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Comparative assessment of wear resistance of combined coatings on carbon steels produced by electrolytic-plasma treatment followed by Cr or Co–W electrodeposition

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ABSTRACT

Introduction. 0.2% *C* and 0.45% *C* carbon structural steels exhibit insufficient wear resistance under reciprocating sliding in lubricated conditions, which limits the service life of machine components. This study investigates the wear resistance of a combined surface treatment involving electrolytic-plasma hardening (quenching or carburizing followed by quenching) followed by the deposition of chromium and *Co–W* galvanic coatings of different thicknesses. **Materials and methods.** Samples were subjected to electrolytic-plasma carburizing at 850 °C for 3 min or quenching at 900 °C in aqueous electrolytes. Subsequently, *Cr* and *Co–W* coatings with thicknesses of 1 and 10 µm were deposited on the prepared surfaces. Wear resistance was evaluated using a reciprocating sliding test with a bearing steel ball (0.1% *C*-15% *Cr*) under a load of 10 N in mineral oil for 1–3 days, with wear volume measured by profilometry. **Results and discussion.** It was found that the combined treatment significantly improved wear resistance compared to the individual hardening methods. On untreated steel, thin galvanic coatings were prone to breakthrough, resulting in low wear resistance of the system. Electrolytic-plasma quenching of 0.45% *C* steel improved the performance compared to the untreated condition; however, the best results were achieved on carburized steel 20. Increasing the coating thickness from 1 to 10 µm led to a decrease in wear resistance. The highest wear resistance was demonstrated by the system consisting of 0.2% *C* steel after electrolytic-plasma carburizing followed by quenching and a thin (1 µm) chromium coating. The obtained results can be used in the development of effective surface hardening technologies for components operating under lubricated sliding conditions (shafts, guides, hydraulic cylinder elements), while maintaining a relatively soft core.

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Introduction

Carbon structural steels *0.2% C* steel and *0.45% C* steel are widely used in mechanical engineering for the manufacture of components operating under friction conditions (shafts, gears, guides, hydraulic cylinder elements, etc.) owing to their good machinability, relatively low cost, satisfactory mechanical properties, and broad heat treatment potential [1]. However, their low surface hardness in the untreated state and insufficient wear resistance under reciprocating sliding significantly limit the service life of friction units and necessitate the application of effective surface hardening methods [2, 3].

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Traditional methods for improving wear resistance include thermochemical treatment (carburizing, nitriding) [4], bulk or surface quenching [5], and the deposition of galvanic protective coatings [6, 7]. Among diffusion methods, electrolytic-plasma treatment occupies a special place [8]. It enables local surface saturation with carbon (carburizing) or nitrogen (nitrocarburizing) with simultaneous quenching in a single technological cycle [8, 9]. Electrolytic-plasma treatment is characterized by high heating and cooling rates, low energy consumption, environmental safety, and the possibility of treating complex-shaped parts. It is established that electrolytic-plasma treatment significantly increases the microhardness and wear resistance of low- and medium-carbon steels through the formation of a martensitic structure and dispersed carbonitrides [8, 9].

Alongside diffusion methods, galvanic coatings are widely applied, in particular hard chromium plating [6, 7]. Hard chromium coatings provide high microhardness (800–1,200 HV), a low coefficient of friction, and excellent wear resistance under abrasive and adhesive wear conditions owing to the formation of microcracks capable of retaining lubricant [6, 7], as well as high corrosion resistance [10, 11]. However, when the coating thickness exceeds 10–20 μm, significant residual stresses accumulate, leading to cracking, reduced adhesion, and a decrease in wear resistance, especially on a soft substrate [12–14]. An alternative to chromium plating is offered by galvanic coatings of iron-group metal alloys with tungsten (e.g., *Co–W*), which possess comparable or superior microhardness, high tribological characteristics, and are regarded as more environmentally acceptable owing to the absence of hexavalent chromium [15, 16].

Particularly promising are combined (duplex) technologies that combine preliminary substrate hardening with subsequent deposition of a protective coating. Such approaches make it possible to simultaneously increase surface hardness, wear resistance, and corrosion resistance while retaining the required properties of the component core. Various duplex systems for steels are actively discussed in the literature. Considerable attention is paid to combinations of plasma nitriding with *PVD* coatings (e.g., *CrN*) and to combinations of conventional diffusion hardening methods with coatings produced by physical and chemical vapor deposition [17–20].

Nevertheless, despite the large number of studies devoted to individual surface hardening methods and duplex technologies, comprehensive works in which electrolytic-plasma treatment is sequentially combined with galvanic coating deposition on carbon steels are virtually absent. Modern review papers on wear-resistant coatings and hybrid hardening methods mainly consider combinations of plasma nitriding with *PVD* and *CVD* coatings, as well as other combinations of thermochemical treatment [20]. Even specialized reviews on electrolytic-plasma treatment do not address the subsequent galvanic deposition of hardening coatings [21]. Similarly, in experimental studies of various duplex systems (plasma nitriding + *PVD* [22, 23], carburizing + nitriding [24], etc.), the combination of electrolytic-plasma hardening with the galvanic deposition of chromium coatings or cobalt-based alloy coatings is not considered. This indicates a clear research gap and determines the relevance of the present study.

In contrast to the previous study by the authors [25], which was performed under dry friction conditions, the present investigation for the first time presents a systematic comparison of the wear resistance of various combinations of electrolytic-plasma hardening of the substrate and galvanic coatings (*Cr* and *Co–W*) under reciprocating sliding in the presence of a lubricant. This friction regime is significantly closer to the real operating conditions of machine components (shafts, guides, hydraulic cylinder elements, etc.).

The purpose of the present work is to investigate the wear resistance of combined hardening coatings on *0.2% C* steel and *0.45% C* steel obtained by electrolytic-plasma carburizing or quenching followed by the galvanic deposition of *Cr* or *Co–W* alloy, and to establish the optimal substrate–coating combinations for achieving the maximum wear resistance under lubricated sliding conditions.

To achieve this purpose, ***the following tasks*** were set:

– to study the wear resistance of *0.2% C* and *0.45% C* carbon steels after electrolytic-plasma treatment (quenching and carburizing followed by quenching) without galvanic coatings under reciprocating sliding in the presence of a lubricant;

– to establish the influence of the substrate material (untreated steel, steel after electrolytic-plasma quenching, carburized steel) on the wear resistance of the combined systems;

– to establish the influence of the thickness and type of galvanic coatings (chromium and *Co–W* alloy) on the wear resistance of the combined systems;

– to determine the optimal combinations of the substrate hardening method and the parameters of galvanic deposition (coating type and thickness) for achieving the maximum wear resistance of the combined coatings under reciprocating sliding in the presence of a lubricant.

