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Review

Hybrid Surface Treatment Technologies Based on the Electrospark Alloying Method: A Review

Oksana Haponova [1,2,*], Viacheslav Tarelnyk [3], Tomasz Mościcki [1] and Nataliia Tarelnyk [3]

[1] Department of Experimental Mechanics, Institute of Fundamental Technological Research Polish Academy of Sciences, Pawińskiego 5B, 02-106 Warsaw, Poland; tmosc@ippt.pan.pl
[2] Applied Material Science and Technology of Constructional Materials Department, Sumy State University, Kharkivska 116, 40007 Sumy, Ukraine
[3] Technical Service Department, Sumy National Agrarian University, H. Kondratiieva 160, 40021 Sumy, Ukraine; tarelnyk@ukr.net (V.T.); natasha-tarelnik@ukr.net (N.T.)
* Correspondence: gaponova@pmtkm.sumdu.edu.ua

Abstract: Technologies for functional coatings are evolving rapidly, with electrospark alloying (ESA) emerging as a promising method for surface modification due to its efficiency and localized impact. This review analyzes the fundamental principles of ESA and the effects of process parameters on coating characteristics and highlights its advantages and limitations. Particular attention is given to hybrid ESA-based technologies, including combinations with laser treatment, plastic deformation, vapor deposition, and polymer-metal overlays. These hybrid methods significantly improve coating quality by enhancing hardness, adhesion, and structural integrity and reducing roughness and defects. However, the multi-parameter nature of these processes presents optimization challenges. This review identifies knowledge gaps related to process reproducibility, control of microstructure formation, and long-term performance under service conditions. Recent breakthroughs in combining ESA with high-energy surface treatments are discussed. Future research should focus on systematic parameter optimization, in situ diagnostics, and predictive modeling to enable the design of application-specific hybrid coatings.

Keywords: electrospark alloying; hybrid technologies; surface plastic deformation; laser treatment; vapor phase deposition; metal–polymer material; coating; structure; properties; roughness; coating quality; sustainable development goals

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1. Introduction

The structural strength of a metal is determined by its bulk and surface mechanical characteristics. Bulk characteristics are usually given by metallurgical alloying. But, the main service characteristics of machine parts, such as reliability, resistance to mechanical wear and corrosion, and fatigue life, are determined by the mechanical properties of the surface layer of the structural metal. There are many technologies for increasing the strength of the surfaces of parts: chemical–thermal treatment, surface plastic deformation (SPD), welding, laser treatment (LT), high-frequency hardening (HFH), etc. [1,2]. It is known [3] that the mechanical behavior of a metal is directly dependent on its structural and phase states. This dependency allows for the functional and operational characteristics of machine components to be selectively modified by altering the structural and phase state of the surface layer.

Methods for creating modified layers on the surface of metals with the necessary functional and operational properties have been sufficiently studied, tested, and widely used in practice. Simultaneously, it is noted that traditional technologies for strengthening metals and alloys have reached their maximum efficiency [4,5]. It has been established that the maximum modification effect is achieved by combining different methods of changing the structural–phase state [6–8]. The combination of different strengthening technologies allows you to create composite layers with different architectures on the metal surface.

Promising methods of surface strengthening and modification are methods based on the treatment of materials with concentrated flows of energy (CFE) [9]. The unique influence of this action on the formation of the structure, microstructure, and surface properties, as well as on the friction and wear processes of metals, was proven in [10,11]. Metallic materials can be strengthened by CFE in various combinations. This allows for the existing technological processes to be intensified and results to be achieved that are unattainable with traditional technology.

Modern methods of surface treatment of CFE metal surfaces include electrospark alloying (ESA), which allows for the creation of surface structures with unique physical, mechanical, and functional properties at the nano level [12,13]. This method is based on the phenomenon of electrical erosion and the transfer of the material of the anode (tool) to the cathode (substrate) during the flow of pulsed discharges in a gaseous medium.

Due to the large list of materials that can be used in ESA (any conductive materials) and the participation of the interelectrode medium in the process of forming surface layers, this method can widely change the mechanical, thermal, electrical, thermoemissive, and other properties of the working surfaces of parts [14]. Despite the simplicity of the technology, ESA is a complex and multi-parameter process.

Combined (hybrid) surface treatment technologies are used to improve the properties of ESA coatings and eliminate the disadvantages of ESA technology. They can consist of sequential ESA and surface plastic deformation, ESA and laser treatment, and other combinations.

Although there are individual studies on the combined use of ESA with LT, SPD, or other methods, there is currently a lack of comprehensive reviews that systematize the types of hybrid technologies, their parameters, and the impact of these on the structure and properties of coatings. For the first time, this review collects, summarizes, and critically analyzes existing hybrid processing approaches based on ESA. It also points out the limitations of each combination and outlines current scientific challenges, particularly issues of scaling, the lack of process control systems, and the application of artificial intelligence technologies for optimization.

The aim of this paper is to review the technology of electrospark alloying (ESA) and the influence of treatment parameters on the structure and properties of surface layers. Additionally, it systematizes current approaches to improving ESA by applying hybrid processing methods, provides a critical analysis of these approaches, highlights current limitations and research gaps, and outlines promising areas for further research.

2. Electrospark Alloying Technology

Electrospark alloying (ESA) is a surface engineering method based on the deposition of alloying material from the anode electrode to the cathode surface using pulsed electrical discharges in an air or protective gas environment (Figure 1). This process provides localized surface treatment with minimal thermal impact and high coating adhesion. The advantages of ESA include the ability to treat selected areas without the need to protect the rest of the surface, no heating of the entire product, and compatibility with a wide range of materials [15–17].

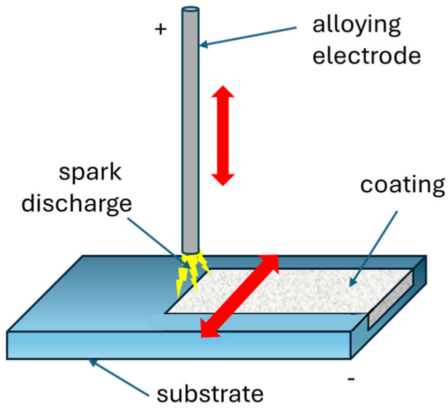


Figure 1. Schematic of the traditional electrospark alloying technology.

The method is actively used to increase hardness, wear, and corrosion resistance [10,18,19], reduce the tendency to adhere during friction [16], restore part size [20], change electrical and emission properties [21], form coatings with controlled phase composition [22], apply radioactive isotopes [23], and produce surfaces with a given roughness [24].

Electrodes of different chemical compositions and manufacturing technologies are used to create coatings with specified properties. The literature provides a wide classification of such materials: graphite, metals, alloys, hard alloys based on tungsten carbides [25], metal–ceramic compositions [26], etc. The fabrication of multilayer coatings using the ESA method, which combines hard wear-resistant and soft antifriction materials, significantly increases the reliability and durability of the parts [27–29].

Key process parameters and their effects.

The effectiveness of ESA depends on several key factors, of which energy parameters play a crucial role. Increasing the discharge energy raises the speed of the ESA process. Discharge energy W_p is defined as [15] as follows:

$$W_p = \int_0^{t_p} V(t) \cdot I(t) dt,$$

where *V(t)* is the voltage function during discharge; *I(t)* is the current function during discharge, and t_p is the pulse duration.

Higher current and voltage increase the depth and rate of material transfer but can lead to overheating, surface roughness, and structural defects [15]. Capacitance, charge voltage, inductance, and resistance determine spark energy and discharge characteristics [30,31]. Optimization of pulse duration and frequency is essential, as excessive values can induce thermal stresses and microcracking, while insufficient energy can result in weak or incomplete coatings [32].

Rapid post-discharge cooling (10^5–10^6 °C/s) facilitates the formation of ultra-fine-grained, nanostructured, or even amorphous surface layers with improved tribological and chemical properties [33–35]. However, the control of these microstructures requires further research.

Despite its many advantages, the traditional method of ESA has significant limitations. Electrodes containing high melting phases often have high erosion resistance, which makes material transfer difficult [36]. In addition, although this method provides high hardness and wear resistance, it does not always improve corrosion or heat resistance. Electrode manufacturing technologies are usually expensive and environmentally hazardous [27–29].

A critical factor is also the non-linear relationship between the alloying time and the increase in cathode mass. After a certain threshold time, t_x, further processing leads to erosion rather than layer growth (Figure 2). The determination of the optimum t_x remains empirical and depends on the discharge energy, the electrode material, and the environment [32].

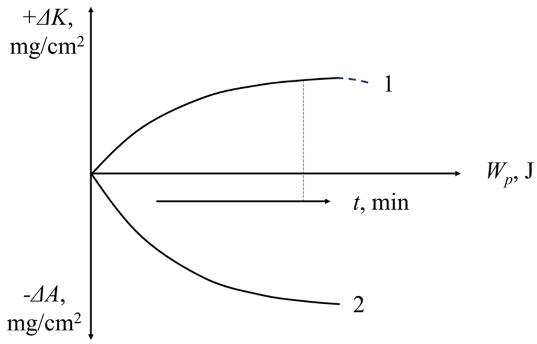


Figure 2. Change in weight of cathode (1) and anode (2) as a function of applied energy and treatment time. ΔA—erosion of the anode; ΔK—gain of the cathode; W_p—applied value of the energy of the spark discharges when depositing a substrate with an area of 1 cm^2.

