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CORROSION PROTECTION STRATEGIES FOR IMPROVING THE PERFORMANCE OF ELASTIC METAL PARTS IN THE AUTOMOTIVE INDUSTRY

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***Abstract:** Elastic metal elements are essential to vehicle safety, durability, and performance, yet their continuous exposure to dynamic loads and harsh environments makes them highly susceptible to corrosion. While corrosion resistance can be addressed through material selection at the design stage, practical and economic constraints often necessitate the use of protective surface treatments. This review summarises current strategies for improving the corrosion resistance and functional performance of automotive elastic components, comparing key coating technologies—such as phosphating, electrochemical oxidation, galvanising, and organic coatings—and highlighting their respective benefits and limitations under service conditions.*

***Keywords:** corrosion protection, elastic metal elements, automotive industry, surface treatment, material resistance, protective coatings*

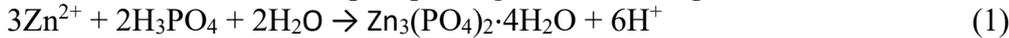
INTRODUCTION

Surface treatment is vital for the design and durability of automotive springs, directly affecting their performance and lifespan. Thermal and surface treatments are widely used in automotive manufacturing to enhance material properties. A recurring defect was observed where springs spontaneously fell out during assembly. Visual inspection revealed reduced plasticity, deformation, and possible thermal treatment issues. Causes included varying manufacturing tools and technologies, different subcontractors for surface treatment, and poor corrosion protection. Measurements and microscopic analysis confirmed that inconsistent surface treatment compromised spring function, leading to improved design and plans to select better corrosion protection methods.

Corrosion poses a major challenge in the automotive industry, causing loss of strength, elasticity, and performance, particularly in elastic parts like springs and clamps exposed to dynamic loads and harsh environments [1]. Protection choice depends on environment, mechanical stresses, service life, and application [1,2]. Humidity, temperature changes, and chemicals accelerate corrosion, while cyclic loads promote corrosion fatigue and crack growth [3,4]. This requires multifunctional protective systems with strong adhesion and deformation resistance, supporting economic and environmental sustainability [5–8]. Corrosion results in serious economic, safety, and environmental impacts, highlighting the need for effective anti-corrosion strategies [9,10]. Surface treatments and coatings serve as barriers against oxygen, moisture, and salts [11–13], playing a key role in minimising metal damage [14]. Understanding coating types and protection mechanisms is crucial for corrosion management [15]. This review focuses on identifying cost-effective corrosion protection methods suitable for automotive parts and assessing their benefits and limitations.

1. Phosphating

Phosphating is a surface treatment that forms phosphate conversion coatings to enhance corrosion resistance, wear resistance, and adhesion of organic coatings. It creates an insoluble layer of phosphate crystals on the metal, acting as a corrosion barrier and providing a textured surface that improves coating adhesion. The process involves a chemical reaction between the metal and a phosphate solution containing phosphoric acid and zinc, manganese, or iron salts [15]. This reaction produces insoluble phosphate compounds that deposit as a microcrystalline layer. The typical chemical reaction for zinc phosphating is shown in equation 1:



Phosphate coatings provide corrosion resistance and a barrier against the spread of corrosion processes. The technological process for forming iron phosphate coatings is much simpler and requires significantly less equipment than forming zinc phosphate coatings, and wastewater treatment is also simple [13]. When iron phosphate coatings are combined with organic coatings, good corrosion protection of steel can be achieved.

