

## COMPARATIVE STUDIES OF THE PROPERTIES OF PROTECTIVE COATINGS ON STEEL SHEETS

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### Abstract

This article presents the results of accelerated tests conducted to determine the durability of steel sheets in a salt spray environment. Steel sheets, protected against environmental impacts using various technologies and then cold-formed, were selected for the tests. It was demonstrated that the most important problem to solve to achieve satisfactory corrosion resistance is achieving dimensional stability of the galvanic coating. Sheet samples containing multiple layers, i.e. polymer and galvanic coatings, were characterized by smaller mass changes due to exposure to corrosive conditions. In these cases, corrosion initiation occurred more readily in areas where the thickness of the galvanic coating varied, as observed in the cross-sections of the sheet metal.

**Keywords:** corrosion test, cold-formed sheet, corrugated galvanized iron, salt spray chamber, hybrid coating

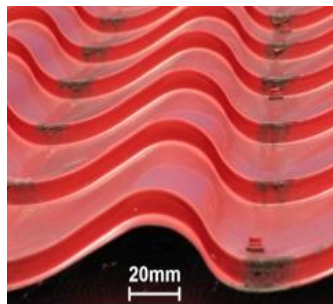
### 1. INTRODUCTION

Protective coatings are applied before the steel sheet profiling process, requiring them to be flexible and deformable, as breakage is unacceptable [1,2]. The sheet profiling process is performed by cold forming. Steel roofing is primarily exposed to electrochemical corrosion [3,4]. This means that the components are damaged by an electrochemical cell consisting of an anode, a cathode, and an electrolyte [5,6].

The steel surface has a heterophasic structure, consisting of a metal matrix, non-metallic inclusions, and inclusions of other metals [7,8]. These areas differ in electrochemical potential. Upon contact with the electrolyte, they form microcells, where the flow of charge causes the dissolution of more electronegative, or anodic, areas [3,6]. Typically, the inclusions present in the alloy possess a higher electrochemical potential than the pure iron matrix. Therefore, upon contact with the electrolyte, a closed circuit is formed. The iron then becomes the anodic region, which undergoes an oxidation reaction, causing the atoms of the matrix metal to enter solution, an irreversible reaction in aqueous environments [9,10].

Corrosion intensity is further increased by the action of local tensile stresses on the element, as these increase the chemical activity of the metal. Steel structures corrode in various environments, such as atmosphere, water, and soil. The intensity of metal corrosion is primarily influenced by the atmosphere in which the product is used. This depends on the climate in which the element operates, as well as the number of pollutants it contains [11-13]. Corrosion processes intensify with increasing relative humidity. In a clean atmosphere, its aggressiveness increases at a relative humidity of approximately 75 %. This significantly increases the rate of corrosion processes. In a polluted atmosphere, the critical value of relative humidity is 60-75 % [14]. Gaseous pollutants in the air increase the electrical conductivity of water and alter its pH. Solid particles such as soot and coal dust can settle on the structure's surface. At high humidity levels, solid pollutants can become condensation points, leading to the formation of electrical cells on the surface of the metal structure. These pollutants can also contribute to mechanical and other types of damage to the roof covering [15,16].

The aim of this study was to assess whether the shape of the profile in a steel roof covering affects its corrosion resistance. The study was undertaken after observing corrosion changes in area of the largest deformation in a metal roofing tile protected with a coating system (**Figure 1**) consisting of a zinc and polymer (hybrid, duplex) coating. The roof covering was exposed to atmospheric conditions characteristic of medium atmospheric corrosivity, which corresponds to category C3 according to the standard [17]. The experiment aimed to determine whether the type of profile in a steel sheet intended for a roof covering affects the effectiveness of corrosion protection. It was also decided to determine the extent to which accidental mechanical damage to the protective coating affects the corrosion resistance of the sheet. Additionally, an attempt was made to determine the extent to which the use of a hybrid (duplex) protection system affects the durability of the roofing sheet.



