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Editorial

Corrosion and Anticorrosion of Alloys/Metals: The Important Global Issue

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Most metal materials commonly used in engineering corrode in atmospheric conditions. The physicochemical and electrochemical interactions of the material with the surrounding environment lead to the gradual destruction of the products, until the complete loss of their mechanical and functional properties. The destructive effect of corrosion has a direct impact on durability, but also on the safety of used products, devices and structures. Corrosion, both in economic and social terms, is an extremely important problem for the economy of all countries. Economic losses are directly related to the need to replace damaged structures, machines, devices or their components, to use expensive corrosion-resistant materials, anticorrosion protection, and indirectly through interruptions in production caused by the need to replace parts or repair damage.

The National Association of Corrosion Engineers (NACE International), the world's largest corrosion association and a world leader in anticorrosion protection, in a report published in 2016 [1], estimates global losses caused by corrosion at 2.5 trillion USD per year, which constitutes 3.4% of the global Gross Domestic Product (GDP) in 2013 [2]. The NACE International report specifies corrosion losses in the world's largest economies at 2.7% of GDP for the United States, 3.8% of GDP for the European Union, including Switzerland and Norway, 4.2% of GDP for India, 5% of GDP for Arab countries, 4.2% of GDP for China, 4% of GDP for Russia and 1% of GDP for Japan. NACE International indicates that with the appropriate use of currently available corrosion control methods, the cost of corrosion losses can be reduced by 15%–35%, which gives a global value of USD 375–875 trillion per year [3].

The data presented by NACE International justify the need to use the best available corrosion protection systems that combine long-term durability and low operating costs. There is also a need to conduct research on the development of new and more durable anticorrosion protection and on expanding the area of their application. Corrosion and the directly related anticorrosion are, therefore, important global problems that affect all metal materials used in various industries, infrastructure, civil engineering, transport, biomedicine, etc.

The reduction in corrosion losses is influenced not only by the appropriate design of the structure itself, but also by the proper selection, execution and operation of the protective coating. When choosing anticorrosion protection in the cost analysis, its durability and the related costs of coating renovation should be taken into account. As shown on the example of a bridge structure protected with a paint coating, the cost of coating a new structure in the production plant is only 1/3 of the cost of coating renovation in operating conditions [4]. Economic protection should, therefore, be characterized by optimal durability under specific operating conditions at the lowest possible renovation costs.

The growing population and technological development cause a continuous increase in the consumption of base metals, which are characterized by low corrosion resistance. For corrosion and anticorrosion of alloys/metals, the steel/zinc metal material pair is by far the most important.

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Steel is the most widely used material in the world due to its versatility, low cost and good strength properties. Carbon steel products are widely used in the automotive industry, infrastructure and construction. It is a material that determines the development of industry and society at large, and its production is constantly growing. At the same time, carbon steel in the conditions of operation in the atmospheric environment shows low resistance to corrosion [5]. Therefore, the use of steel makes it necessary to properly protect the steel product against corrosion.

Zinc is the most important metal used in anticorrosion protection of steel. Zinc is a metal with a relatively low electrochemical potential ($E^{\circ}(Zn^{2+}/Zn) = -0.761$ V [6]) and a high tendency to corrosion [7]. However, in most environments, the corrosion rate of zinc is low because its surface is quickly covered with corrosion products that inhibit further corrosion [8]. Zinc coatings are currently the most effective way to protect the steel surface against corrosion. They act as a barrier, preventing oxygen and moisture from reaching the steel surface. However, the electrode potential of the joined metals: iron and zinc ($E^{\circ}(Fe^{2+}/Fe) = -0.447$ V; vs. SHE [6]) is decisive for the effect of corrosion. The contact of two metals with different electrode potential leads to the formation of corrosion cells. Under such conditions, the zinc coating is an anode providing sacrificial protection to the steel surface. These properties mean that zinc coatings are willingly used for anticorrosion protection not only of carbon steels, but also of high-strength steels after heat treatment [9], cast iron [10], as well as wires intended for high-speed drawing [11]. The ability of zinc to protect steel is also used in other anticorrosion techniques, such as cathodic protection of steel objects (pipelines, ship hulls) in the ground and in sea water. The dissemination of European standards regarding the requirements for the use of electrochemical anticorrosion systems has resulted in increased interest in the use of zinc anodes (protectors) for this purpose in recent years [12].

Anticorrosive zinc coatings are applied to steel surfaces by various methods such as electroplating, mechanical plating, sherardizing, thermal spraying, as well as painting with zinc-rich coatings. However, the hot dip galvanizing process is by far the most commonly used. Hot dip galvanizing coatings are characterized by good corrosion resistance, and their durability in medium-aggressive environments ranges from several dozen to even 100 years [13]. The zinc coating obtained by the hot dip galvanizing method allows for safe and efficient functioning of steel structures for many years while maintaining the lowest operating costs of the coating. It is estimated that the cost of producing 1 m^2 of a protective system based on a high-zinc primer and polyurethane paint is 1.6 times higher than the cost of producing 1 m^2 of hot-dip zinc coating. However, the annual operating costs in this case are already 5 times higher for this protection system compared to the hot-dip zinc coating [14].

