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Functional properties of coatings used in various industries

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Abstract: Modern industries are increasingly utilizing technologies based on concentrated energy flows. Technologies utilizing concentrated energy sources are primarily used for machining components made of difficult-to-machine engineering materials, as well as for manufacturing highly complex shapes that would be labor-intensive and time-consuming using traditional methods. This article examines two processing methods used to produce anti-wear coatings: electro-spark deposition (ESD) and laser cladding. By controlling electrode erosion parameters, such as current intensity or capacitor capacitance, we can shape coatings with different functional properties. By controlling laser parameters, such as power, scanning speed, and pulse duration, it is possible to create coatings with different surface properties. The paper presents these processes in the context of producing coatings for various applications, including military technology.
Keywords: coating, electro-spark deposited, laser cladding, properties

1. INTRODUCTION

By applying new engineering materials or protective coatings, it is possible to improve the functional properties of machine parts so that they are resistant to corrosion, abrasion and erosion, and possess high fatigue strength. The new materials, for instance, alloy steels, are usually costly, which is undesirable, because the higher the cost of the material, the higher the price of a finished product. However, if an element is to be subjected to high loads, then strength rather than cost is a primary factor.

Applying protective coatings to machine parts is economically justifiable if the wear is local or if the coating material is expected to display properties different from those of the substrate. Most surface layers are technological surface layers (TSLs) - they are produced before objects are used. Functional surface layers (FSLs), on the other hand, are applied during maintenance.

In the era of globalization, products and companies gain competitiveness by improving manufacturing processes and focusing on new technologies. The fact that the introduction of new products is usually accompanied by the use of new, highly durable materials leads

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to a significant increase in demand for unconventional, high-performance machining processes.
In addition to optimizing existing and applied processes, In addition to the optimization of already known and used processes, the consistent implementation of new technologies also brings results. These include beam technologies that use a concentrated energy beam, such as: laser cladding (Zhao et al., 2023), electrical discharge machining (Kamenskikh et al., 2023), electron beam treatment (Valkov et al., 2020), plasma spraying (Wang et al., 2016), HVOF spraying (Özbek et al., 2016), laser hardening treatment (Anusha et al., 2020), electro-spark deposited processing (Radek, 2023), laser alloying (Jeyaprakash et al., 2019).
The role of beam technologies is growing in the shaping of desired surface properties. These technologies are used primarily in the processing of difficult-to-machine structural materials, as well as in the production of components with very complex shapes, which would be very labor-intensive and time-consuming to manufacture using traditional methods.
Technologies that use a concentrated energy beam include, among others, electro-spark machining and laser machining. Electro-spark deposition has already undergone dynamic development and currently occupies an established position among surface treatments. Laser machining continues to experience dynamic development, also in the field of surface engineering. The above-mentioned technologies meet the requirements of industry.
A characteristic feature of beam technologies is that materials are processed as a result of the impact of a concentrated energy beam. By controlling the energy beam, we can process selected areas of the workpiece. The diameter of the energy beam spot varies from a fraction of a nanometer to several dozen centimeters. This depends on the basic physical phenomenon occurring in a given technology. The smallest impact field is characteristic of methods involving an electron beam or a laser beam. The energy beams used here can be focused and controlled by optical or magnetic lens systems or mirrors, and the size of the spot at the focus depends only on the wavelength of the electron or laser radiation.
The paper presents the technology of coating production by electro-spark deposition and laser cladding, as well as their selected functional properties. It was found that coatings applied using the above-mentioned technologies can be successfully used in various industries, including military applications.

2. ESD PROCESSING

The possibility of using electro-spark coatings in various industries is quite interesting. One example is the method of producing and repairing zinc surface layers using electrical discharges to treat metal objects. Zinc coatings can be applied or used to repair zinc layers on components and equipment used, among other things, in military applications (Fig. 1).