**Figure 1** Corrosion changes observed after 15 years on a roof made of metal roofing tiles protected with a hybrid system

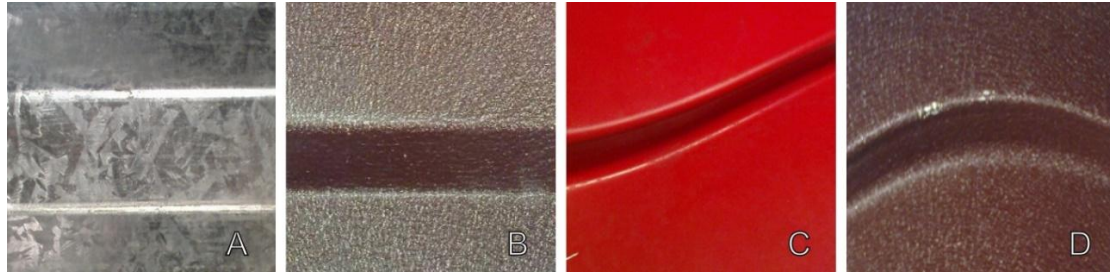
## 2. MATERIALS AND METHODS

The tests were performed on products differing in the protective system used and the shape of the profile. The test material consisted of samples of DX51D low-carbon steel sheet, cold-rolled to a nominal thickness of 0.5 mm, hot-dip galvanized on both sides. This steel is used for components formed by bending and profiling. DX51D steel is characterized by a tensile strength (yield strength value is not provided) in the range of 270-500 MPa with a relative elongation of approximately 22 % for a measured section of 80 mm [18, 19]. The results of tests conducted on a large statistical sample between 2005 and 2010 showed an average yield strength of 304 MPa (with a standard deviation of 18.7) and tensile strength of 369 MPa (with a standard deviation of 11.9) [20].

The adhesion of the metallic (+organic) coating on the sheet metal samples tested met the requirements for corrosion testing standard [21]. Bends of 180° were made on the sheet metal coatings, and no cracks or flaking that would disqualify them were observed. The thickness of the zinc coating on the test samples was measured using microscopic microscope sections.

Samples of four different types of steel sheet were collected for testing, in accordance with the recommendations of the standard [21]. The tests were conducted on two types of trapezoidal sheet metal (A - corrugated galvanized iron and B - with organic coating) and two types of sheet metal with a metal roofing tile profile (C and D), differing in the geometric properties of the coating systems (**Figure 2**). The metal roofing tile samples, designated C, were collected from the same batch of material used to create the coating shown in **Figure 1** but stored at a constant temperature of approximately 15 °C and protected from sunlight. Samples from each material group were cut using hand-held sheet metal shears. The cut edges were protected against corrosion. The surface area of the samples (the organic coating) and the weight of the samples were measured. Although the components used in the tests were brand new (not previously used on a roof), minor mechanical damage to the coatings, distributed randomly, could be observed on the sample surfaces. These defects occurred during the shaping of the sheet metal profile, storage, and transportation. A characteristic flower-like structure was observed on the surface of sample A, indicating that the coating did not contain any

lead. Although such a coating may be less resistant to plastic deformation, sufficient adhesion was found during the assessment of the coating's adhesion to allow for the preparation of samples for corrosion testing.



**Figure 2** Tested samples taken from sheet metal profiles with visible randomly distributed scratches on the coating

The tests were conducted in an environmental chamber. The adopted test program was considered adequate for assessing the actual resistance of the roofing sheets, which is confirmed by previously published studies, e.g., [2,3,7,9]. The sample size for the environmental tests was 14 for each material group. The corrosive environment consisted of an aqueous solution of sodium chloride at a ratio of 50 g/l and a pH of approximately 7. The chamber was maintained at a pressure of 110 kPa and a temperature of approximately 35 °C. The chamber was serviced at least once every 24 hours of the test. Periodically, after rinsing the test samples of the deposited brine and drying them, the surface condition and weight of the samples were inspected. Several samples were used to prepare metallographic tests. The metallographic samples were observed under an optical microscope and photographically documented.