Materials and methods

Materials

The objects of the study were specimens of *0.2% C* steel and *0.45% C* steel. The specimens were parallelepipeds measuring 6 × 6 × 15 mm.

These steel grades were chosen because they allow the application of different electrolytic-plasma treatment techniques. *0.45% C* steel is capable of quenching without prior saturation, whereas *0.2% C* steel requires carbon saturation for surface quenching. The use of two steel grades makes it possible to test both quenching without saturation and surface hardening after carburizing.

After electrolytic-plasma treatment, a galvanic coating of chromium or *Co–W* alloy was deposited on the prepared surface. The microhardness (*HV*) and wear resistance under reciprocating sliding of the resulting combined coatings were studied. All combinations of materials and processing methods investigated in this work are presented in Table 1.

Table 1

Summary table of materials and surface treatment combinations investigated in this study

0.2% C steel	–	–
0.2% C steel	–	*Cr*
0.2% C steel	–	*Co–W*
0.2% C steel	Carburizing	–
0.45% C steel	Quenching	–
0.45% C steel	Quenching	*Cr*
0.45% C steel	Quenching	*Co–W*
0.2% C steel	Carburizing	*Cr*
0.2% C steel	Carburizing	*Co–W*
0.2% C steel	–	–

Electrolytic-plasma treatment

Electrolytic-plasma treatment was performed on a laboratory setup of original design.

The electrolyte composition for carburizing followed by quenching (wt.%) was: 10% glycerol, 10% ammonium chloride, balance distilled water. Carburizing was performed at a treatment voltage of 200–220 V, a specimen temperature of 850 °C, and an electrolyte temperature of 15–20 °C for 3 min, which allowed a hardened layer thickness of approximately 50 μm to be obtained [21]. After saturation, quenching was performed in the same electrolyte by switching off the current supply.

Electrolytic-plasma quenching (without prior saturation) was performed at a treatment voltage of 200–220 V and a specimen temperature of 900 °C in an electrolyte maintained at 15–20 °C. The electrolyte composition (wt.%) was: 15% ammonium chloride, balance water. After the specimen temperature reached 900 °C and a holding time of 30 s, quenching was performed in the same electrolyte by switching off the current supply.

After electrolytic-plasma treatment, the specimens were subjected to minimal mechanical processing to remove oxide layers and prepare the surface for galvanic coating deposition (abrasive paper of grit *P2000*). All specimens were finished to a surface roughness of ***Ra*** = 0.15 μm (±10%).

Galvanic deposition

For the electrochemical deposition of chromium, a standard chromium-plating electrolyte was used (CrO_3 – 250 g/L, H_2SO_4 – 2.5 g/L) at a temperature of 55 °C and a current density of 50 A/dm^2. The chromium-plating time was selected according to the required coating thickness.

Before chromium deposition, the surface was degreased, immersed in the electrolyte under open-circuit conditions for 60 s, and subsequently activated anodically in the same electrolyte for 15 s at a current density of 250 mA/cm^2 [26].

Galvanic *Co–W* coatings were deposited from a citrate electrolyte of the following composition [27]: sodium tungstate ($Na_2WO_4{\cdot}2H_2O$) – 0.2 mol/L; cobalt sulphate ($CoSO_4{\cdot}7H_2O$) – 0.2 mol/L; citric acid ($C_6H_8O_7$) – 0.04 mol/L; sodium citrate ($Na_3C_6H_5O_7$) – 0.25 mol/L; boric acid (H_3BO_3) – 0.65 mol/L. The electrolyte pH before deposition was 6.7.

Deposition was carried out at an electrolyte temperature of 80 °C and a current density of 20 mA/cm^2. The deposition time was selected according to the required coating thickness.

Galvanic coatings were deposited with a thickness of 1 µm (to evaluate inter-layer wear resistance) and 10 µm (to evaluate the wear resistance of the galvanic coating alone). The thickness of the galvanic coatings was calculated on the basis of the deposition rate determined from the current efficiency, density, and composition of the *Co–W* alloy obtained in previous studies [15] and literature data [25, 28–30].

Verification of the thicknesses of both types of galvanic coatings was performed by analysis of cross-sections after deposition on *0.2% C* steel. The cross-sections were etched (nital) for 60 s.

Tribological tests

Wear resistance was evaluated by the reciprocating sliding method on a laboratory setup of original design (ball-on-flat configuration). The tests consisted of sliding a counter-body in the form of a ball 6.35 mm in diameter made of *ShKh15* (equivalent to *AISI 52100*) bearing steel (854 ± 8 HV) against the coating surface under a load of 10 N. This load was selected because of the low loads typical of real lubricated friction pairs in mechanisms (e.g., rod–linear bearing). The use of loads below 10 N would multiply the duration of the tribological tests and would not allow a wide series of specimens to be examined.

The counter-body was not subjected to mechanical processing before testing; a new ball was used in each test. The specimen velocity relative to the counter-body was 96 double strokes per minute with a stroke length of 1 mm, corresponding to a linear speed of 0.192 m/min. The tests were performed in a mineral oil (*MANNOL 8029 LC-2*) at a temperature of 25 °C.

The tests were carried out for 1, 2, and 3 days for each specimen. The wear dynamics at different sliding durations (1–2–3 days) were evaluated. For each combination of material and sliding time, three parallel specimens were tested to assess reproducibility.

Wear resistance was assessed by measuring the wear scar area from profilometry data and subsequent conversion to wear volume taking into account the track length. Profilometric measurements were performed with a *Mitutoyo Surftest SJ-410* profilometer.

In addition to the wear resistance of the combined coatings, the wear resistance of the individual surface treatment variants and of the untreated steel was also studied.

After the tribological tests, the elemental composition and the distribution of elements in different zones of the wear tracks were determined by energy-dispersive X-ray spectroscopy (*EDX*) using an *X-Act* detector (*Oxford Instruments*, UK) installed on a *Tescan Vega 3* scanning electron microscope (*Tescan*, Czech Republic). The analysis was carried out at an accelerating voltage of 20 kV.