Modern approaches to improve the efficiency of ESAs include powder feeding into the interelectrode gap [17], processing in inert gas [37,38] or vacuum [39], and the use of new electrode fabrication methods: pressing and sintering [40], hot pressing [41], and spark plasma sintering [42]. However, many of these are expensive or inefficient in industrial production.

A promising direction is the use of a special process medium (SPM). These are pastes, gels, or suspensions containing dispersed alloying components [42–46]. This approach makes it possible to implement the processes of alitization [43], cementation [44], nitriding [45], sulfidation [46], and synthesis of multicomponent coatings, thus extending the functionality of the technology (Figure 3).

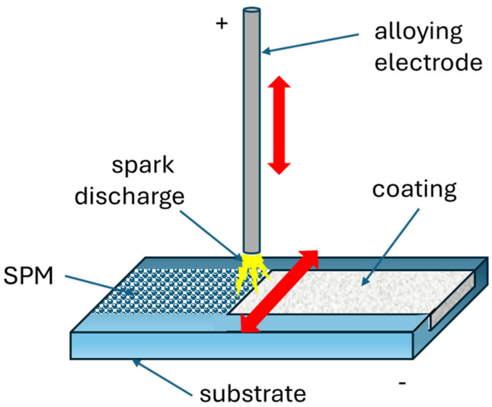


Figure 3. Scheme of the electrospark alloying technology using a special process medium.

The ESA method remains a promising tool for surface modification where localized treatment, reliable adhesion, and minimal thermal impact are important. At the same time, the process needs to be improved to meet modern requirements such as uniformity and continuity of the coating, controllability of the phase composition, environmental safety, and high productivity. The development of combined (hybrid) technologies opens up new possibilities for the formation of multifunctional coatings with improved properties. Further research should aim at creating universal models for optimizing ESA modes depending on the material, structure, and operational requirements of the coating.

3. Hybrid ESA Technologies

As with any surface treatment process, ESA has certain disadvantages related to the poor quality of the surface microrelief, the presence of pores, the possibility of crack formation, reduced fatigue strength, limited thickness of the formed layer, and the presence of residual tensile stresses in the coating [47]. Due to these disadvantages, the development of combined surface modification technologies based on ESAs is becoming increasingly important. The use of combined processing technologies makes it possible to improve the surface quality after ESA, reduce porosity, form compressive stresses in the surface layer, and improve the surface quality.

Figure 4 shows the main directions in the development of hybrid technologies based on ESA that have been applied in manufacturing. This list is not exhaustive, as the ESA method is rapidly improving, and new hybrid technologies are emerging. The main hybrid technologies combine ESA with subsequent surface treatment using concentrated energy and material flows (laser, ion, plasma treatments, etc.) and ESA with subsequent surface plastic deformation (SPD). The list may also include technologies for the formation of multilayer (combined) electrospark coatings. These hybrid methods can form a surface layer with the required properties [48–51].

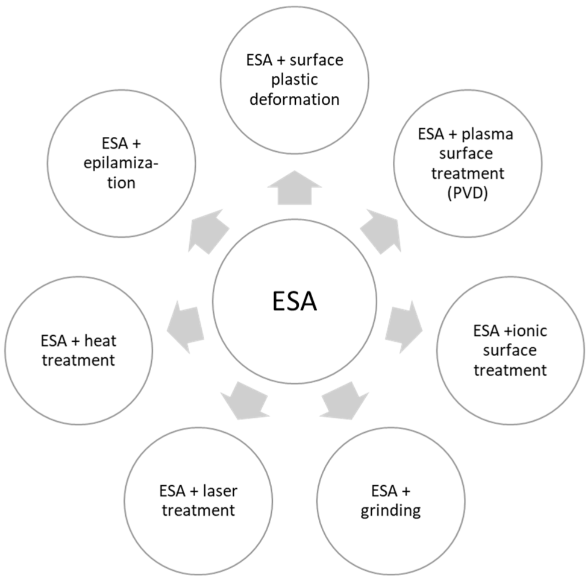


Figure 4. Directions for the development of combined (hybrid) technologies based on the ESA method.

An analysis of the literature has shown that the most popular technologies used in practice are combined ESA followed by surface plastic deformation (SPD). Running-in, diamond polishing [52], abrasive-free ultrasonic finishing (AFUF) [53], and others are used as the main SPDs. The choice of a particular combination depends on the purpose and the equipment available.

Combining ESA with subsequent surface treatment using concentrated energy flows is a promising direction for development. Studies [54–56] consider combined treatment processes, which include the effect on the hardened surface of a spark discharge followed by laser treatment (LT), to be very promising. LT makes it possible to reduce the porosity of ESA coatings, eliminate scratches, cracks, and inhomogeneities, and increase the density of the coating. Localized melting of the coating and underlying steel substrate occurs under the influence of a laser beam. As a result of thermocapillary convection caused by the uneven temperature distribution over the surface of the melt bath and the return of the plasma flow, the alloying material is transferred to the bath volumes, allowing for the depth of the alloy layer to be increased many times over. However, as a result of LT, burn-out (evaporation) of low-melting components is possible. Therefore, the use of combined technologies to produce coatings containing LT requires further research.

More recently, plasma-deposited films have been widely used as protective coatings [57], including magnetron sputtering [58]. Low adhesion is the main disadvantage of such coatings. To overcome this problem, deposition technologies such as laser cladding and electrospark alloying are used, which provide high adhesion due to metallurgical reactions occurring at the coating-substrate interface, and the molten substrate material mixes with the deposited material. However, the resulting coatings exhibit high surface roughness and microcrack formation, which affects resistance to aggressive environments. The problem of defectivity of electrospark coatings can be solved by vacuum deposition and magnetron sputtering. Combined coatings exhibit better oxidation resistance, corrosion resistance, wear resistance, etc. [59].

Despite significant progress in the development of hybrid technologies, universal criteria for selecting the optimal combination of methods depending on the operating conditions have not yet been formulated. This indicates the need for further systematic analysis and accumulation of empirical results, including quantitative comparisons of coating quality indicators such as diffusion depth, microhardness, wear resistance, adhesion, and residual stress.

Hybrid technologies based on electrical discharge alloying (EDA) have a high potential for industrial implementation due to low energy consumption, ease of implementation, and the ability to locally process complex surfaces. ESA is an environmentally safe method as it does not use toxic reagents or generate significant emissions [10]. However, combining it with other methods such as LT, SPD, physical vapor deposition (PVD), and others may increase resource usage. Nevertheless, integrating processes and automating them can optimize these costs. Individual surface treatment methods, such as ESA, LT, PVD, HIPIMS (high-power impulse magnetron sputtering), and others, have already found industrial applications. For hybrid technologies to be widely implemented in industry, an economic analysis must be conducted that considers equipment costs, processing duration, and the effectiveness of coatings in real operating conditions. Further research should cover the entire life cycle of hybrid technologies, as well as developing cost-effectiveness ratio models for specific industries such as aviation, energy, and medicine.

3.1. Improvement in Combined ESA and SPD Processing Methods

Surface plastic deformation (SPD) methods are effectively used to increase the wear resistance and durability of parts after ESA. They are based on the impact of a deforming tool (ball, roller, indenter of another shape) with a certain pressure applied according to the rolling, sliding, or pressing pattern (Figure 5).

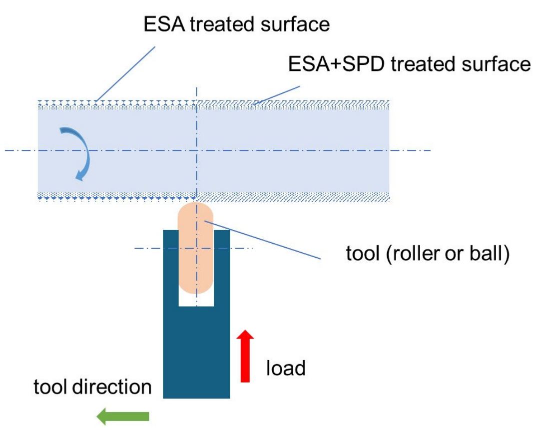


Figure 5. Scheme of the running-in process for ESA coatings.

There are many advantages to SPD, including technological simplicity, low labor intensity, no need for expensive equipment, and the ability to process parts of any geometry or size. The main results are increased hardness, reduced roughness, and increased resistance to fatigue, wear, and corrosion [28].

Among the various SPD methods are bead blasting, chasing, surface rolling (rolling) with a roller and a ball, smoothing, vibration treatment, hardening turning, surface mandrel grinding, etc.

The use of SPD after ESA can eliminate the characteristic disadvantages of the latter, such as microcracks, high roughness, and tensile stresses [20,59]. Therefore, combining ESA and SPD is a promising way to enhance the performance properties of the hardened layer.

It should be noted that SPD can not only strengthen the surface of the parts but also restore them by forming, for example, several support areas on the shaft neck. In addition, this method can be used to create special microreliefs on the hardened surfaces of parts.