The unit mass change values of the samples were calculated in relation to the surface area of sample. The dependencies of the unit mass change of the samples on their exposure time in the environmental chamber were presented as graphs.

### 3. RESULTS AND DISCUSSION

The results of coating thickness, measured on microscopic sections, are summarized in **Table 1**. No differences were found between the coating thicknesses measured at the embossed areas and where the sheet metal was not plastically deformed during profile shaping. For the C samples, observations showed that the zinc layer contained pores and was damaged in places, as well as discontinuities. The damage occurred during the technological process, which can be inferred from the fact that it was subsequently filled with a paint coating. This coating was the thickest of all the coatings compared. Also, there was significant variability in the galvanic coating thickness and a localized lack of zinc coating beneath a good quality paint coating.

**Table 1** Coating thickness on sheet metal samples before exposure in the environmental chamber

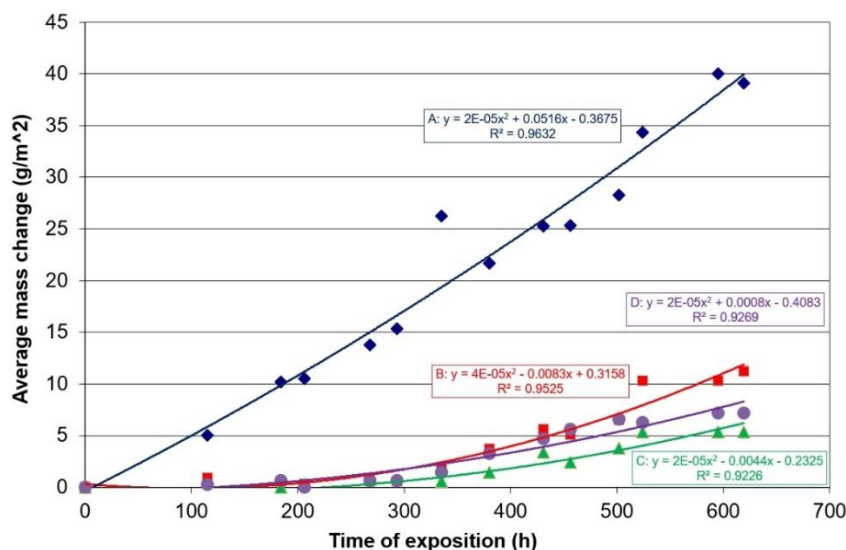
Sample	Layer thickness (µm)					Mean sum
	Zn			Paint - mean		
	At least	Mean	STD	Ground	Cover	
A	6.6	12.78	4.26	-	-	12.78
B	8.2	16.12	9.70	10.5	6.05	32.67
C	0.0	12.45	8.45	4.4	21.20	38.05
D	15.0	16.50	2.38	10.0	15.60	42.10

The average zinc coating thickness across all sample groups tested was close to the minimum recommended thickness of a hot-dip galvanized coating intended for use as part of a coating system under an organic coating,

which should be a minimum of 14  $\mu\text{m}$  [18]. It should be noted that the actual recommended thickness for comparison purposes for the stand-alone zinc coating, which was present on the A samples, is 20  $\mu\text{m}$ . This means that the average zinc coating thickness on the A samples was only approximately 64 % of the recommended value. At the same time, if the gaps in the zinc coating observed on the C samples are disregarded, the A samples had a coating with a minimum thickness of only 6.6  $\mu\text{m}$ .