Microhardness

To analyze the wear mechanisms of the combined coatings, the microhardness of the substrates and of the galvanic coatings was measured. Microhardness was determined on a *Falcon 503* microhardness tester (*Innovatest*, Netherlands) by the *Vickers* method at a load of 20 g and a dwell time of 10 s. For each material, at least five measurements were performed and the results were averaged.

Results and discussion

It is shown that the results of thickness measurements of the galvanic coatings (Fig. 1) confirm the correctness of the deposition time calculation for obtaining coatings of the prescribed thicknesses (1 and 10 µm, within a measurement error of 20%). The selected deposition times were used in all subsequent experiments on deposition onto different substrates.

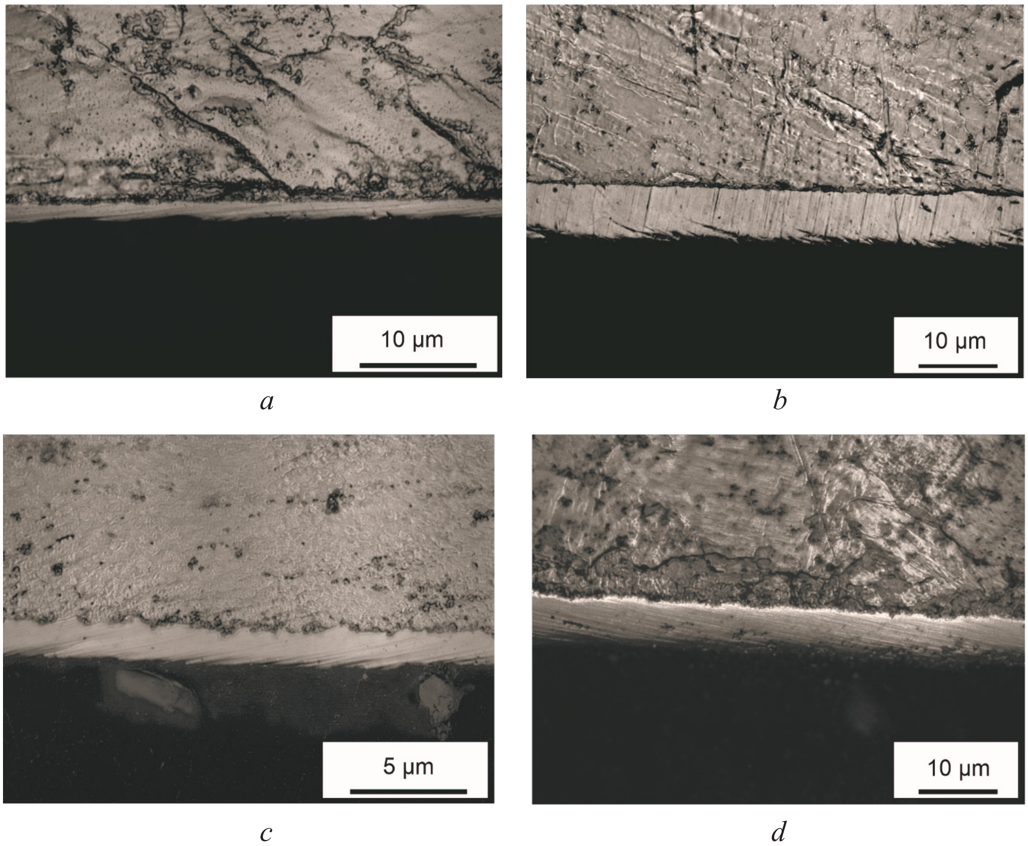


Fig. 1. Microphotographs of cross-sectional polished sections of galvanic *Cr* and *Co–W* coatings deposited on a steel substrate after etching:
a – *Co–W* coating with a thickness of 1 µm; *b* – *Co–W* coating with a thickness of 10 µm; *c* – *Cr* coating with a thickness of 1 µm; *d* – *Cr* coating with a thickness of 10 µm

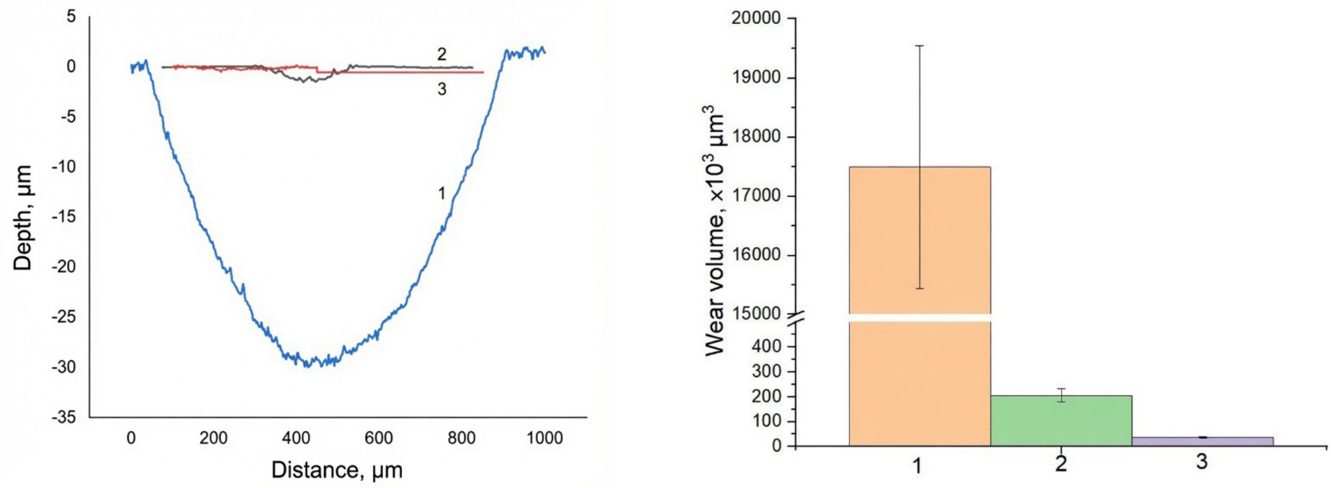
Fig. 2 shows the profilograms (*a*) and the volumetric wear (*b*) of the substrates used for galvanic coating deposition: untreated *0.2% C* steel, carburized *0.2% C* steel, and *0.45% C* steel after electrolytic-plasma quenching. The treated steels exhibit significantly lower wear. Moreover, the surface after carburizing shows lower wear than after quenching.

