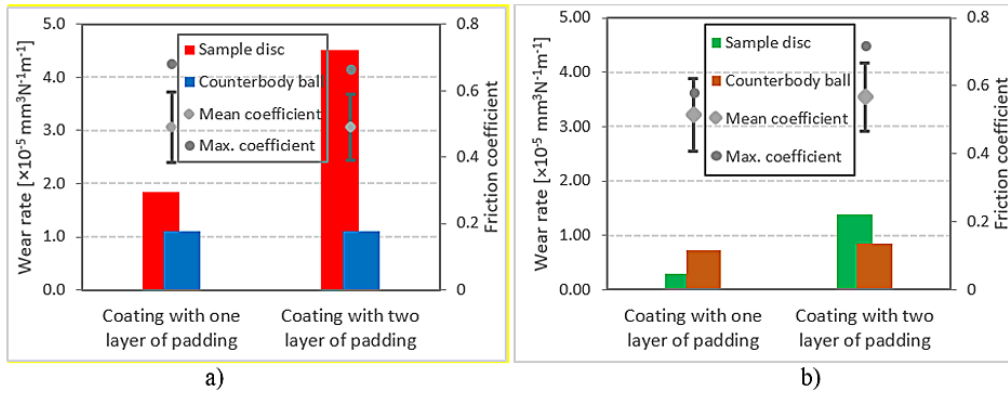
Fig. 5. Wear rate and friction coefficient versus load of: 5 N (a) and 20 N (b)
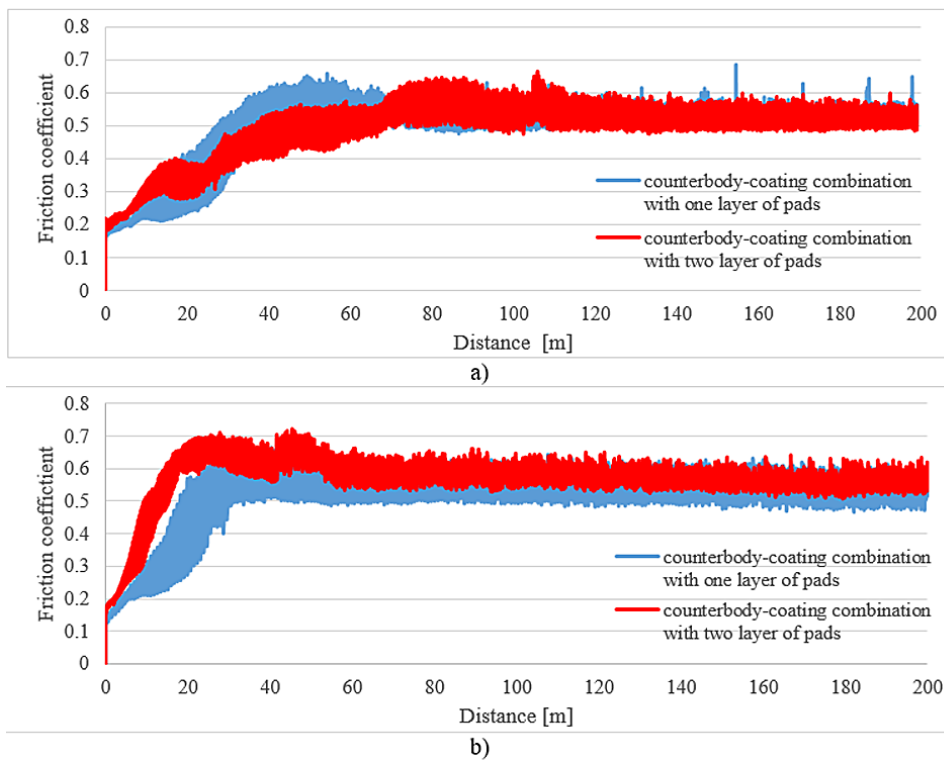

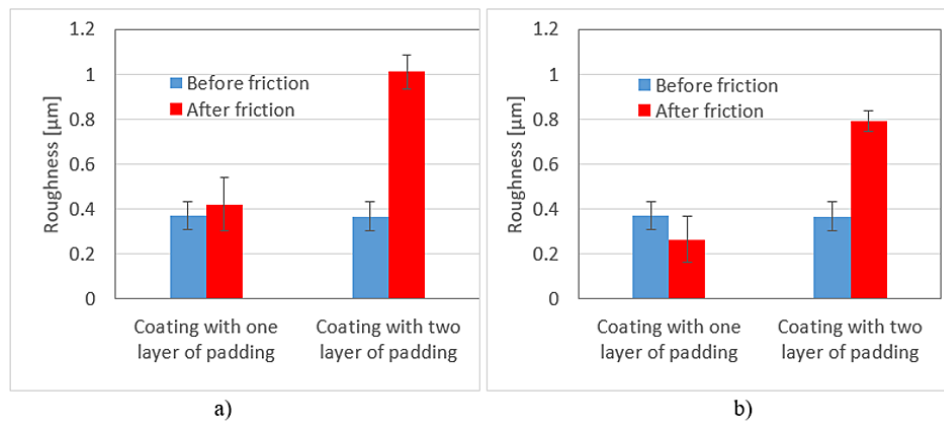**Fig. 6.** Variations in the friction coefficient under load of 5 N (a) and 20 N (b)