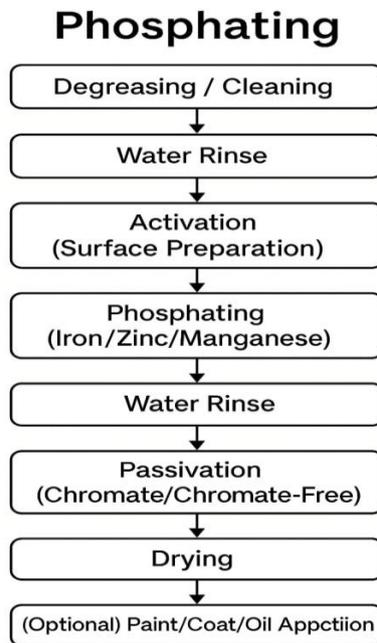


Fig. 1. A diagram presenting the process sequence of the phosphating technique

Figure 1 illustrates the main stages of the phosphating process, which include surface preparation, phosphating, and drying. Proper surface preparation is crucial because any remaining oxides or grease cause uneven phosphate layers. This step also activates the metal surface to ensure a uniform conversion coating [10]. Phosphate deposition can be done by immersion or spraying, depending on the solution type and part geometry [15,16]. Spraying is faster, but immersion typically produces coatings with better corrosion resistance and adhesion. Immersion times range from 1 to 90 minutes, with bath temperatures between 20 and 99 °C; however, optimal coating quality and speed are achieved at 30–60 °C [5,7].

Zinc phosphating involves treating steel surfaces with zinc salt solutions to form a thin (5–15 μm), porous crystalline zinc phosphate layer [5,6,7]. This coating serves mainly as a pre-treatment that enhances paint and polymer adhesion, improves wear resistance and lubricity. The process requires careful surface preparation—degreasing, pickling, and rinsing—followed by immersion in a controlled phosphating bath (50–90°C) containing zinc salts, phosphoric acid, and accelerators. Post-treatment rinsing and sealing or oil application further improve corrosion resistance and lubrication.

Zinc phosphating is a cost-effective, low-impact surface treatment widely used in automotive,

machinery, and metal fabrication industries due to its simple application, strong adhesion, and compatibility with various coatings. It enhances wear properties and improves adhesion of subsequent layers like paint or oil, with good control over coating parameters. However, the phosphate layer alone provides limited corrosion protection and mechanical strength, requiring strict surface cleanliness and precise control of pH, temperature, and reagent concentrations. The process also generates wastewater containing heavy metals and phosphates that need specialised treatment. Despite these environmental and performance limitations, zinc phosphating remains a reliable and popular pre-treatment method, balancing cost, functionality, and industrial applicability.

2. Electrochemical oxidation

Electrochemical oxidation is a process in which steels, as well as other metals - most often aluminium, titanium, magnesium and their alloys - undergo chemical oxidation by means of an electric current passing through an electrolyte solution [17]. The process is widely used to improve the mechanical and chemical properties of metals by forming a protective oxide layer on the surface. This layer provides a significant increase in the resistance of the metal to corrosion, wear, and mechanical damage, as well as the possibility of decorative treatments that extend the service life of the treated components. The electrochemical oxidation process involves redox reactions that occur when a constant electric current is applied to a metal in an electrolytic bath. In this process, the metal acts as an anode, and the electrolyte (most often composed of acids or salts) serves as a conductor of ions. As a result of electrolysis, an oxide layer is formed on the metal surface, which is porous at first and provides protection for the metal against external aggressive factors. The processing steps of the electrochemical oxidation are described in Figure 2.

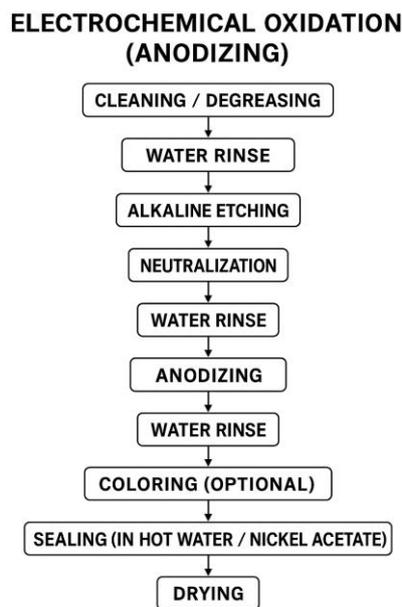


Figure 2. A diagram presenting the process sequence of the electrochemical oxidation