Fig. 1. Drive wheel mounting bolts (Leopard 2PL tank)

The studies analyzed the microstructure, chemical composition, surface roughness, and corrosion resistance of the applied surface layers. An MHD alloy (Zn with Ni and Al additives) was used for electro-spark alloying, from which an electrode was made, matching the shape and dimensions of the EIL-8A device holder. The parameters of the electro-spark treatment were as follows: capacitor capacity C = 150 μF, current intensity I = 0.7 A, voltage U = 230 V, exposure time τ = 2 min/cm^2. The substrate material was C45 steel. Analysis of the microstructure using a Joel JSM-5400 scanning electron microscope showed that the thickness of the coatings obtained ranged from 15 to 35 μm (Fig. 2). When using higher magnifications, closed pores were discovered in the coating. A linear analysis perpendicular to the surface proved the linear distribution of Fe and Zn elements, which are key to the proper functioning of the coating. The course of the element distribution line indicates a small diffusion layer range.

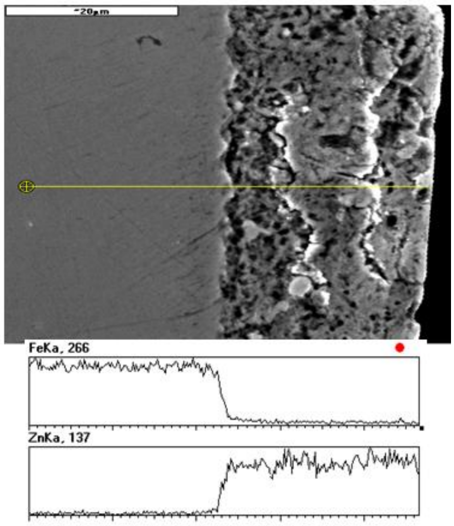

Fig. 2. Microstructure and linear distribution of elements in zinc coatings

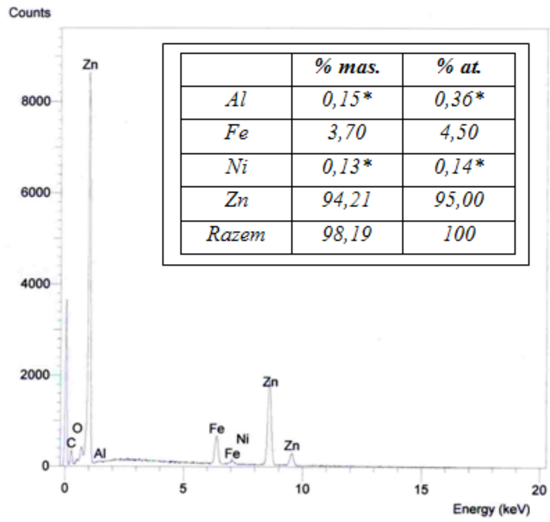

Fig. 3. X-ray spectrum of the zinc layer and approximate analysis of chemical composition

As a result of spot analyses of the chemical composition (EDS) at various points on the coating, it was determined that it consisted of 94-97% zinc and the remainder iron (Fig. 3). No aluminum was observed, which was present in a certain amount in the applied

MHD alloy. This fact can be explained by the very rapid oxidation of Al during the application of the coating, due to the prevailing conditions (lack of gas shielding). Light elements with a high affinity for oxygen are removed from the surface of the electrode material almost immediately. The Ni content was also negligible (very low content in the alloy before application, practically trace amounts in the applied layer).
The tests also showed that the use of protective gas (argon) during the application of zinc coatings using the ESD method reduces roughness and increases the corrosion resistance of the surface layers produced. Corrosion resistance tests were carried out using the potentiodynamic method, which is currently one of the most widespread and modern electrochemical tests. Samples with zinc coatings applied by electrosparking under ambient conditions and in an argon atmosphere were tested, as well as a sample cut from hot-dip galvanized sheet metal. Cathodic and anodic polarization curves were obtained by polarizing the samples at a potential change rate of 0.2 mV/s (in the range of ±200 mV from the corrosion potential) and 0.4 mV/s in the range of higher potentials. Samples with a separated area of 10 mm diameter were polarized to a potential of 500 mV. The polarization curves were obtained after 24 hours of exposure in the tested solution (3.5% NaCl) in order to establish the corrosion potential. The tests were performed at room temperature of 21°C ±1°C. The obtained corrosion resistance results are presented in the graph (Fig. 4).