It is established that chromium coatings 10 µm thick exhibit higher wear resistance than *Co–W* coatings (Fig. 3). This result contradicts earlier studies [25] in which, under dry friction conditions, the *Co–W* coating demonstrated higher wear resistance than *Cr*. The high wear resistance of chromium coatings in a lubricated environment is explained in different ways. Some authors attribute it to the cracked structure of the coating, where the cracks act as channels for lubricant supply to the contact zone [30, 31]; others deny the role of the cracks and associate the effect with the high wettability of the chromium surface during wear [32].

In general, the wear process of a combined coating can be divided into three stages:

– wear of the galvanic coating (without influence of the substrate);

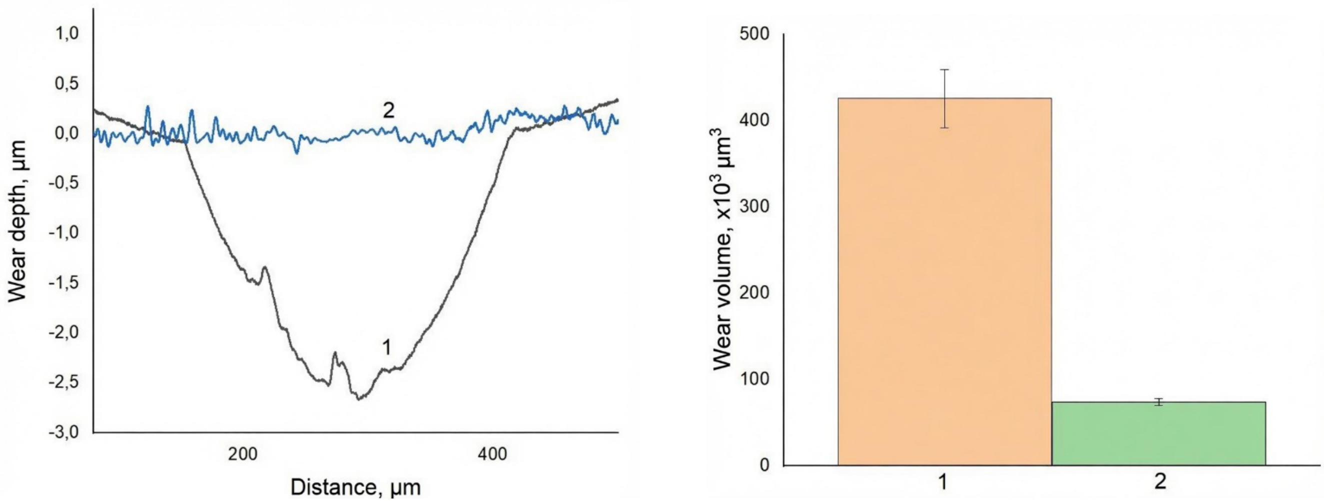
– wear of the thin part of the galvanic coating near the interface with the substrate and transition of wear into the substrate. On a soft substrate, coating breakthrough and destruction of the galvanic coating may occur at this stage (Fig. 4);



a *b*

Fig. 2. Results of tribological tests of 0.2% *C* steel after electrolytic-plasma quenching, carburizing (with subsequent quenching) in comparison with untreated 0.2% *C* steel:

a – examples of friction track profilograms (one representative sample from the series); (*b*) volumetric wear values. 1 – untreated 0.2% *C* steel; 2 – carburized 0.2% *C* steel; 3 – electrolytic-plasma quenched 0.45% *C* steel



a *b*

Fig. 3. Results of tribological tests of *Cr* and *Co–W* electrodeposited coatings:

a – examples of friction track profilograms (one representative sample from the series); *b* – volumetric wear values. 1 – *Co–W* electrodeposited coating (10 µm); 2 – *Cr* electrodeposited coating (10 µm)

– wear of the substrate with the participation of abrasive particles of the destroyed galvanic coating. This is confirmed by *EDX* analysis of the wear tracks (Fig. 5). Coating particles remain in the wear track even when the track depth greatly exceeds the coating thickness.

The influence of the substrate material was studied using the example of 1 µm thick *Co–W* deposition (Fig. 6). Systems with a modified steel substrate demonstrate higher wear resistance compared with the unmodified substrate. The use of a galvanic coating without substrate hardening does not lead to a substantial increase in the wear resistance of the system. An increase in coating thickness is not a solution to this problem, because as the coating wears and becomes thinner, the wear proceeds intensively (as shown in Fig. 5) and similarly leads to breakthrough of the coating itself (Fig. 3).

The adhesion of the galvanic coating plays an important role in the wear resistance of the system. The quality of coating adhesion was assessed indirectly by visual analysis of the wear track and by examination of micrographs of the cross-section of the combined coating (Fig. 1). When the coating detaches from the