Various combined coatings are of great importance in engineering practice, and improving their quality is an urgent task.

The surface treatment after preliminary ESA has certain peculiarities. Due to the relatively small thickness of the layers formed during ESA (tens of microns), their subsequent grinding to reduce surface roughness is, in some cases, difficult or completely unacceptable. It reduces the surface roughness, relieves the final tensile stresses, and allows for ball rolling (BR) [59,60]. After this treatment, the electrospark-coated macrostresses become compressive, and their magnitude is almost independent of the running-in effort. This indicates that the plastic flow of the coating material occurs during the running-in process of the coating.

One of the most promising methods of finishing SPD parts is diamond smoothing (DS), which, unlike ball or roller running-in, allows for the parts with very high hardness to be processed [61]. The use of a spherical diamond as a tool allows for local plastic deformation, reduction in surface roughness, and reduction in waviness and porosity.

In a series of papers [28,62,63], studies were carried out to investigate the structural states of ESA coatings after subsequent SPD–diamond smoothing (DS) and ball rolling (BR). The stress–strain state of the surface layer after SPD of ESA coatings was evaluated [62], as well as the influence of technological parameters on the microgeometry, structure, and properties of the combined coatings [28,63].

As shown in Figures 6 and 7, the effectiveness of SPD as a method of reducing surface roughness depends on R_{cp} and the material of the ESA alloy electrode. If the value of Ra is largely determined by the radius of the diamond indenter for coatings obtained with a tungsten electrode, the influence of the indenter radius decreases with increasing plasticity of the electrode material (chromium and nickel) (Figure 6). It is characteristic that for SPD DS (Figure 7), almost all points of the Ra = f(R_{cp}) dependence fit on the same curve for all coatings, irrespective of the alloying electrode material. The authors explain this effect by the mechanism of surface formation, which consists of two processes: deforming the soft substrate of the coating and cutting the microroughness [63]. In [62], formulas are proposed for the calculation of the necessary deformation force depending on the material of the alloyed electrode, soft and hard coating.

Analysis of the surface layer microstructure after ESA+ SPD with DS shows that the surface quality improves with increasing indenter diameter. At the same time, there are no defects that occur during the SPD. DS with indenters R = 3 mm and R = 4 mm at forces of 1920 and 1330 MPa, respectively, is preferred. The smoothed surface has less roughness; no cracks are observed in the layer, and the hardness distribution is uniform.

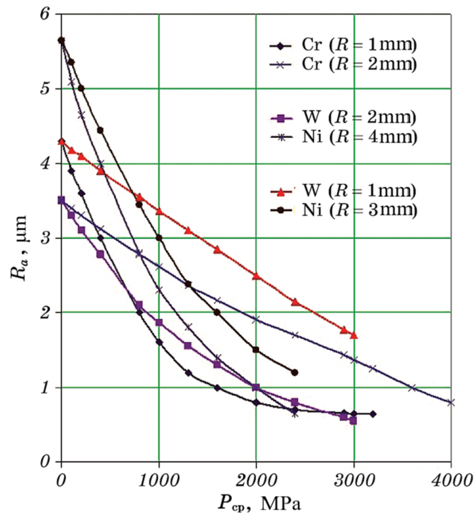


Figure 6. The surface roughness (Ra) of steel 45 (carbon steel with a carbon content of 0.45%) after combined treatment (ESA with tungsten, chromium, and nickel, followed by DS) depends on the force (P_{cp}) diamond smoothing (DS) at different radius of the diamond indenter (R) [63].

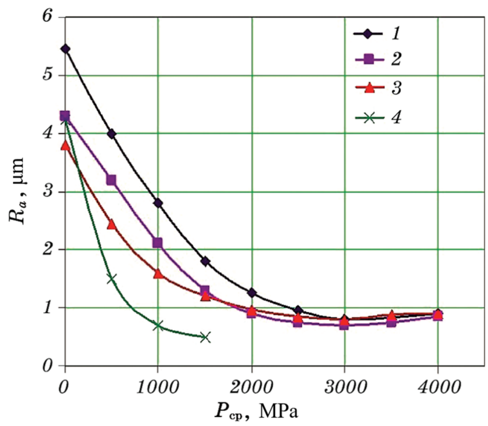


Figure 7. The surface roughness (Ra) of steel 45 (carbon steel with a carbon content of 0.45%) after combined treatment (ESA with nickel (1), tungsten (2), chromium (3), and tin (4), followed by BR) depends on the force (R_{cp}) of ball rolling [63].

Table 1 shows how the main SPD methods used after ESA compare with each other. The impact of these methods on the roughness, hardness, and thickness of the hardened layer was evaluated. Among the methods studied, ball rolling (BR) was found to be the most effective in reducing roughness at low initial surface topography, particularly after ESA with low discharge energy (0.6 J) when Ra decreased to 0.11–0.21 μm. At the same time, the efficiency of BR decreases under conditions of high energy (6.8 J), probably due to structural complications arising from strong thermomechanical effects during ESA, as well as the formation of a hardened, high-strength layer that is less susceptible to further plastic deformation. DS and BR are the most promising methods of reducing roughness while simultaneously increasing hardness through peening. However, excessive hardening should be avoided as it can increase residual stresses in the surface layer, reducing fatigue strength and potentially leading to microcracks.

It is obvious that the deformation focus is less localized with BR, which, of course, changes the hardening conditions of the layer. BR provides a more uniform force effect on the surface layer. During BR of ESA tungsten coatings (diameter of ball 19 mm at P_{cp} = 1380 MPa) on steel 45, the obtained layers are characterized by high quality: there are no macro defects (rolls, cracks); the surface is even; the hardened layer has a uniform hardness of 8000 MPa, which gradually decreases from the surface to the substrate [63].

Table 1. The results of the effect of the following treatment technology on the surface parameters after cementation ESA (CESA) at different discharge energies of steel AISI 321 (before treatment Ra = 0.5 μm) [59,64].

Discharge Energy of ESA, J	Method of Treatment *	Total Layer Depth After Treatment, μm	Microhardness **, MPa	Roughness Ra, μm
0.6	CESA	48	10,130	0.9–1.0
	CESA + AFUF	50	8800	0.2
	CESA + AFUF + grinding	48	8410	0.6
	CESA + Grinding	18	7230	0.6
	CESA + BR	30	9500	0.11–0.21
2.83	CESA	200	9740	5.8-6.7
	CESA + AFUF	210	9700	0.8
	CESA + AFUF + grinding	195	9500	0.8
	CESA + Grinding	130	7900	0.8
	CESA + BR	96	8400	0.53–0.71
6.8	CESA	250	11,000	10.0–14.5
	CESA + AFUF	244	9850	0.8
	CESA + AFUF + grinding	220	8750	0.8
	CESA + Grinding	110	6700	0.8
	CESA + BR	115	9000	1.23–1.58

* CESA—cementation by electrospark alloying; AFUF—abrasive-free ultrasonic finishing; BR—ball rolling; ** in [59,64] microhardness value in HV units.

However, additional strengthening is not always necessary, given the increase in stresses in the surface layer. The ESA + AFUF combination provides an optimal balance of low roughness (~0.8 μm) and high microhardness (up to 9850 MPa), with sufficient hardened layer thickness (Table 1).

Unfortunately, the currently available literature does not provide specific, experimentally verified, or derived recommendations for determining the magnitude of expected deformations of soft antifriction metal coatings or combined electrospark coatings (CESC). In addition, there is no information in the literature on the structure of CESCs subjected to subsequent or preliminary SPD processing, nor on the influence of such hardening technology on the durability and other properties of the products. This circumstance indicates the need for a wide range of experimental and theoretical studies aimed at identifying the separate influence of various factors on the quality parameters of the surface layer since even the most successful solution to the problem of elastoplastic deformation of the hardened ESA layer cannot be a reliable tool for determining the expected behavior of the layer material during SPD.

It is advisable to focus on studying the deformation mechanisms of ESA + SPD coatings, as well as developing models that can predict the effect of SPD on the structure and properties of the layer. The optimal SPD parameters for coatings formed by different electrodes must be determined, taking into account the depth, hardness, and phase composition of the layer. Particular attention should be paid to analyzing the microstructure, residual stresses, and durability under real friction and fatigue loading. The results of these studies will enable the creation of scientifically based recommendations for the industrial application and further automation of ESA + SPD technologies.

3.2. Improvement in Combined ESA and LT Methods

Combined material handling methods, in particular, the combination of ESA and laser treatment (LT), have become important tools in modern surface hardening technologies.

This approach makes it possible to solve a wide range of problems that are difficult to solve using traditional processing methods [17,64]. LT makes it possible to reduce the porosity of ESA coatings, eliminate scratches, cracks, and inhomogeneities, and also increase the density of the coating [65,66]. Under the influence of a laser beam, local melting of the ESA coating and the underlying steel substrate occurs. As a result of the thermocapillary convection caused by the uneven temperature distribution at the surface of the melt and the return of the plasma flow, the alloy diffuses into the substrate, allowing for the depth of the alloy layer to be significantly increased [67].