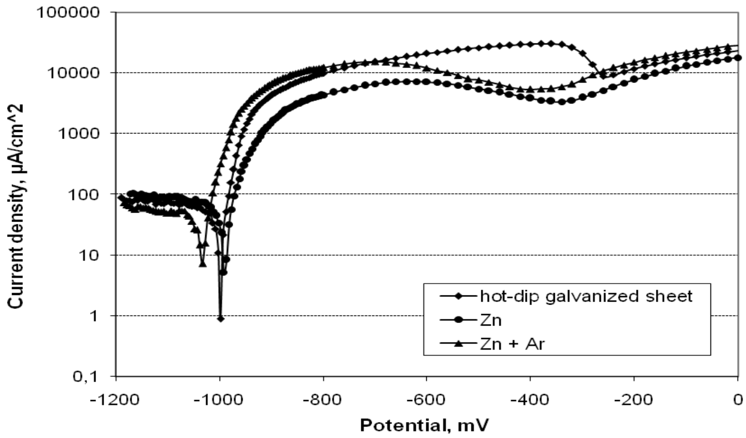

Fig. 4. Polarization curves of the tested materials

The highest corrosion resistance was demonstrated by the zinc coating applied in an argon atmosphere, with a corrosion current density of 64 μA/cm^2. The zinc coating applied in the ambient atmosphere had an I_{kor} = 98 μA/cm^2, while the hot-dip galvanized sheet samples had a corrosion current density of 76 μA/cm^2. The corrosion resistance results obtained for electro-spark applied coatings were influenced by their roughness. Zinc coatings applied in an argon atmosphere had a roughness of Ra = 4.51-6.86 μm, while zinc coatings applied in the ambient atmosphere had a roughness ranging from 8.50 to 11.90 μm. It was found that by controlling the process parameters, it will be possible to obtain surface layers with thicknesses of around 100 μm, which will allow the ESD method to be used as a standalone method of zinc coating. In combination with robotic processing, this will be a method of protecting elements, e.g., with complex shapes and at the same time made of materials that cause significant difficulties in hot-dip galvanizing (e.g., the Sandelin effect).

3. LASER CLADDING

Laser cladding involves melting additional material in the form of powder (LMD) or wire (WLMD) with the appropriate gas shield using laser radiation energy, while simultaneously melting the base material. These materials are mixed and melted together to form a surface layer on the clad substrate, known as the cladding layer. Due to low thermal impact on the substrate material, flexibility, laser cladding is widely used for surface modification, repair, and regeneration of high-value components in automotive, aerospace, and tooling applications. High potential application especially for branches, where surface with specific properties is required. The laser cladding process is used to deposit a high-alloy (thermal, corrosion or wear resistant) material on surface of low alloy steel and upgrade those properties.

WLMD – Wire Laser Metal Deposition it is a cladding process, where heat source in form of laser beam is used to melt additional material on surface of the substrate creating complete metallographic fusion. Compare to LMD method with metal powder deposition, required higher laser power (for CO_2 laser keyhole effect is required, therefore, surface power density exceed $2 \cdot 10^6$ W/cm^2), in effect high mixing with substrate can be observed. Moreover, higher energy affect in higher thermal stress-strain in material. The most advantages over LMD, there are no problem in obtaining 100% density of base material (no porosity – gas concave, and no problem with not complete melting of metal powder particles like in LMD). Properties are result of mixing cladded material with substrate (with dominate properties of cladded material, however in first layers diffusion of elements like iron and carbon is clear visible), therefore, similar substrate and claddedd material is recommended, or buffer layers). Laser power 4 kW, speed of process head movement 1.5 m/min, shielding gas helium 15 l/min, focal length 270 mm, focal point 0.3 mm set on surface of material, wire feed rateb1.5 m/min (similar to cladding speed). Laser cladding was performed using 307L welding wire (diameter ø1 mm) on a substrate made of S355J2 structural steel (thickness 25 mm). Figure 5 shows the process head and the substrate material prepared for the cladding process and the effects of multi-layer cladding in the form of an SEM image showing the boundaries of the cladding layers on a cross-section of a metallographic sample.