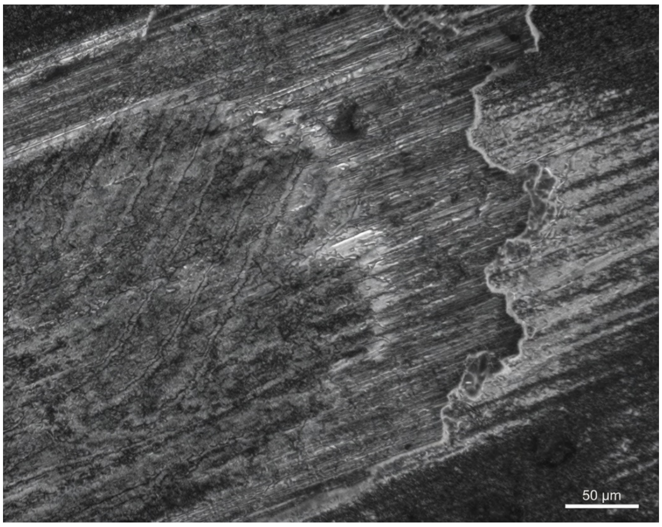


Fig. 4. Co–W coating delamination on a soft substrate after friction

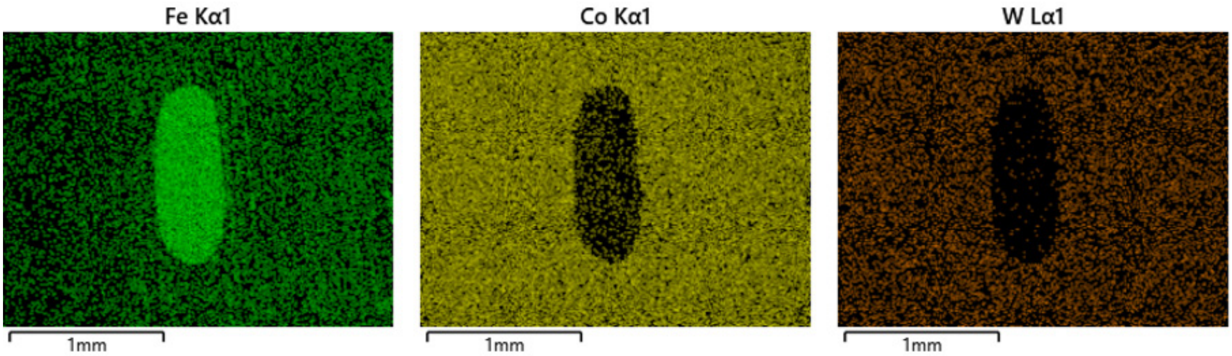
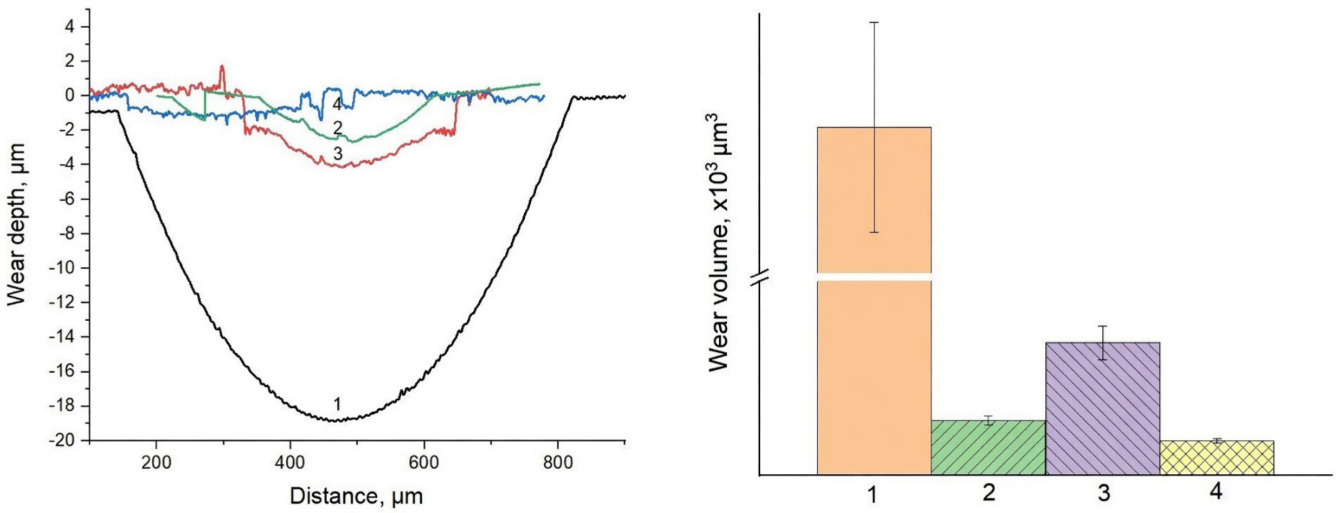


Fig. 5. EDX analysis of the friction track of the combined coating.
Accelerating voltage: 20 keV



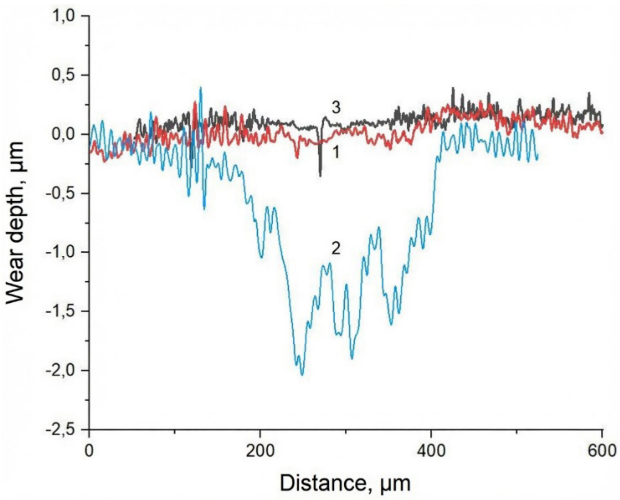
a *b*

Fig. 6. Results of tribological tests of *Co–W* coatings deposited on various substrates:

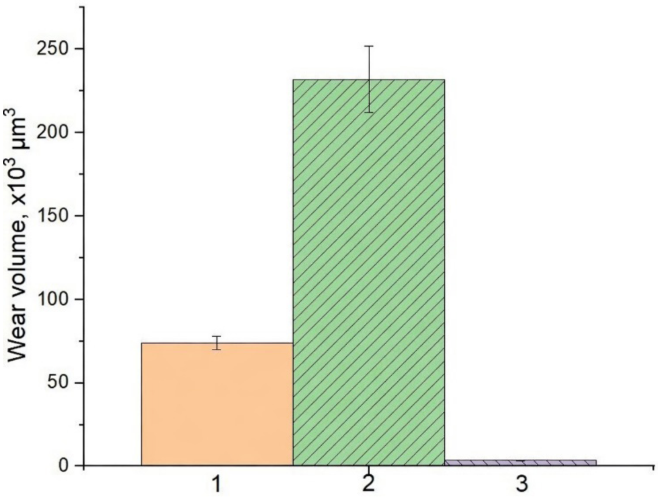
a – examples of friction track profilograms (one representative sample from the series); *b* – volumetric wear values. 1 – *Co–W* coating (1 μm) deposited on untreated steel; 2 – *Co–W* coating (10 μm); 3 – *Co–W* coating (1 μm) deposited on 0.45% *C* steel after electrolytic-plasma quenching; 4 – *Co–W* coating (1 μm) deposited on 0.2% *C* steel after carburizing substrate surface, fracture flakes form around the wear track (Fig. 3). Such flakes always appear during sliding of a galvanic coating deposited on untreated steel, and also in cases of inadequate surface preparation before galvanic deposition even on treated steel, ultimately resulting in high wear values.