Fig. 7. Roughness Ra of coatings with one and two layers of padding under load of: 5 N (a) and 20 N (b)
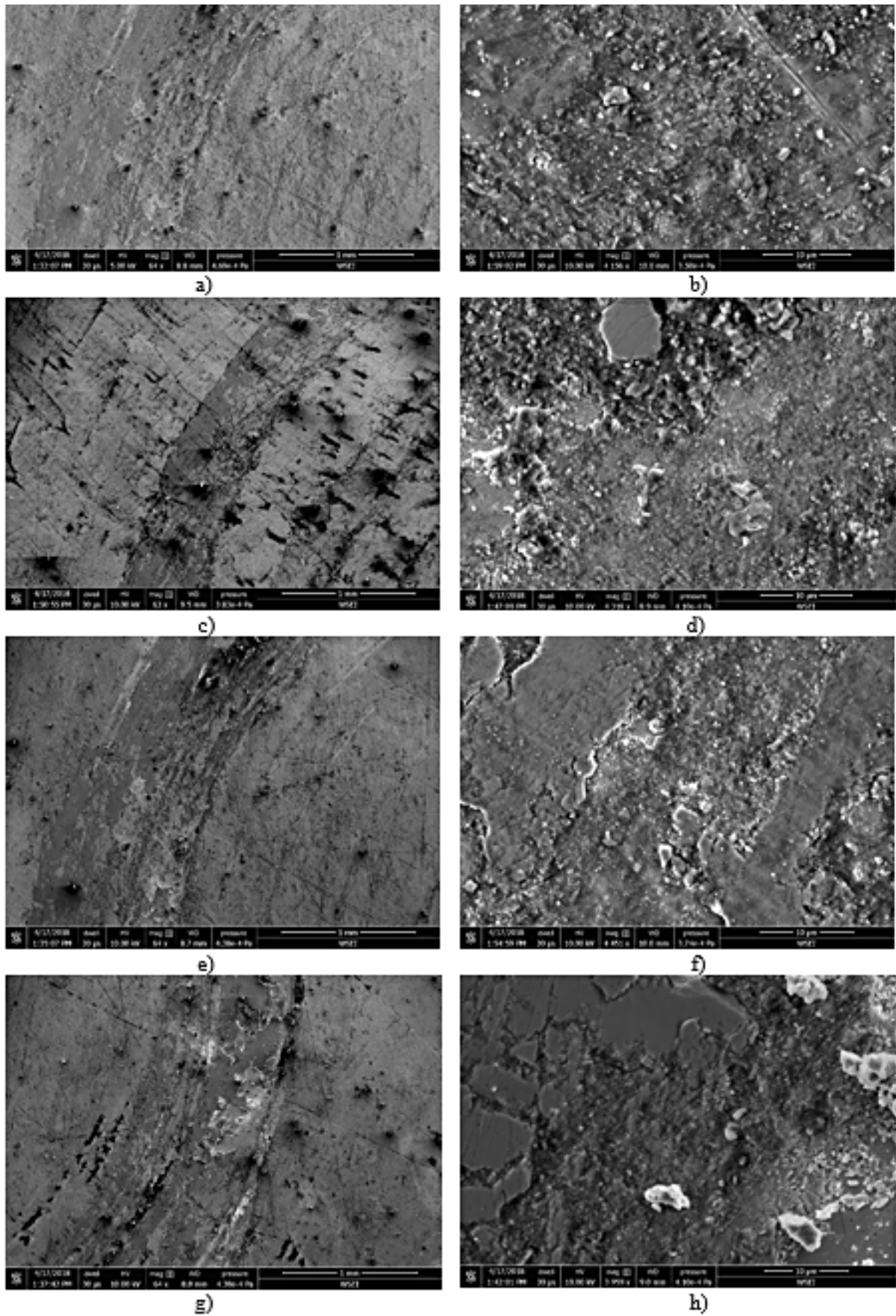
Fig. 8. Coating surface after friction: under load of 5 N applied to coatings with one
layer of padding (a-b) and two layers of padding (c-d) and under load of 20 N applied
to coatings with one layer of padding (e-f) and two layers of padding (g-h)

slightly increases (up to 0.421 µm). In contrast, for the above loads, the roughness of the double-layer pad coating increases about 2–3 times.

6. The analysis of wear tracks has revealed that the friction surfaces have a flake-layered structure of varying flake shapes and sizes. The surfaces also show the presence of strains that are more visible under a load of 20 N for the coatings with both one layer and two layers of padding.

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