Authors [14,68,69] highlight key characteristics of combined ESA + LT coatings, noting that the microstructure and properties are significantly influenced by treatment parameters. These coatings exhibit better adhesion to the substrate compared to those treated with ESA or LT alone, as well as improved homogenization of the chemical composition. The structure and crystallization are also enhanced, and microcracks are filled, leading to higher coating density and improved corrosion resistance. The coating thickness increases, while roughness is reduced compared to ESA coatings, although it is higher than the substrate surface. However, LT may cause the evaporation of low-melting components, suggesting that further research is needed to optimize the combined ESA+LT coating process.

The effect of laser treatment (LT) on the structure, phase composition, and wear resistance of high-entropy coatings ($Ti_{0.5}W_{0.25}Cr_{0.5}FeCo_{1.75}Ni_3Al$ and $Ti_{0.8}W_{0.25}Cr_{0.5}FeCo_{1.75}Ni_3AlB_{0.6}$) obtained by ESA was investigated in [70]. XRD analysis revealed significant changes in the phase composition following LT, notably, an increase in the BCC solid solution and the disappearance of boride diffraction peaks (see Figures 8 and 9). These results imply that LT can effectively prevent boride phase precipitation in ESA coatings. Microstructural analysis showed the formation of a heat-affected zone extending up to 100 μm, while the distribution of chemical elements and microhardness remained uniform. Achieving high-quality coatings requires a careful selection of LT parameters. Wear resistance tests indicated that the combined ESA + LT coatings exhibited a 40-fold and 2.4-fold increase in wear resistance under quasi-static and dynamic loading, respectively, when tested with a Si_3N_4 indenter compared to laser-untreated coatings. Similarly, wear resistance with a carbide indenter (WC-6% Co) increased by factors of 36 and 2.6, respectively [70].

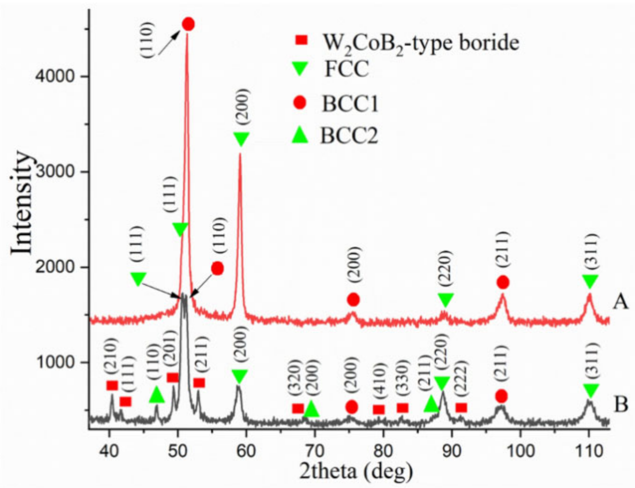


Figure 8. X-ray diffraction patterns of the as-cast alloys $Ti_{0.5}W_{0.25}Cr_{0.5}FeCo_{1.75}Ni_3Al$ (**A**) and $Ti_{0.8}W_{0.25}Cr_{0.5}FeCo_{1.75}Ni_3AlB_{0.6}$ (**B**) [70]. The alloys were produced by arc melting using metals with a purity of >99.5 at.% and titanium diboride powder.

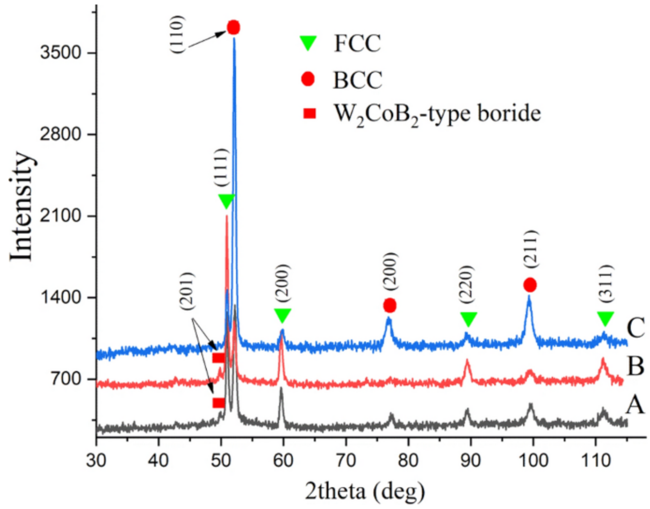


Figure 9. X-ray diffraction patterns from the surface of $Ti_{0.8}W_{0.25}Cr_{0.5}FeCo_{1.75}Ni_3AlB_{0.6}$ coatings obtained by the ESA method at different discharge energies: (**A**) 0.52 J, (**B**) 1.1 J, and (**C**) 1.1 J with subsequent laser treatment (ESA + LT) [70]. The following parameters were used for the laser surface treatment: an irradiation wavelength of 1.06 μm; a laser pulse duration of 5 ms; a focal length of the system of 100 cm; a pulse frequency of 10 Hz; a spot diameter of 1.25 mm; a voltage of 550 V; a radiation energy of 3.9 J; a power density of 0.65×10^5 W/cm^2. The ESA and laser treatment were carried out in air.

The combined technology of ESA, followed by LT, has been used to form hard wear-resistant [54,71], ceramic [65,72], and special coatings [70,73]. The authors have shown that LT after ESA can modify the microstructure and phase composition of coatings, resulting in changes in their physical and mechanical properties. The combined technology allows for improving surface quality, reducing roughness, increasing wear resistance, eliminating unfavorable tensile stresses caused by ESA, providing better corrosion resistance, etc.

Using a hybrid of ESA and LT technologies effectively improves the mechanical and physical properties of surface layers. However, a series of issues must be addressed to maximize efficiency when introducing this technology to manufacturing.

These include the optimization of ESA and LT parameters; the application of new laser processing methods, such as laser cladding and laser melting with powder addition; modeling and simulation of treatment processes to determine the optimal parameters; material selection for ESA, such as the use of complex alloying systems for coatings; and the application of multi-stage processing technologies for the formation of multilayer coatings. The results of the research will enable better treatment of materials for a wide range of applications requiring high-performance characteristics to be achieved.

3.3. Improvement in the Technology of Restoring Worn Surfaces of Parts Using the ESA Method with Subsequent Application of Metal–Polymer Materials

A current direction is the combination of electrical impact on the surface with the subsequent application of polymer [9] and metal–polymer materials (MPM) [10]. The combined technology of ESA + MPM makes it possible to achieve the required level of micro-uniformity (roughness) and the subsequent blade machining to ensure a different ratio of areas of deposited metal and metal–polymer material.

The advantages of the hybrid ESA + MPM technology (ESA method followed by the deposition of metal–polymer materials) are obvious: the continuity of the surface is 100%; the roughness is much lower, and the hardness is higher. Due to the possibility of applying ESA coatings using a wide range of electrode materials, it is possible to vary the mechanical, thermal, electrical, and other properties of the working surfaces of parts in a wide range [74]. The penetration of MPM into the cavities and micron irregularities of the restored parts eliminates the possibility of corrosion pits in these cavities. The wear resistance, reliability, and durability of the remanufactured parts are higher than those remanufactured using individual technologies.

It should be noted that in the application of the ESA + MMP combined technology method, different options for surface formation are possible. The ESA method can vary the height of micro-irregularities, and their subsequent machining by blade cutting (cutting tool blade) can provide different ratios between the areas of deposited metal and metal–polymer material [75].

The disadvantages of the ESA + MPM technology are the low hardness and strength of the formed surface layer, especially in cases where the MPM layer is applied after ESA. In this context, a method has been proposed in [76], where the surface layer is reinforced with at least one wire layer after ESA; then MPM is applied, and after polymerization, the formed layer is subjected to finishing treatment. However, this method is not without its disadvantages. These are, first of all, difficulties associated with fixing the reinforcing wire on the repaired area and uneven distribution of the reinforcing material, both on the vertical and on the horizontal plane of the repaired surface. In the work [74], it is recommended to use a wear-resistant material in the form of powder as a reinforcing material.

Despite its undeniable advantages, the combined ESA + MPM technology also has disadvantages. These are, first of all, the following:

- reduction in the hardness and strength of the formed surface layer, consisting only of MPM, which is located above the coating applied by the ESA method;
- MPM performs well in compression and much worse in shear, which negatively affects their use in friction surface restoration [77].

The main application of the combined ESA + MPM technology is the restoration of the surfaces of parts in non-separable joints (bearing seats, half-couplings, etc.).

In [78,79], a combined ESA + MPM technology is proposed, which includes the deposition of an ESA coating on the worn surface of the part with a metal electrode; the application of MPM on the treated surface, which is reinforced with wire before polymerization. In this case, on the worn surface of part 1 (Figure 10), layer 3 of a coating of any hard wear-resistant metal (chromium, nickel, etc.) is applied by the ESA method. In this case, a transition layer 2 is formed between the applied metal and the part, representing the mutual diffusion penetration of the anode and cathode elements. The coating can be applied by varying the discharge energy in the range of 0.036–6.8 J. As the discharge energy increases, the coating thickness and surface roughness rise. Subsequently, a metal–polymer material 4 is applied to the ESA surface. The authors show that the use of combined ESA technology with subsequent application of MPM allows for increasing the strength and wear resistance of the formed coatings.