When comparing the various substrate hardening approaches, it is evident that the combination of a 1 µm *Co–W* coating deposited onto an electrolytic-plasma-quenched substrate yields the poorest wear resistance. Specifically, this system exhibits greater wear than the same coating applied to a carburized and quenched substrate, and also surpasses the wear of a 10 µm *Co–W* coating deposited directly onto an untreated substrate. The highest wear resistance is observed for the combination of a *Co–W* coating deposited on a substrate after carburizing followed by quenching. In this case the wear resistance is even higher than that of the *Co–W* coating alone, despite the fact that sliding occurs against the same galvanic alloy in both cases. The difference in the tribological behavior of *Co–W* coatings of 1 and 10 µm thickness can hypothetically be explained by analogy with chromium coatings – by the increase in residual stresses resulting from the greater thickness [12–14]. For *Co–W*, however, this requires additional investigation. The results also allow the conclusion to be drawn that replacing combined hardening by an increase in the thickness of the galvanic coating is not expedient.

A similar trend is observed when comparing the influence of the substrate material for combined coatings with galvanic chromium plating. Overall, all chromium coatings exhibit low wear that is barely noticeable and is detectable only by a change in the surface roughness of the coating at the contact zone with the counter-body (Fig. 7). It can also be seen that a thin chromium coating (1 µm) on a carburized substrate has higher wear resistance than a thick coating (10 µm). Although in both cases the chromium coating obtained under identical electrodeposition conditions was subjected to wear, the thinner coating with a lower level of residual stresses [12–14] possesses higher wear resistance.



a



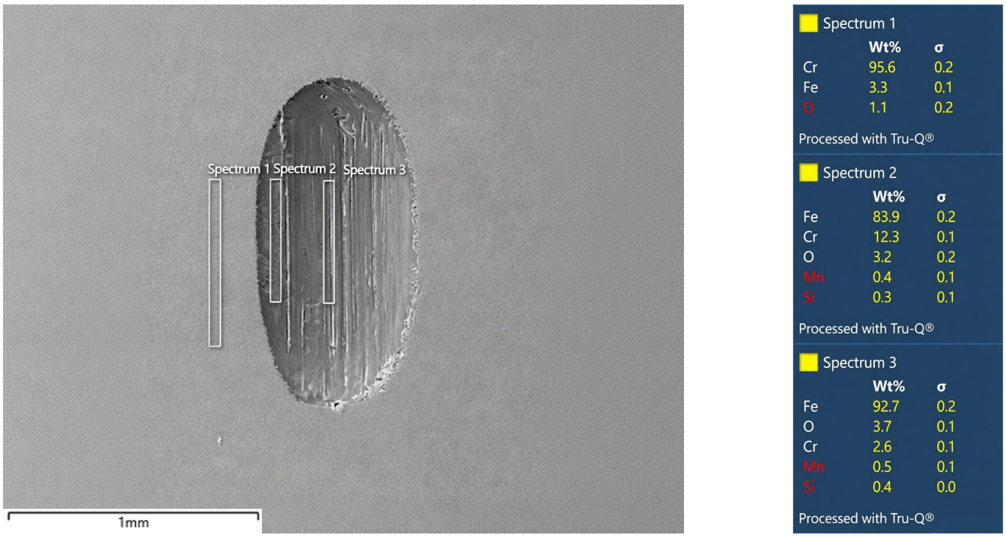
b

Fig. 7. Results of tribological tests of *Cr* coatings deposited on various substrates:

a – examples of friction track profilograms (one representative sample from the series); *b* – volumetric wear values. 1 – *Cr* galvanic coating (10 µm); 2 – *Cr* galvanic coating (1 µm) deposited on 0.45% *C* steel after electrolytic-plasma quenching; 3 – *Cr* galvanic coating (1 µm) deposited on 0.2% *C* steel after carburizing

Elemental analysis of the surface after wear was performed for three treatment variants: chromium deposited on untreated *0.2% C* steel; chromium deposited on *0.45% C* steel after electrolytic-plasma quenching; and *Co–W* deposited on *0.45% C* steel after electrolytic-plasma quenching. All galvanic coatings were 1 µm thick. The analysis was carried out in three zones: the galvanic coating surface not subjected to sliding; the zone at the boundary of the wear track; and the zone in the center of the wear track.

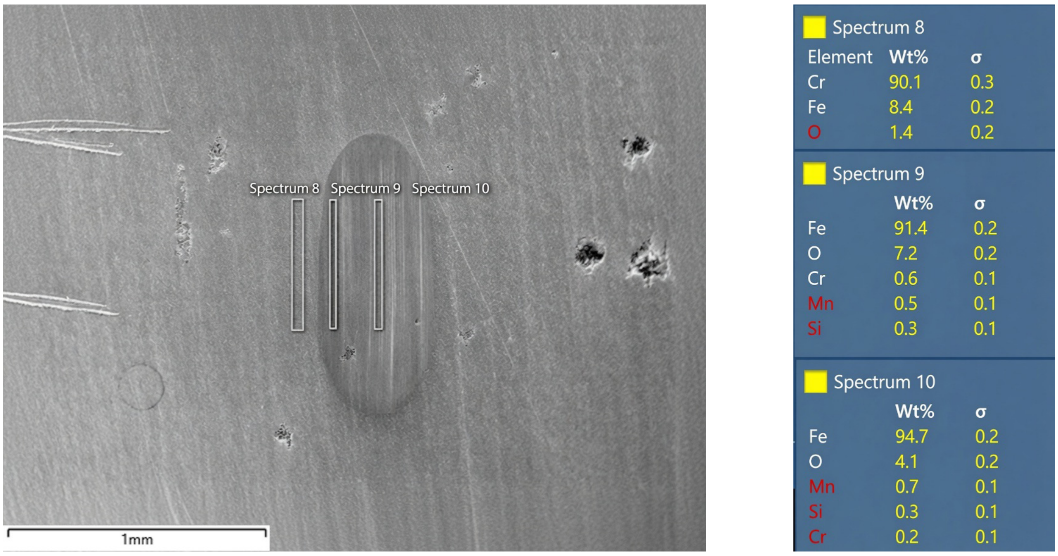
The analysis (Figs. 8–10) showed that the surface not subjected to sliding contains mainly the elements of the galvanic coating and a small amount of iron atoms associated with the penetration depth of the radiation. Inside the wear tracks, mainly iron atoms of the substrate are observed, with only a small content



a *b*

Fig. 8. EDX analysis of the friction track of a chromium coating deposited on an untreated 0.2% *C* steel substrate:

a – *SEM* image of the friction track with marked *EDX* analysis zones; *b* – surface composition of the investigated zones (wt. %)