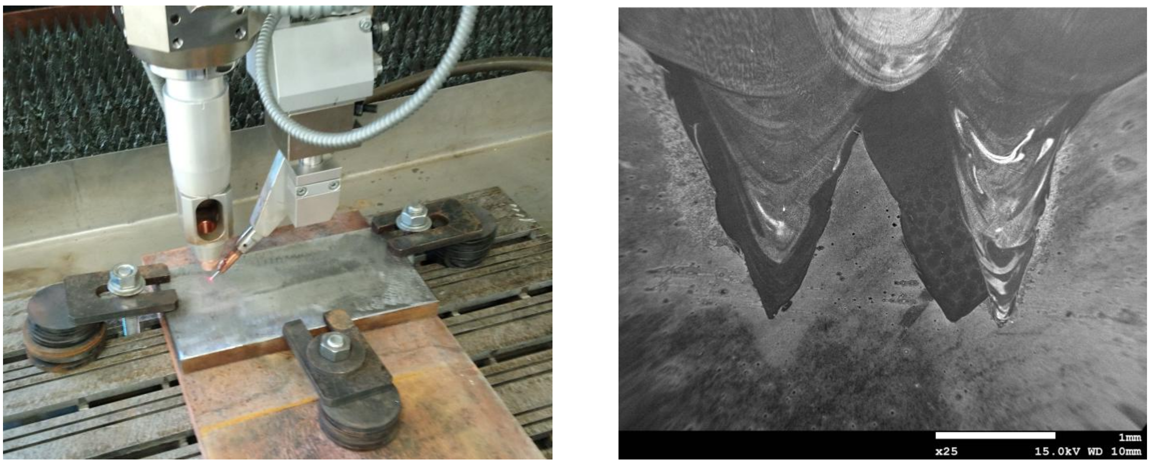

Fig. 5. Laser cladding process using wire (left) and SEM image of clad layers on a cross-section (right)

LMD – Laser Metal Deposition, laser cladding method using laser beam to melt metal powder on substrate surface and by obtaining temperature of molten additional material higher that melting point of substrate, substrate surface start melt and creating metallurgical bound with both substrate and cladded material. Low surface power density affect in comparing to WLMD, low thermal stress-strain, low mixing factor between cladded material and substrate, resulting in properties of cladded material are strongly related to properties of cladded material starting from first layer, some iron and carbon diffusion visible in first layer. Limitation of this method is obtaining material density, due to problem of complete melting of deposited material (partial powder particles stay not melted or not completely melted, often trap in gas concave, related to trap of inert gas transporting metal powder to deposition area). Figure 6 shows the application of the coating by laser cladding using powder and the effects of cladding in the form of an SEM image showing the resulting weld bead on a metallographic sample cross-section.

Fig. 6. Laser cladding process using powder (left) and SEM image of clad layers on a cross-section (right)

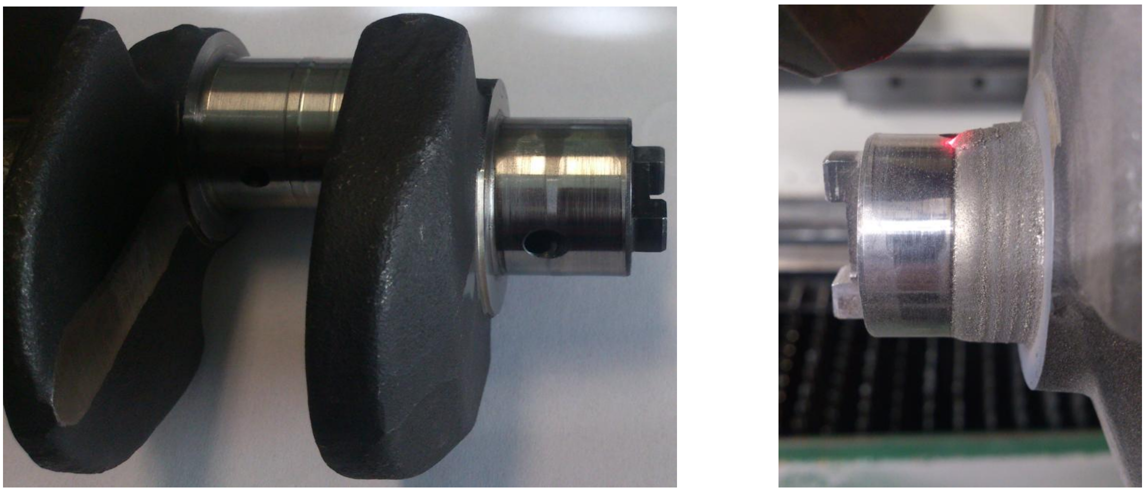

Fig. 7. Surface of a worn crankshaft (left) and laser cladding process of a worn crankpin (right)