Electrochemical oxidation is carried out in different electrolytes, including sulfuric acid (industrial standard for controlled porous layers), chromic acid (for higher corrosion resistance or thicker oxides), and phosphoric acid (for larger pores and improved adhesion). Oxide formation proceeds through three stages [13]: initiation (formation of the primary oxide), growth (thickening, pore development, and structural stabilisation), and passivation (the layer reaches a protective thickness that limits further dissolution). The process is strongly influenced by electrolyte composition, current density, temperature, and time: alkaline electrolytes promote hydroxide formation, saline media accelerate dissolution, higher currents increase growth rate but also porosity,

and elevated temperature or longer oxidation increases layer thickness while potentially reducing compactness.

The resulting oxide films are chemically stable, wear-resistant, and suitable for aggressive environments [18]. Electrochemical oxidation is widely used in automotive, aerospace, construction, and medical industries, and the porous structure enables dyeing or application of organic/metallic coatings for added functionality. Hard-anodized layers offer significantly increased microhardness, making them suitable for components under friction or abrasive load. Process parameters (temperature, current density, electrolyte composition) allow precise control of oxide thickness and structure. However, the method has limitations, including sensitivity to surface preparation, limited toughness of the oxide film, high energy demand and process complexity, environmental and safety constraints, and material-specific applicability.

3. Galvanising

Galvanising is one of the most widely used processes for protecting metal products from corrosion, especially in the construction, automotive and manufacturing industries. The main purpose of galvanising is to provide steel and iron components with long-lasting protection against rust and wear by using a layer of zinc that is applied to the metal surface [19]. Zinc is a sacrificial victim — it reacts more easily with oxygen and moisture than the metal, protecting the base material through its oxidation. Galvanising can be done by different methods depending on the requirements of the application and the type of material. The processing steps of the hot-dip and electrolytic galvanising process are described in Figure 3.

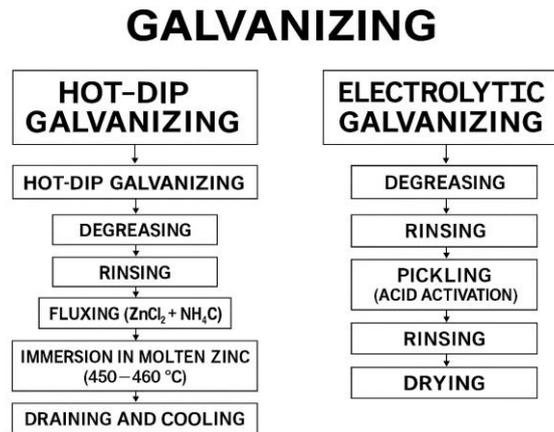


Figure 3. A diagram presenting the process sequence of the hot-dip and electrolytic galvanising process

The main galvanising methods include electrolytic, hot-dip, and mechanical galvanising [20]. *Electrolytic galvanising* deposits a 5–25 µm zinc layer from acidic or alkaline zinc electrolytes, providing both barrier and sacrificial protection; pulse plating improves density while electroless zinc enables coating of complex shapes. Its key advantages are low cost, good corrosion protection, and precise thickness control, though it is sensitive to surface preparation, limited in thickness, and involves environmentally demanding electrolytes. *Hot-dip galvanising* immerses steel in molten zinc at about 450 °C, forming thick (up to >100 µm), metallurgically bonded intermetallic layers that offer long-term corrosion and abrasion resistance. It ensures full coverage and low maintenance but may alter part dimensions, produce a rougher finish, and cannot be used on heat-sensitive materials. *Mechanical galvanising* deposits zinc by mechanical impact—through cold spraying, particle impaction, or friction-based methods—making it suitable for temperature-sensitive components and environmentally restrictive applications, though coating uniformity, thickness control, and coverage of complex geometries are limited. Overall, each method provides reliable

corrosion protection but differs in coating thickness, durability, environmental impact, and applicability depending on material and component design.