a *b*

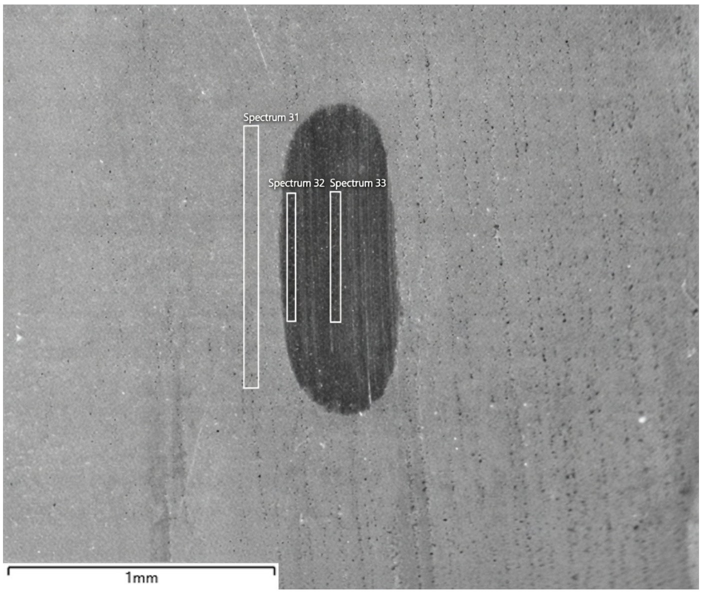
Fig. 9. EDX analysis of the friction track of a chromium coating deposited on electrolytic-plasma quenched 0.45% *C* steel substrate:

a – *SEM* image of the friction track with marked *EDX* analysis zones; *b* – surface composition of the investigated zones (wt. %)

of the elements of the galvanic coatings, indicating the presence of particles that participate in the sliding of the substrate after the galvanic coating has worn away.

It is revealed that the highest wear resistance among the studied galvanic coatings (*Co–W*, *Cr*) is observed for thin coatings deposited on carburized *0.2% C* steel. Fig. 11 shows that the lowest wear occurs for the combination of *0.2% C* steel after carburizing with a chromium coating.

On the basis of the obtained data, it can be concluded that on untreated steel the dominant wear mechanism is abrasive wear initiated by coating breakthrough (delamination). A thin coating (1 μm) is unable to withstand the contact stresses on a soft substrate, which leads to its rapid destruction. The hard coating



a

Spectrum 31

	Wt%	σ
W	43.7	0.5
Co	39.1	0.4
Fe	11.8	0.2
O	5.5	0.2

Spectrum 32

	Wt%	σ
Fe	92.4	0.4
Co	4.0	0.1
O	1.5	0.2
W	1.2	0.3
Mn	0.6	0.1
Si	0.3	0.1

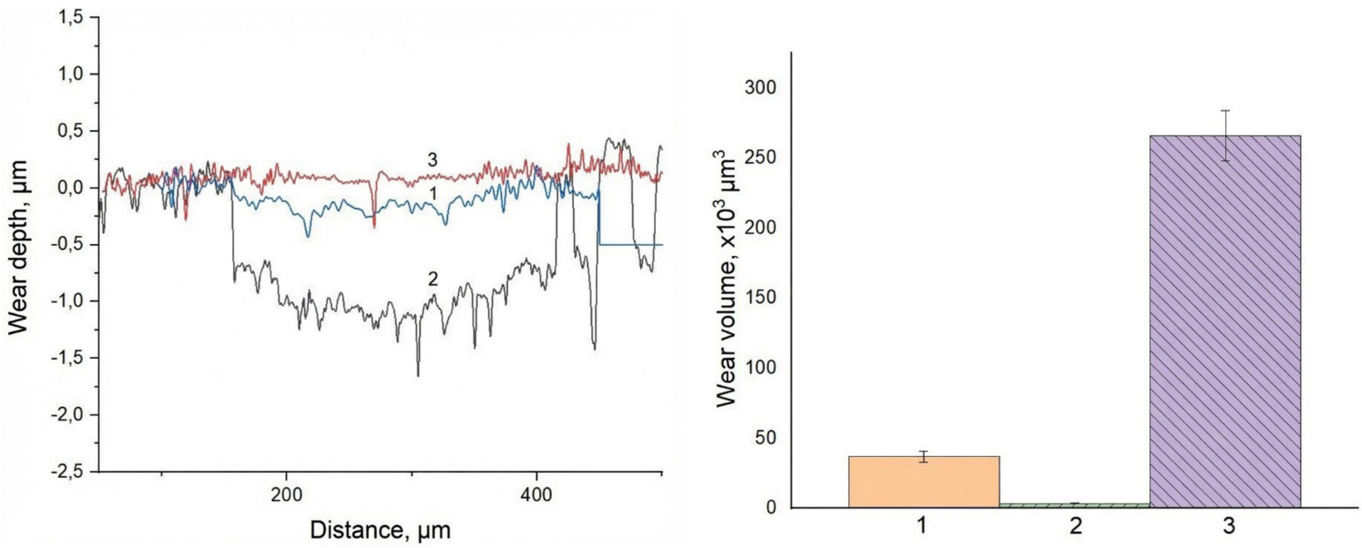
Spectrum 33

	Wt%	σ
Fe	94.8	0.4
O	3.8	0.2
Mn	0.7	0.1
Co	0.3	0.2
Si	0.3	0.1
W	0.1	0.4

b

Fig. 10. EDX analysis of the friction track of a *Co–W* coating deposited on electrolytic-plasma quenched 0.45% *C* steel substrate:

a – *SEM* image of the friction track with marked *EDX* analysis zones; *b* – surface composition of the investigated zones (wt. %)



a *b*

Fig. 11. Results of tribological tests of 1 µm thick *Cr* and *Co–W* coatings deposited on a carburized (followed by quenching) 0.2% *C* steel substrate in comparison with the uncoated substrate:

a – examples of friction track profilograms (one representative sample from the series); *b* – volumetric wear values. 1 – 0.2% *C* steel after carburizing without a galvanic coating; 2 – *Co–W* galvanic coating deposited on carburized 0.2% *C* steel; 3 – chromium galvanic coating deposited on carburized 0.2% *C* steel

fragments (*Co–W* or *Cr*) then act as abrasive particles, further contributing to wear. Their presence in the wear zone even at large depths (Fig. 4) confirms this mechanism.