Figure 7 shows an example of the application of the LMD method for the regeneration of a worn crankshaft surface, view of mechanical wear and cladding process fifth layer, overlapping 50%, laser power 2.3 kW, linear cladding speed 1.2 m/min, shielding gas Argon 10 l/min, powder transport Gas Helium 6 l/min. Focal length 256 mm, focal point related to clad layer width, in this case equal to 2 mm.

Figure 8 shows the microstructure and linear distribution of elements in the layer laser-deposited using the LMD and WLMD methods. Clearly uniform Cr and Ni distribution in both cases confirm high mix ratio, and uniform composition. Slightly elevated iron in WLMD indicates higher diffusion between substrate and deposited layers. Both deposition method provide layers with uniform composition, main differences can be observed in dendrites grow orientation, suggesting differences in solidification.

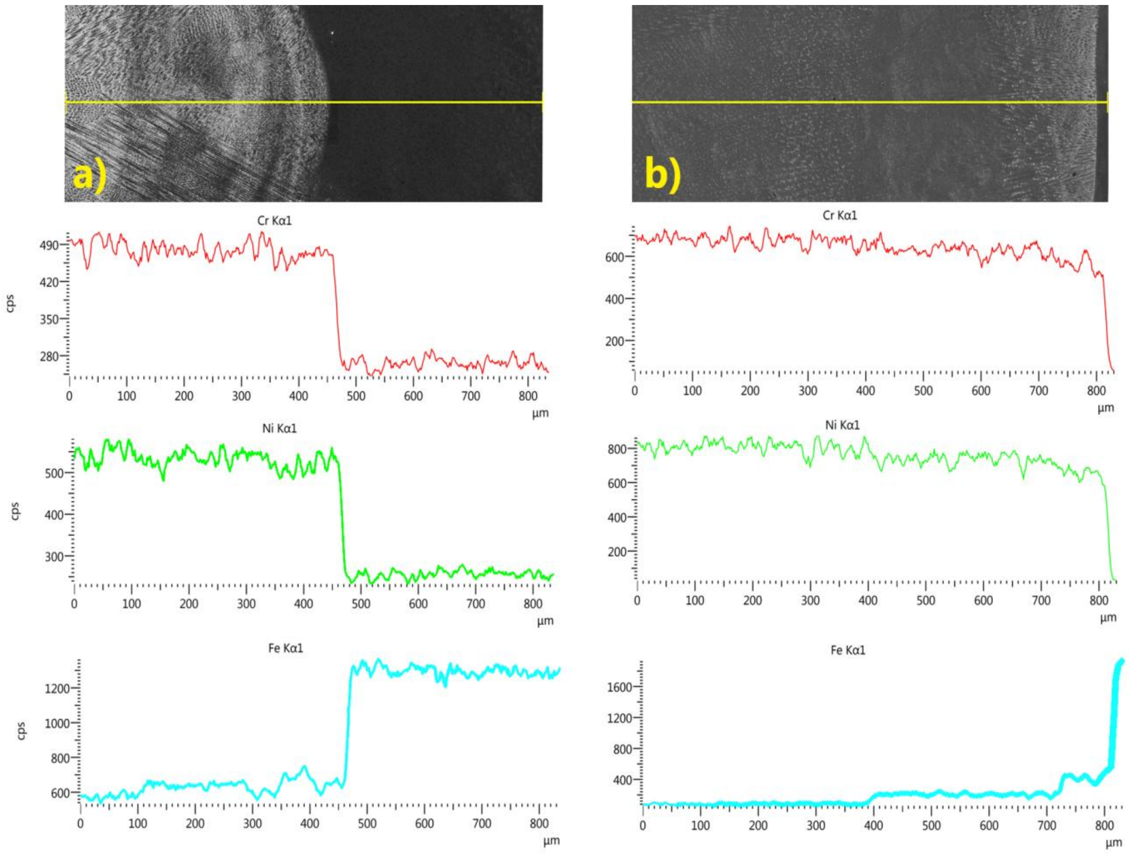

Fig. 8. Cr, Ni and Fe distribution from deposited material to substrate in cross section for laser cladding of 307L steel on structural steel substrate using: a) WLMD, b) LMD method