The galvanizing process has been used to protect steel against corrosion for over 150 years (French patent S. Sorel from 1836). However, over the last few decades, there has been a steady increase in the demand for galvanized products. In 1960, the galvanizing industry consumed 32% of global zinc production, while in 2022 this consumption is estimated at 50%. In addition, the world production of zinc increased from 6.8 million tons in 1960 to over 13 million tons in 2021 [15]. According to statistics, in 2019, over 8.1 million tons of structural steel were galvanized in Europe [16], which means an increase in production by over 20% in the last decade (6.6 million tons of steel in 2011 [17]). In North America, 4.9 million tons of steel were galvanized in 2019, and production increased by approx. 10% compared to 2014 [18]. However, China is currently the largest producer of galvanized steel in the world, where approximately 44 million tons of steel were galvanized in 2017 [19]. Statistics show that the amount of galvanized steel in China has been growing exponentially over the last few decades.

A separate group of products are galvanized steel sheets commonly used in the construction and automotive industry, coated with zinc using the continuous method developed by T. Semdzimir. The first galvanizing plant for continuous galvanizing of sheets was launched in Poland in 1933 [20], and the technology of continuous galvanizing of sheets was patented by the inventor in 1937. The International Lead and Zinc Study Group (ILZSG) states in its 2017 report that there are over 500 continuous sheet metallization lines, of which over 130 are located in Europe [1]. The continuous method of galvanizing sheets is the most efficient and economical technique for producing anticorrosion protection on steel.

Zinc plays a very important role in corrosion protection. However, its natural resources are limited. Total global zinc resources are currently estimated to be around 250 million tons. Due to the relatively high demand for this metal and the constantly growing consumption, especially in anticorrosion protection, global reserves are able to cover the demand only for the next 17 years [21]. This requires rational management of the available zinc resources and continuous research into the development of new and more effective anticorrosion protections obtained by an equally economical method, which is hot-dip galvanizing.

Already in the 1980s, coatings obtained on sheets using the continuous method in Zn-Al baths were developed and implemented for production; e.g., Galfan (ZnAl5RE0.1-0.3) [22,23] and Lavegal (ZnAl30Mg0.2Si0.2) [24]. Long-term corrosion tests have shown that these coatings show 2–4 times higher corrosion resistance than traditional hot-dip galvanizing coatings [25]. The increase in corrosion resistance allows for a reduction in the thickness of the coating, which leads to lower consumption of zinc. An important economic aspect is also associated with the fact that part of the zinc in the bath is replaced by cheaper aluminum, and at the same time, the introduction of a metal with a lower specific gravity into the coating reduces the weight of the coating material to create a coating of the same thickness. In the last two decades, the interest in Mg as an additive to Zn-Al baths has increased significantly. This led to the development of many new bath compositions, which have been used for the production of coatings on sheets using the continuous method for several years. In Japan, the following coatings are produced on an industrial scale: SuperDyma (Zn-11Al-3Mg-0.2Si) [26] and ZAM (Zn-6Al-3Mg) [27]. In Europe, the MagiZincTM (Zn, 1%–2% Mg, 1%–2% Al) process is being developed [28], as well as Magnelis (Zn-3.5% Al-3% Mg) [29]. Magnesium additionally increases the corrosion resistance of the coatings [30], and additionally, reduces the weight of the coating and the consumption of zinc.

In recent years, the subject of the production of ZnAlMg coatings is still very topical, as evidenced by numerous publications on the microstructure [31], properties [32] and improvement of coating properties [33]. However, these coatings are produced continuously only on steel sheets. Their favorable properties encourage work on the development of the technology for producing ZnAlMg coatings on steel structures by the batch hot-dip method. The main limitation of their application is the lack of a suitable flux [34–36], excessive dissolution of iron in the bath [37] and the formation of a periodic layered structure [38]. Recent studies, however, show that it is possible to produce these coatings by the batch hot-dip method [39], and the addition of Si can eliminate the unfavorable periodic layered structure. The latest research also indicates the possibility of their use for specific products, e.g., reinforcing bars [40]. For several years, it has been observed that this is a new direction in the development of metal coatings intended to protect steel surfaces against corrosion.

This Special Issue focuses on current trends in science, engineering and technology related to the corrosion and anticorrosion of alloys/metals. It includes basic and applied research related to the mechanisms and modeling of corrosion of metal materials and the processes of their protection and reduction in the effects of corrosion.

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