It is often necessary to restore flat and curved worn surfaces of parts made of hard, wear-resistant metals, for example, pump housings, compressors, centrifuges, gearboxes, etc. (Figure 11).

In this case, after the ESA coating has been applied to treated surface 1 (see Figure 11), a mesh made of hardened, heat-treated wire with a minimum mesh size of 1.0–1.5 $\times$ 1.0–1.5 mm^2 is applied. In this case, the thickness of the MPM applied should ensure that the wires (2) of the mesh are covered by at least half of their diameter. The mesh can be fixed outside the surface to be restored by any known method, e.g., with glue (3). Once the mesh is in place, it is necessary to continue to apply the MPM until it is completely covered. In the case of significant wear, the mesh application can be repeated as many times as necessary.

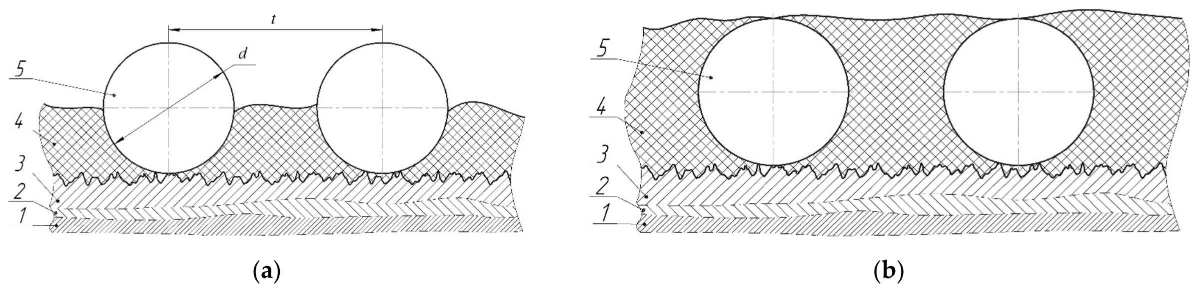


Figure 10. Restoration of worn surfaces of rotating bodies by the combined technology of ESA + MPM (wire reinforcement): (**a**) a schematic illustration of the stage of dipping the reinforcing wire into the MPM layer applied after ESA; (**b**) a schematic illustration of the completed coating, including the MPM layer reinforced with a wire layer. 1—part, 2—forming transition layer, 3—ESA coating made of hard wear-resistant metal, 4—metal–polymer material, 5—reinforcing wire [75].

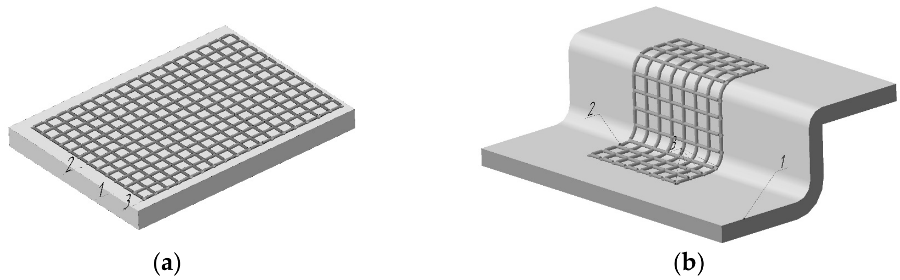


Figure 11. Surface schemes for restoring worn surfaces: (**a**)—flat, (**b**)—curved: 1—substrate, 2—reinforcing mesh, 3—intermediate adhesive layer (glue) [78].

Thus, as a result of the application of the proposed method for restoration of worn surfaces of parts, a layer is formed, the quality, wear resistance, reliability, and durability of which is higher than when using ESA methods and applying MPM separately for restoration.

The formation of the structure and properties of coatings obtained by the combined ESA technology with subsequent application of MPM is shown in [10], where the authors investigated coatings on austenitic AISI 321 steel. The surface was first treated by ESA with a graphite electrode, then by ESA with an aluminum electrode and a hard alloy. MPM was applied to the T15K6 hard alloy coating, pre-reinforced with powder in the form of a VK6 hard alloy mixture added to a two-component epoxy system filled with Loctite 3478 ferrosilicon at a reinforcement concentration of ~60%. This produced a coating up to 1.5 mm thick with a microhardness of 9500–10,100 MPa. The surface roughness was Ra = 1.2 μm. This technology is proposed for the restoration of worn surfaces of rotating bodies (e.g., pump shafts).

The complex structure of ESA + MPM coatings has been confirmed by electron microscopy [80]. On the surface, there is a ‘dark’ layer. Its microhardness is between 5000 and 5400 MPa. Deeper in the metal, a ‘light’ layer is formed. The microhardness of this layer gradually decreases toward the substrate (Figure 12). The use of a wear-resistant material in the form of powder as a reinforcement is recommended in [74].

In order to increase the thickness and hydroabrasive wear resistance, it is proposed to carry out laser treatment of the combined ESA + MPM coatings [80]. LT of coatings promotes the formation of a characteristic layered microstructure, whose parameters depend on the chosen mode of treatment. As shown in Table 2, increasing the laser pulse duration while decreasing the frequency to 50 Hz results in the growth of the hardened layer’s thickness and an increase in its microhardness. This is due to a deeper thermal effect and improved surface modification. Comprehensive studies of the influence of LT parameters enable the identification of key regularities and the establishment of optimal processing conditions that provide the required combination of strength and performance characteristics of the coating.

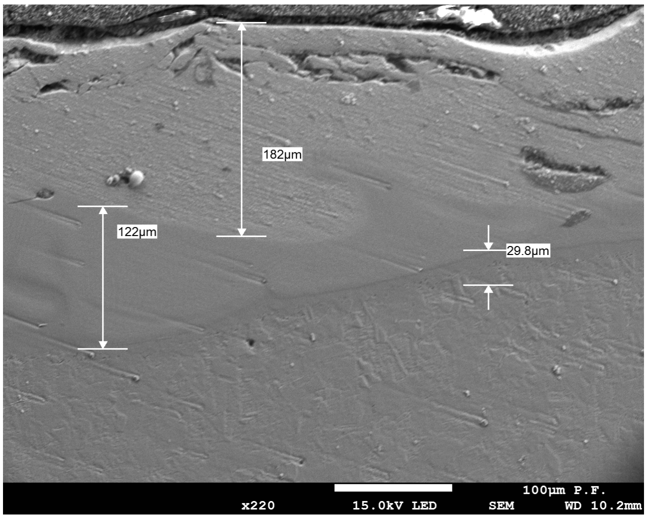


Figure 12. Microstructure of the coating (substrate–AISI 321) steel after sequential ESA T15K6 (discharge energy W_p = 0.55 J), ESA T15K6 (W_p = 0.90 J), and MPM deposition. MPM is a mixture of VK6 powder and a two-component epoxy system filled with Loctite 3478 ferrosilicon [80].

Table 2. Characteristics of surface layers on AISI 321 steel after hybrid technology: ESA (alloying electrode hard alloy T15K6, ESA mode–discharge energy 0.55 J, then 0.90 J) + MPM (VK6 hard alloy powder in two-component epoxy system filled with Loctite 3478 ferrosilicon) + LT.

LT Mode	Thickness, μm	Microhardness, MPa	Continuity, %	Surface Roughness, Ra, μm
Mode 1 (supply 120 mm/min, voltage 500 V, laser pulse 0.3×10^{-3} s, frequency 100 Hz)	10/100 *	6110/2650 *	65/100 *	2.1
Mode 2 (supply 120 mm/min, voltage 500 V, laser pulse 0.3×10^{-3} s, frequency 50 Hz)	40/130	7200/4500	90–95/100	3.3
Mode 3 (supply 120 mm/min, voltage 500 V, laser pulse 1×10^{-3} s, frequency 50 Hz)	50/190	8900/6500	90–95/100	6.2
Mode 4 (supply 120 mm/min, voltage 550 V, laser pulse 1×10^{-3} s, frequency 50 Hz)	100/230	9250/7250	100/100	8.1
Mode 5 (supply 120 mm/min, voltage 600 V, laser pulse 1×10^{-3} s, frequency 50 Hz)	420/260	10,000/7300	100/100	9.0

* 'Dark' layer/'Light' layer.

Studies [80,81] have shown that the deposition of MMP on AISI 321 steel increases the thickness of the wear-resistant layer by up to 600 μm, giving it a microhardness of between 7300 and 10,000 MPa. At the same time, ESA + MPM + LT coatings are 7.5 times more resistant to hydroabrasive wear than uncoated steel and 1.5 times more resistant than steel after ESA and ESA + MPM without LT (Figure 13). This strengthening technology has found its application to increase the service life of parts centrifuges OGSh-631K-02–machines for the separation of heterogeneous systems in a centrifugal field. Centrifuge screw flights are exposed to abrasive water jet wear, turbine blades, centrifuge compressor impellers, and fan wheels to abrasive gas jet wear, etc. The combined technology based on ESA is shown to be promising.