4. SOCIAL, ENVIRONMENTAL AND TECHNOLOGICAL IMPACT

The development of advanced surface engineering techniques, specifically electro-spark deposition and laser cladding, is deeply integrated into the broader context of modern technical progress and its impact on the socio-technical environment.

The primary technological benefit of enhancing the wear resistance of machine components is the extension of their operational lifecycle, which directly supports the reliability and efficiency of industrial systems. Research into the mechanical behavior of advanced material structures, such as auxetic cellular materials and the influence of structural defects on their strength, highlights the importance of precise material selection and surface integrity in preventing premature failures. Furthermore, the use of non-contact measurement methods for analyzing parametric vibrations and the study of wave dispersion in periodic half-spaces underscore the necessity of advanced diagnostic tools in optimizing the performance of mechanical systems protected by modern coatings (Doliński et al., 2025; Janus & Marschalko, 2026; Czerwiński, 2026). Moreover, the reliability of technical facilities enhanced by advanced coatings has a direct impact on system safety and human-technical environment interactions. Enhancing the functional properties of critical components minimizes the risk of sudden failures, thereby increasing the safety of operators and the general public (Pacana et al., 2026).

From an environmental and sustainability perspective, the application of durable WC-Co coatings aligns with the global drive toward reducing industrial emissions and optimizing resource management. The development of low-emission insulating materials and the implementation of strategies for particle emission prevention reflect a growing commitment to minimizing the environmental footprint of engineering activities (Izdebska-Mucha et al., 2025; Przybek et al., 2025). Moreover, addressing hydrocarbon pollution in technical environments and promoting sustainable ecotourism through better community resource management are parts of a holistic approach where technical durability and environmental protection must coexist (Honkisz & Bielaczyc, 2025).

The social and safety-related dimensions of technical progress are equally critical. Enhancing the surface properties of critical infrastructure elements, such as railway track foundations (Kozioł & Pilecki, 2025) or geological mining workings (Maj, 2025), is essential for public safety. This is complemented by the analysis of structural stability in civil engineering, such as gabion retaining walls (Grodecki, 2025) or shallow footing settlements (Truty & Obrzud, 2025), where the reliability of every component is paramount.

The socio-cultural dimension of engineering manifests in the creation and preservation of spaces that define communal life. The physical reliability of technical solutions – such as those discussed in this study – is a fundamental prerequisite for maintaining the integrity of facilities that foster social identity and provide a medium for cultural or sacred experiences (Sowa & Gosztyła, 2026). The stability of the technical environment, enhanced by advanced material science, ensures that public spaces in evolving urban structures can safely fulfill their social functions (Raś-Grabowy, 2025). Furthermore, the synergy between technical precision and humanistic perception, often initiated during the educational process of visual encounter and drawing, highlights that every technological innovation ultimately serves to create a more resilient and meaningful human environment (Sedelies, 2025).

Finally, the impact of industrial technologies extends into the cultural and social sphere. The adaptive reuse of industrial heritage (Łakomy & Tang, 2025) and the preservation of historical urban fabric (Łakomy, 2025; Martyka & Mikrut-Kusy, 2025) demonstrate that technological progress should respect historical context. Modern engineering not only shapes the physical mobility nodes like railway stations (Janda, 2026) but also influences social identity and the human-centric perception of public spaces. Thus, the durability provided by advanced coatings is a fundamental technical requirement that supports the preservation of both modern and historical technical environments.

5. CONCLUSION

Coatings produced using a concentrated energy stream are modern layering techniques that provide exceptional hardness, wear and corrosion resistance, and precise thickness control. Due to their properties, they have found applications in numerous industries. The modern economy must also be open to innovative approaches in surface engineering technologies, including electro-spark deposition and laser cladding.

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