The most dimensionally stable coating system was found on the D metal roofing tile samples, for which the standard deviation of thickness was 2.38  $\mu\text{m}$ . This metal roofing tile also had the thickest polyester coating compared to the similarly protected B and C sheets. The zinc coating on sample A, which was unpainted, had the lowest thickness, averaging 12.85  $\mu\text{m}$ . This was comparable to the average thickness of this hot-dip coating measured on the other samples. However, the coating system on samples B, C, and D had a combined thickness more than twice as high. This resulted in quantitatively larger and more extensive corrosion changes on the surface of sample A compared to the samples with the duplex coating system. After more than 600 hours of exposure in the environmental chamber, at least one layer of the duplex coating system on the samples was still intact. Occasionally, damage to the intermediate (structural) coating occurred. The external paint coating had a changed, irregular surface with gaps in areas where light sodium chloride deposits were present.

The results of the calculated unit mass change of individual samples during their exposure in the environmental chamber presents **Figure 3**. It can be seen, the largest mass change occurred for the A trapezoidal profile sheet protected solely by a zinc coating. For the remaining sample groups, mass changes occurred to a much smaller extent, which leads to the conclusion that simply increasing the number of layers (thickness) of the coating system increases the sheet's resistance to corrosive environments. A similar conclusion can be drawn from the analysis of the results of surface observations of the tested samples performed during service in the environmental chamber.



**Figure 3** Average mass change related to surface area during exposure in the environmental chamber of the tested samples

The results of the measurements of sample mass changes during the corrosion test, summarized in the graphs in **Figure 3**, indicate that the hybrid coating systems provide better corrosion protection compared to the protection provided by galvanic coating alone. The average unit mass change for the A trapezoidal sheet metal sample group was several times greater than for the other groups. Corrosion changes for the galvanized trapezoidal profile sample A were visible on average after just 8 hours from the start of exposure in the environmental chamber. For the remaining sample groups, this time was no shorter than approximately 100

hours. The exposure time of the samples in the environmental chamber before surface changes were observed varies significantly between samples. It may seem surprising that the C metal roofing tile samples were the most resistant to the corrosive environment. This is explained by the good quality of the paint coating, which performed its function properly during the samples' exposure in the corrosive environment. This coating, approximately 25 µm thick, in which only about 4 µm of ground layer, was an effective barrier to the corrosive agent. No corrosive changes occurred on the surface of the samples despite the defects in the zinc coating mentioned before.

The corrosion changes observed on the roof covering made of C metal roof tiles protected with the duplex system (**Figure 1**) occurred in the embossed areas, not because the coating system was deformed (stretched, damaged) there. The reason for the limited corrosion resistance was the discontinuity of the zinc coating, which – after polymer damage – should still provide corrosion protection to the steel sheet. If the zinc coating were intact (continuous), corrosion would have progressed more slowly despite the wear of the polymer coating. It can be concluded that ensuring adequate dimensional stability of the zinc coating would have increased resistance to corrosive environments regardless of the roofing sheet profile.

The average unit mass change was the appropriate parameter for assessing the corrosion resistance of roofing material samples. This parameter was determined by the test time for all groups of samples. Based on the conducted tests, this effect was estimated at least in 92 % (**Figure 3**).

#### 4. CONCLUSION

The durability of sheet metal formed for roofing purposes was significantly greater for samples containing coating systems (B, C, and D). Sheet metal samples containing multiple layers (not only galvanic, but also polymer and polyester coatings) were characterized by smaller mass changes caused during the corrosion test. In these cases, corrosion initiation occurred more readily in areas where the galvanic coating thickness varied. Randomly distributed, random damage to the paint coating does not constitute a more likely site for corrosion initiation, provided the galvanic coating remains continuous.

The type of profile of steel sheet intended for roofing has no significant impact on its corrosion resistance, provided that the protective coatings are applied correctly. It was demonstrated that the most important problem to solve to achieve satisfactory roofing durability is achieving dimensional stability of the galvanic coating. The galvanic coating on samples with trapezoidal profile A was more than twice as thin as the combined thicknesses of the coating systems in the remaining sample groups. This fact resulted in its reduced durability under the simulated corrosive environment.

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