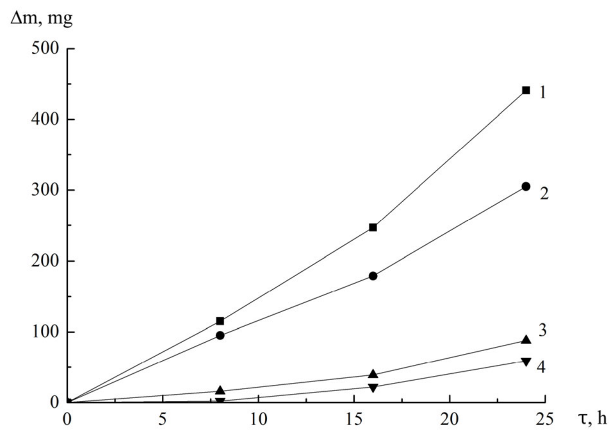


Figure 13. Abrasive wear (weight loss) versus testing time for the samples AISI 321 in series: 1—uncoated; 2—ESA T15K6 (Wp = = 0.55 J) + ESA T15K6 (Wp = 0.90 J); 3—ESA T15K6 (Wp = 0.55 J) + ESA T15K6 (Wp = 0.90 J) + MPM; 4—ESA T15K6 (Wp = 0.55 J) + ESA T15K6 (Wp = 0.90 J) + MPM + LP. MPM is a mixture of VK6 powder and a two-component epoxy system filled with Loctite 3478 ferrosilicon. LP regimes: supply 120 mm/min; voltage 550 V; laser pulse 10^{-3} s; frequency 50 Hz [81].

Combined ESA and MPM technologies produce high-strength, continuous coatings with low roughness, increased wear resistance, and durability. This effect is further enhanced by subsequent laser treatment. Further research should focus on optimizing reinforcement parameters (wire or powder), improving adhesion between layers, studying the effect of microstructure on performance, and developing models to predict wear resistance and durability in complex production conditions.

3.4. Combined ESA Processing and Vapor Phase Deposition (VPD)

For many industries, it is important to form hard, wear-resistant coatings on the working surfaces of parts in combination with other functional properties (corrosion resistance, heat resistance, certain tribotechnical properties, etc.). Increased hardness is usually achieved by forming carbides, nitrides, borides, intermetallics, MAX phases, etc., in the coatings. A fairly common method for obtaining the phases listed is vapor phase deposition (CVD, PVD, ion nitriding, magnetron sputtering, etc.) [82–85]. Alloys based on iron, copper, titanium, nickel, magnesium, and composites such as hard alloys are used as substrates [86–88]. Although these methods are promising, their widespread use in industry is limited by the low thickness of the coatings, the poor adhesion to the substrate (in most cases), the use of expensive equipment, the high cost, the complexity of controlling the formation of the coating, etc.

In order to ensure better adhesion to the substrate, reduce porosity and improve the integrity of the protective coating obtained by vapor phase deposition (VPD) methods, reduce roughness, and ensure high surface quality, it is proposed to use hybrid technologies consisting of the pre-treatment of the surface using the ESA method.

Therefore, the authors of [89] propose a double treatment, ESA, followed by plasma nitriding, to ensure the hardness and wear resistance of aluminum–bronze and cast iron surfaces. It has been shown that ESA with an electrode tool made of AISI-304 steel can achieve a surface hardness of 600 $HV_{0.2}$ (~6000 MPa) on an aluminum–bronze substrate and 1100 $HV_{0.2}$ (~11,000 MPa) on a cast iron substrate (Figure 14).

The hybrid technology of ESA, followed by ion–plasma nitriding, has found a practical application for the formation of a protective coating on the shaft-bearing journal or the surface of a sleeve pressed thereon [90]. It has been shown that ESA with an aluminum electrode tool ensures the formation of an aluminum sublayer, and subsequent nitriding contributes to the saturation of the surface with nitrogen and the formation of a favorable structure and phase states. A 300 μm hardened layer with a maximum surface microhardness of 7700 MPa was obtained on 37Cr4 steel. For the final surface treatment of the shaft neck, which is subject to increased roughness requirements, the sequence of ESA with aluminum, surface plastic deformation (abrasive-free ultrasonic finishing, AFUF), and plasma nitriding was carried out. In addition, SPD prior to nitriding increases the diffusion zone of the nitrided layer, contributing to the intensification of the nitriding process.

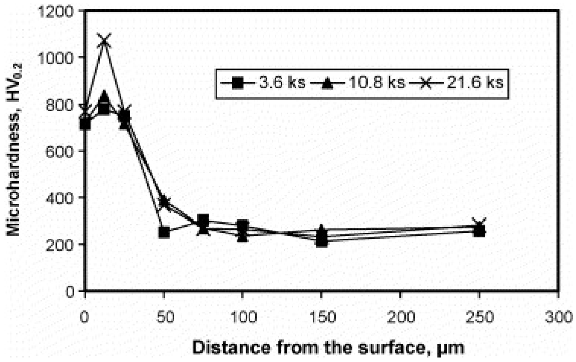


Figure 14. Influence of nitriding duration on the microhardness of cast iron samples coated by ESA (parameters of ESA: capacitor 150 µF, voltage 50 V, alloying electrode: AISI-304 stainless steel [89].

When 37Cr4 steel is nitrided after ESA with a hard alloy electrode tool (VK 6), a hardened layer with a microhardness of 10,500 MPa and a thickness of 100–120 µm is formed [63]. However, the high surface roughness Ra = 3.5 µm does not allow for these coatings to be used without additional processing (e.g., SPD). In order to improve the ESA process, the authors propose a sequential ESA process of VK8 + Cu + VK8 followed by nitriding. It is shown that the copper sublayer contributes to better adhesion of the hard alloy and has a positive effect on the roughness. Therefore, for practical application, multilayer ESA coatings with subsequent ion–plasma nitriding are recommended, which have a satisfactory roughness Ra = 0.6 µm, 100% continuity, a significant depth of the formed layer (up to 120 µm), and a microhardness that decreases smoothly with depth and reaches 9500 MPa on the surface on 37Cr4 steel.

It should be noted that for heat-treated parts under the layer of increased hardness after ESA, a softening zone appears–a zone of reduced hardness. This causes the hardened layer to be pushed through, resulting in wear of the part. According to [91], ion nitriding before or after ESA can eliminate zones of reduced hardness when electrodes made of pure, hard, wear-resistant metals are used. In addition, there is a gradual change in the hardness of the hardened layer and an increase in the overall depth of the zone of increased hardness.

After surface hardening of journals for rolling bearings (RB) (cementation, gas nitriding, carbonitriding, etc.), deviations of the surfaces from the required geometrical shape are possible, and to eliminate these, it is necessary to remove part of the surface layer [86]. Since the hardness of the hardened surface layer decreases as the surface deepens, the hardest part of the surface is removed. If the wear is significant (>1 mm per diameter), the worn shaft journals are bored out, and bushings are pressed onto them. The bushings are subjected to surface hardening prior to use. The outer surface of the bushing is ground to the nominal bearing size. Therefore, after pressing the bushing onto the shaft, its outer diameter may decrease by up to 0.3 mm, resulting in a significant reduction in the hardness of its surface and the need to restore it. It is practically impossible to restore the hardness of the surface layer of the pressed bushing without the necessary preliminary disassembly using the above-mentioned technologies.

Combined ESA technologies followed by plasma nitriding are also recommended to provide better corrosion resistance. In [92], a coating of high-entropy alloy (HEA) AlCoCrFeMnNi on a 1045 steel surface using the ESA method was proposed to deposit, followed by plasma nitriding at 500 °C for 8 h. The authors showed that despite the high content of passivating elements (Al, Cr) in the HEA, ESA coatings exhibited insufficient resistance in an aggressive environment due to the presence of cracks and high stresses [93]. However, subsequent nitriding significantly improves corrosion resistance. This is primarily due to diffusion processes that occur during treatment. Nitrogen atoms diffuse into the coating, heal (fill) cracks and pores, dope the surface layers, distort the crystal lattice, and form nitrogen-containing phases (Figure 15). In addition, the heat treatment during nitriding reduces stresses in the coating.

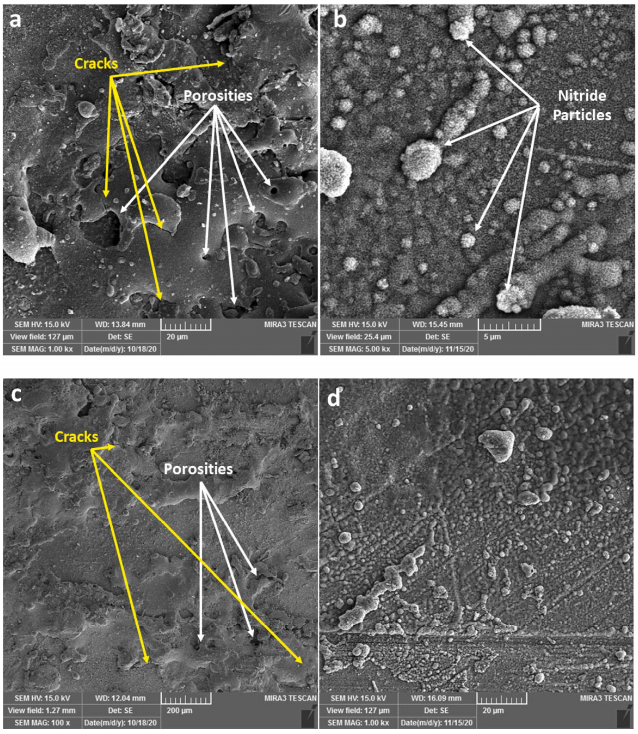


Figure 15. The morphology of the samples after ESA (**a**,**c**) and after ESA and modification by plasma nitriding (**b**,**d**), resulting in a smoother morphology and closing of the surface crack network. Substrate: 1045 carbon steel; alloying electrode: high-entropy alloy (HEA) AlCoCrFeMnNi; plasma nitriding parameters: 500 °C for 8 h, constant voltage of −600 V [92].