On hardened substrates (carburized *0.2% C* steel and *0.45% C* steel after electrolytic-plasma quenching) the wear mechanism changes substantially. The hard diffusion layer prevents early coating breakthrough, and wear for a prolonged period occurs predominantly within the galvanic layer itself. With increasing coating thickness, the role of fatigue wear increases; this is probably associated with the accumulation of residual stresses and subsequent cracking and spalling of the coating.

Table 2 presents the wear test results for the combined and individual hardening methods at different sliding duration.

Table 2

Tribological test results of combinations of substrate hardening methods and galvanic coatings

Subsrate	Coating	Friction duration (days)		
		1	2	3
		Mean wear volume (×10^3 μm^3)		
–	*Co–W* (10 μm)	335	426	430
–	*Cr* (10 μm)	48	74	63
0.45% *C* steel (*EPT* quenching)	Uncoated	156	205	467
0.45% *C* steel (*EPT* quenching)	*Co–W* (1 μm)	804	1025	0
0.45% *C* steel (*EPT* quenching)	*Cr* (1 μm)	129	232	0
0.2% *C* steel (untreated)	Uncoated	12,578	17,495	23,020
0.2% *C* steel (untreated)	*Co–W* (1 μm)	6,334	8,127	0
0.2% *C* steel (carburized)	Uncoated	–	37	44
0.2% *C* steel (carburized)	*CCo–W* (1 μm)	–	266	271
0.2% *C* steel (carburized)	*Cr* (1 μm)	1	3,5	8

Microhardness measurements of the substrates and galvanic coatings were performed to explain the wear resistance differences (Table 3).

Table 3

Microhardness measurement results of substrate materials and galvanic coatings

Material	Load (g)	
	20	
	Microhardness (HV)	Error
0.2% *C* steel (untreated)	20	228
0.45% *C* steel (untreated)	20	217
0.45% *C* steel (*EPT* quenching)	20	1,178
0.2% *C* steel (carburized)	20	1,245
Co–W	20	850
Cr	20	952

The experimental data enable the observed differences in coating behavior to be interpreted within the framework of contact mechanics. On untreated *0.2% C* and *0.45% C* steels (microhardness 217–228 HV), the contact condition corresponds to a "hard coating on a soft substrate" configuration. Under these circumstances, a thin galvanic coating (*Cr* or *Co–W*) lacks adequate mechanical support from the underlying material, experiences substantial bending stresses, and is consequently prone to rapid failure. The resulting coating debris then promotes abrasive wear.

On hardened substrates – specifically, carburized *0.2% C* steel and *0.45% C* steel subjected to electrolytic-plasma quenching, with microhardness values of 1,178–1,245 HV – the contact condition corresponds to a "hard coating on a hard substrate" configuration. The elevated hardness of the diffusion layer furnishes the requisite load-bearing capacity, effectively suppressing substantial substrate deformation and forestalling premature coating breakthrough. Under these circumstances, wear is largely confined to the coating layer.

Comparison of the microhardness of the coatings shows that the microhardness of chromium (952 HV) is somewhat higher than that of the *Co–W* alloy (850 HV). This, together with the structural features of the coatings, may explain the higher wear resistance of chromium coatings under lubricated sliding conditions.

Conclusion

It is established that combined treatment, which includes electrolytic-plasma hardening of the substrate followed by the deposition of galvanic coatings, is an effective method for improving the wear resistance of carbon steels under reciprocating sliding in the presence of a lubricant. It is shown that the wear resistance of the combined coatings depends on both the properties of the substrate and the thickness and type of the galvanic coating. The highest wear resistance is achieved with an optimal combination of the substrate hardening method and the type of protective coating.

On the basis of the analysis of the tribological test results, the following conclusions can be drawn:

1. It is shown that electrolytic-plasma treatment without galvanic coatings significantly increases the wear resistance of *0.2% C* and *0.45% C* steels. After 2 days of sliding, the wear volume of untreated *0.2% C* steel is 17,495 × 10^3 μm^3, whereas that of carburized *0.2% C* steel is 37 × 10^3 μm^3 (a reduction of more than 470 times). Carburized *0.2% C* steel exhibits higher wear resistance than *0.45% C* steel after electrolytic-plasma quenching.

2. The substrate material exerts a decisive influence on the wear resistance of the combined coatings. On untreated steel, thin galvanic coatings are prone to coating breakthrough (the wear of 1 μm *Co–W* coating on untreated *0.2% C* steel after 2 days is 8,127×10^3 μm^3). The best results are achieved on carburized *0.2% C* steel: the wear volume of the system "carburized *0.2% C* steel + *Cr* (1 μm)" after 2 days is 3.5×10^3 μm^3, which is more than 2,300 times lower than that of untreated *0.2% C* steel without coating and more than 2,300 times lower than that of 1 μm *Co–W* coating on an untreated substrate.

3. The thickness and type of the galvanic coating substantially affect wear resistance. An increase in thickness from 1 to 10 μm results in an increase in wear. After 2 days of sliding: for the chromium coating, the wear of *Cr* (1 μm) on carburized *0.2% C* steel is 3.5×10^3 μm^3, whereas the wear of *Cr* (10 μm) is 74×10^3 μm^3 (an increase of more than 20 times); for the *Co–W* coating, the wear of *Co–W* coating (1 μm) on carburized *0.2% C* steel is 266×10^3 μm^3, whereas the wear of *Co–W* coating (10 μm) is 426×10^3 μm^3.

4. It is established that the highest wear resistance is achieved with the combination of *0.2% C* steel after electrolytic-plasma carburizing followed by quenching and a thin (1 μm) chromium coating. After 2 days of sliding, the wear volume of this system is 3.5×10^3 μm^3, which is substantially lower than that of the analogous system with a 1 μm *Co–W* coating on the same substrate (266×10^3 μm^3). This combination eliminates the problem of coating breakthrough and provides the maximum wear resistance while retaining a relatively soft core of the component.

5. The combined method of surface hardening of steel makes it possible to eliminate the problem of galvanic coating breakthrough and also increases the wear resistance of the galvanic coating by reducing its thickness.

The combination of a chromium coating on *0.2% C* steel after electrolytic-plasma carburizing followed by quenching is an optimal approach to creating a hard component surface while retaining a soft core. The presence of the galvanic coating also makes it possible to obtain a thicker hardened surface layer, because carburizing without galvanic coatings has a depth limitation, just as the chromium coating has a thickness limitation. As a result, an increased thickness of the hardened layer can be achieved and the wear resistance of the system as a whole can be improved.

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Conflicts of Interest

The authors declare no conflict of interest.

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