Galvanising is an effective and cost-effective process for protecting metals from corrosion and mechanical damage. Galvanising methods provide different advantages depending on the specific requirements of the application. The process has its limitations, such as the possibility of degradation at high temperatures and environmental restrictions.

4. Cold spray coating

Cold spray coating is a solid-state deposition technique that relies on the kinetic energy of high-velocity particles—commonly plastics—accelerated by gases such as helium or nitrogen to impact and bond onto substrates without the use of heat [21,22,23]. The process efficiency depends on factors like particle size, target temperature, and material properties. During coating, powdered materials are fed into a high-speed gas stream, and upon impact, the particles deform and mechanically bond to the substrate surface. Cold spray is simpler and less expensive than conventional thermal spraying methods, but it operates within a limited range of materials and conditions.

Electrostatic powder coating is a dry finishing process where finely ground polymer powders are electrostatically charged and sprayed onto conductive substrates, followed by thermal curing to form a continuous, durable film. This technique is widely used in industries such as automotive, appliances, construction, and industrial manufacturing due to its high transfer efficiency, environmental safety (no VOC emissions), and excellent mechanical and chemical resistance. The process involves thorough surface preparation—such as degreasing, mechanical or chemical treatment to enhance adhesion—and precise control of powder charging, deposition, and curing parameters to ensure uniform coating thickness and optimal film properties [16,18]. The processing steps of the cold spray process are described in Figure 4.

COLD SPRAY COATING

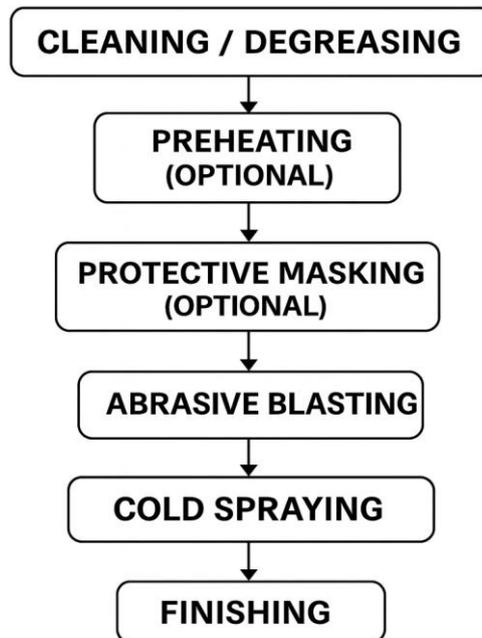


Figure 4. A diagram presenting the process sequence of the cold spray process.

Advantages of electrostatic powder coating include its cost-effectiveness, reduced material waste, strong corrosion and abrasion resistance, and the ability to produce smooth, uniform, and

aesthetically appealing finishes. Its limitations include the requirement for conductive substrates (or pre-treatment for non-conductive ones), challenges in coating complex geometries or shadowed areas, sensitivity to curing conditions, and relatively high initial equipment costs.

Overall, cold spray coating offers an economical, low-thermal-impact method for depositing materials on temperature-sensitive substrates, while electrostatic powder coating provides a versatile, environmentally friendly finishing option with superior durability and aesthetic qualities. Both methods are valuable in modern industrial surface engineering for protective and decorative applications.

CONCLUSION

This review explored corrosion protection coatings, highlighting their definition, economic and environmental impacts, and critical role in preventing damage. These coatings act as barriers, protecting substrates through various mechanisms. We discussed different coating types and how surface engineering enhances their adhesion, wear, and corrosion resistance. Performance testing remains essential to assess coating effectiveness. Advances in materials and technologies are enabling multifunctional coatings that go beyond corrosion prevention. Continued research, innovation, and collaboration are vital to meet evolving industrial demands and promote sustainable, long-lasting protection across sectors.

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