The capabilities of ESA technology for forming multilayer functional coatings with an improved set of characteristics can be significantly expanded by combining it with magnetron sputtering (MS) technology [94,95]. The relatively large thickness of the coatings formed using the ESA + MS technology is a fundamental advantage of the hybrid technology and allows for filling the application niche where the thickness of classical vacuum coatings is insufficient. The ESA sublayer is designed, first of all, to ensure ideal adhesion (due to local melting) and a large coating thickness (up to 100 μm). At the same time, the ESA layer using classical synthesis technology may contain substrate elements, which limit the ability to control the composition and properties of such a coating. The upper layer, formed using the MS technology and with a thickness of up to 10 μm, determines higher mechanical characteristics due to the absence of substrate elements in the composition and the possibility of including reactive gas elements, nitrogen and carbon, in the coating composition [22]. It is important that when using ESA and MS technologies, it is possible to use starting materials (electrode tool and sputtered target) of the same composition. With hybrid technology, ESA coating defects are cured; the quality of coatings is improved, as well as the productivity and efficiency of deposition are increased [94].

Therefore, hybrid ESA technologies with subsequent deposition from the gas phase have considerable potential for further development and improvement, allow for a significant improvement in coverage indicators, and are recommended for introduction into production.

4. Industrial Application of Hybrid Technologies

Hybrid coatings produced by the electrospark alloying process are widely used in industry due to their unique properties that combine high wear and corrosion resistance. In particular, ESA coatings are used in mechanical engineering to restore and protect the surfaces of friction units such as shafts, gears, and bearing seats. This significantly extends the service life of equipment and reduces repair costs.

A comparative analysis of the parameters of coatings obtained using various hybrid technologies based on electrospark alloying (ESA) reveals a notable enhancement in the functional properties of the treated surfaces (see Table 3). In particular, combining ESA with AFUF or LT can significantly reduce surface roughness (Ra 0.2–0.8 μm) while maintaining or even increasing hardness. This is important for parts requiring high wear resistance and accuracy. Meanwhile, the use of additional technologies (MPM, HIPIMS, and ion–plasma nitriding) affects not only microhardness and layer thickness but also the morphology and structure of the coatings (Figure 16). Thus, the results demonstrate the wide range of possibilities offered by hybrid ESA technologies for adjusting coating characteristics depending on specific production needs, emphasizing their potential applications in the mechanical engineering, energy, and aerospace industries.

Table 3. Parameters of coatings produced by ESA and hybrid technologies based on ESA.

Method of Treatment *	Treatment Regimes	Materials	Coating Parameters		
			Thickness, μm	Hardness, MPa	Roughness, Ra, μm
ESA [59,64]	Discharge energy W_p = 0.6 J W_p = 2.83 J W_p = 6.8 J	Substrate—carbon steel with 0.45% C, alloying electrode–graphite	48 200 250	1013 974 1100	0.9–1.0 5.8–6.7 10.0–14.5
ESA + AFUF [59,64]	ESA: W_p = 0.6 J; AFUF: frequency 18–22 kHz, running-in speed 50 m/min, feed rate—no more than 0.2 mm/rev, number of passes—1		50	880	0.2
	ESA: W_p = 2.83 J; AFUF: same		210	970	0.8
	ESA: W_p = 6.8 J; AFUF: same		244	985	0.8
ESA [70]	Consistently at W_p = 1.1 J, mode of 7 min/cm^2 and W_p = 0.24 J, mode of 1.5 min/cm^2	Substrate—AISI 1020 carbon steel, alloying electrode–$Ti_{0.8}W_{0.25}Cr_{0.5}FeCo_{1.75}Ni_3AlB_{0.6}$	30−35	10,500 ± 500	–
ESA + LT [70]	ESA—consistently at W_p = 1.1 J, mode of 7 min/cm^2 and W_p = 0.24 J, mode of 1.5 min/cm^2; LT—irradiation wavelength 1.06 μm, laser pulse duration 5 ms, focal length of the system 100 cm, pulse frequency 10 Hz, spot diameter 1.25 mm, voltage 550 V, radiation energy 3.9 J, power density 0.65 × 10^5 W/cm^2		25−30	11,500 ± 500	–
ESA [96]	Voltage 230 V, capacitor 300 μF, current 2.1 A, deposition time 2 min/cm^2	Substrate—carbon steel with 0.45% C, alloying electrode–WC-Co alloy (95 wt % WC–5 wt % Co)	25−35	1013	2.64−3.16
ESA + LT [96]	ESA: same; LT: pulse duration time 0.5 ms, frequency 45 Hz, stroke of laser beam 0.35 mm, speed of movement 230 mm/min		30–40	953	9.87–10.57
ESA [80]	Consistently at W_p = 0.55 J and W_p = 0.90 J	Substrate—12Kh18N10T, alloying electrode–hard alloy T15K6; MPM—VK6 hard alloy powder in two-component epoxy system filled with Loctite 3478 ferrosilicon	50	5000–5400	37
ESA + MPM + LT [80]	ESA: same; LT: supply 120 mm/min, voltage 500 V, laser pulse 0.3 · 10^{-3} s, frequency 50 Hz		40	'Dark' layer 7200	3.3
			130	'Light' layer 4500	–
ESA + MPM + LT [80]	ESA: same; LT: supply 120 mm/min, voltage 600 V, laser pulse duration 1 · 10^{-3} s, frequency 50 Hz		420	'Dark' layer 10,000	9.0
			260	'Light' layer 7300	–

Table 3. *Cont.*

Method of Treatment *	Treatment Regimes	Materials	Coating Parameters		
			Thickness, µm	Hardness, MPa	Roughness, Ra, µm
ESA [94]	ESA: discharge current 120 A, pulse frequency 3200 Hz, pulse duration of 20 µs	Substrate—molybdenum; ESA medium–argon; alloying electrode–$HfSi_2$–$MoSi_2$–HfB_2 ceramics; HIPIMS medium–argon	6	23,200 ± 400	2.9
ESA + MS (HIPIMS) [94]	ESA: same; HIPIMS: average power 1 kW, peak power 50 kW, peak current 50 A, frequency 1 kHz, pulse duration 50 µs		6÷12	–	5.5
ESA [59]	ESA: consistently Cu (current 0.5–0.6 A; voltage 38.5–56.1 V; capacitance 20 µF) and hard alloy VK8 (current 2.0–2.2 A; voltage 68.7 V; capacitance 300 µF)	Substrate—carbon steel with 0.45% C, alloying electrode–Cu and hard alloy VK8; plasma nitriding medium–mixture of ammonia and nitrogen	20	7600–9500	0.9
ESA + ion–plasma nitriding [59]	ESA: same; ion–plasma nitriding; temperature 520 °C, 12 h.		70	2800–5750	0.6

* ESA—electrospark alloying; AFUF—abrasive-free ultrasonic finishing; LT—laser treatment; MPM—metal–polymer material; MS—magnetron sputtering; HIPIMS—high-power impulse magnetron sputtering.

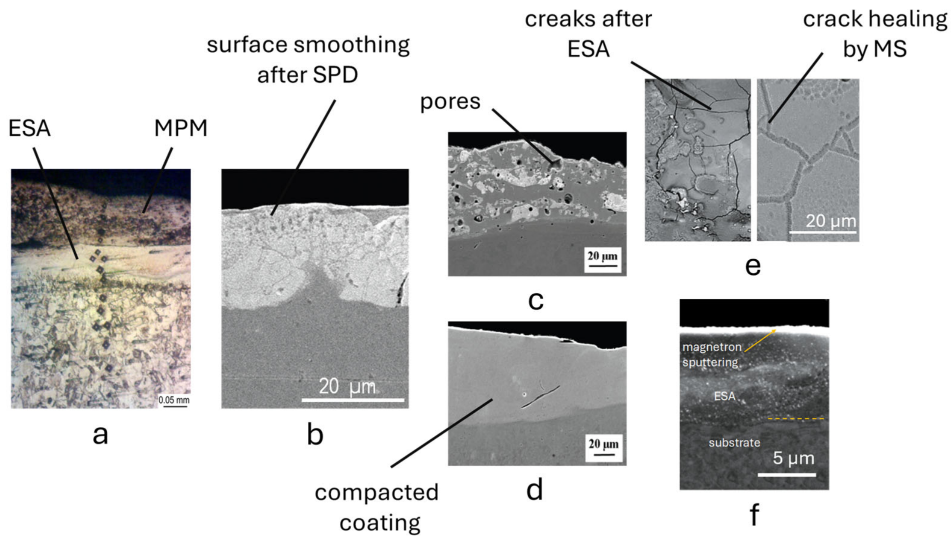


Figure 16. The effect of hybrid ESA technologies on coating morphology and microstructure: (**a**) ESA + metal–polymer material coating with imprints after microhardness testing; (**b**) ESA + surface plastic deformation coating; (**c**) ESA coating before laser treatment; (**d**) ESA + laser treatment coating; (**e**) surface of ESA + magnetron sputtering coating; (**f**) cross-section of ESA + magnetron sputtering coating.

Studies [10,59,81] have shown that applying combined metal–polymer materials followed by surface plastic deformation (SPD) significantly improves the quality of steel parts by increasing their hardness and wear resistance without significantly affecting the substrate metal. This is particularly relevant for rotating components in mechanical systems that operate under high loads and wear. Examples include the spiral and cylindrical surfaces of centrifuge screws, subject to hydroabrasive wear, and the hubs of blower blade wheels (Figure 17).

Research [14,16,17] confirms the effectiveness of ESA hybrid technologies in creating tribotechnical coatings that reduce friction and improve the service life of parts. The use of modified MoS_2-based electrospark coatings, as described in [20,42], demonstrates the potential for significantly improving antifriction properties, which is particularly beneficial for bearings and moving mechanisms in industrial equipment.

The combination of ESA technology and LT is a promising method of forming hybrid coatings that are stronger and have a longer service life. Such coatings are used on an industrial scale to protect the working surfaces of pump parts, bearings, and tool steels.

Practical results reported in references [54,65,67] indicate significant improvements in wear resistance and friction reduction in tribosystem components.

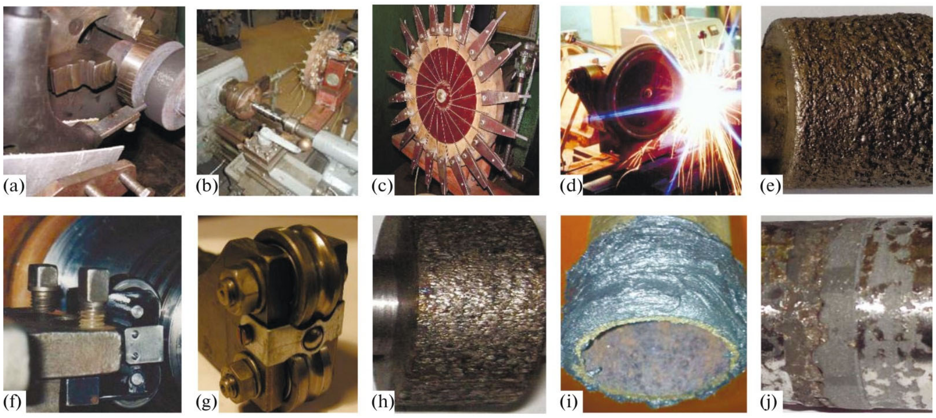
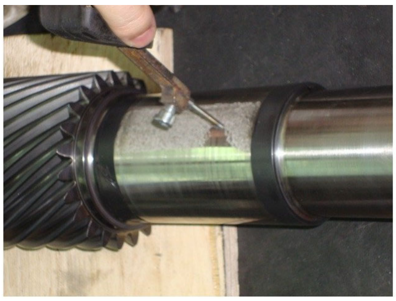
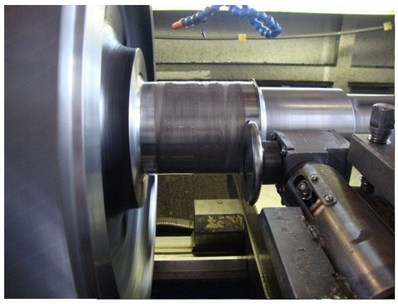


Figure 17. Formation of combined coatings on 12Kh18N10T (AISI 321) steel using the ESA method and a mechanized unit in industrial conditions: (**a**) ESA cementation (CESC), alloying electrode–graphite; (**b**) ESA alitiation, alloying electrode–aluminum; (**c**) tool to mount electrodes of hard alloy; (**d**) ESA with hard alloy T15K6; (**e**) surface of sample with CESC; (**f**) ball rolling (BR); (**g**) tool for BR; (**h**) surface of sample after BR; (**i**) surface of sample with metal–polymer material (MPM) reinforced with VK6 hard alloy; (**j**) turned surface of sample [10].

Furthermore, several studies [23,27,35,47,49–52,61,96,97] have investigated the use of hybrid ESA technologies to restore and enhance critical components in industrial equipment. These include the restoration of rotor mounting journals in screw compressor bearings [23], reinforcement of metal impulse end seals operating under high dynamic loads [27,61], refurbishment of pump components exposed to radiation environments [35], and performance improvement in slider bearings in high-speed turbine compressors [47] (Figure 18). Additionally, the application of ESA for the reconditioning of sliding-bearing bushes in tribologically demanding systems has also demonstrated substantial benefits [49–52]. These integrated surface engineering approaches can significantly improve the operational reliability of parts in industrial settings, extending their lifespan and minimizing unplanned downtime and maintenance expenses.



(**a**)



(**b**)

Figure 18. The ESA of the bearing journals of the gear shaft (**a**) and the SPD of the bearing journal of the gear wheel (**b**). The turbocompressor is a GTT-3 model manufactured by TRIZ LTD [97].

Despite the effectiveness of hybrid technologies that combine ESA with additional treatments such as laser, ion, plasma, and thermochemical processes, their implementation on a large industrial scale remains limited due to technological, economic, and organizational issues. One of the key problems is the lack of standardization of technological modes, which limits the predictability of results and the stability of coating performance under different operating conditions. Furthermore, the limited integration of ESA processes into modern automated production lines hinders the scalability of the technology for mass production. Limited research has been conducted into the formation mechanisms of hybrid structures and their long-term behavior under cyclic loading, corrosion, and radiation exposure. This is critical for the aviation, energy, and chemical industries. Similarly, insufficient modeling and digital support of ESA processes complicate the design of new coating compositions with specified properties.

Promising areas for further research include developing intelligent ESA process control systems based on machine learning and creating multifunctional nanostructured coatings that combine wear, heat, and anti-corrosion resistance. There is also interest in developing new ESA methods using new classes of materials, such as high-entropy alloys and nano- and amorphous alloys. Additionally, there is significant interest in assessing the environmental impact and economic viability of hybrid technologies compared to conventional surface modification methods.

Hybrid technologies based on ESA demonstrate significant potential for improving sustainability and reducing the negative environmental impact of industrial processes. Combining ESA with other eco-friendly methods, such as MS or PVD, reduces resource consumption and energy costs in production processes. This leads to a reduction in CO_2 and other pollutant emissions, meeting the current requirements of sustainable development and environmental safety, particularly Goals 9 (industry, innovation, and infrastructure) and 12 (responsible consumption and production), according to the 2030 Agenda for Sustainable Development.

5. Summary and Outlook

The formation of functional coatings is a highly promising approach to improving the durability, hardness, and wear resistance of machine parts and tools. Electrospark alloying (ESA) has proven to be a promising method for surface modification, offering localized treatment, minimal thermal impact, and strong adhesion of coatings. ESA enables the deposition of hard, wear-resistant layers from a wide range of conductive materials with controlled properties.

Hybrid (combined) surface treatment technologies are used to improve the quality of ESA coatings and impart specific properties to surfaces. The main combination technologies are ESA with subsequent surface treatment with concentrated energy and material flows (laser treatment, ion implantation, plasma deposition, etc.) and ESA with subsequent surface plastic deformation (SPD). The list may also include multilayer (combined) electrospark coatings, which can be used to form a surface layer with the required properties. The review highlights that such hybrid technologies significantly enhance surface properties, enabling tailored microstructures, improved adhesion, increased thickness, and reduced roughness.

Despite these advantages, the multi-parameter nature of hybrid treatments complicates process control and optimization. For instance, the combination of ESA and SPD requires further investigation into the stress–strain behavior, optimal loading conditions, and indenter geometry. ESA, followed by LT, has shown promising results, particularly in modifying surface roughness and structural uniformity in hard coatings. However, combinations involving vapor-phase deposition remain underexplored.

Another challenge is the lack of management systems that can automate hybrid ESA processes in real time. To achieve industrial scalability, it is necessary to investigate process stability and repeatability of results, as well as the possibility of integrating digital technologies. While there is currently almost no literature on the application of artificial intelligence (AI) and machine learning (ML) to hybrid ESA processes, their potential is significant. AI/ML applications can facilitate intelligent parameter selection, predict coating properties, and enable adaptive control of hybrid technologies.

Future research should focus on the following aspects:

- Quantitative optimization of hybrid treatment parameters through experimental–computational synergy;
- Development of physical–mathematical models to predict coating behavior based on process inputs;
- Application of machine learning for intelligent selection of processing modes to balance performance and coating quality;
- In-depth studies on residual stresses, adhesion strength, and long-term performance in operational conditions.

By addressing these research gaps, hybrid ESA-based technologies can be advanced into highly customizable surface engineering solutions for various industrial applications.

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