Pamukkale Univ Muh Bilim Derg, XX(X), XX-XX, 20XX

Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi

Pamukkale University Journal of Engineering Sciences

The effect of forming process on the corrosion characteristics of DX51D galvanized steel sheets

Şekillendirme işleminin DX51D galvanizli çelik sacin korozyon davranişina etkisi

Alaaddin TOKTAŞ[1], Mustfa DÜLGER[2], Gülcan TOKTAŞ[1]*

[1]Department of Mechanical Engineering, Balıkesir, Faculty of Engineering, Balıkesir University, Türkiye.
atoktas@balikesir.edu.tr, gzeytin@balikesir.edu.tr
[2]Anka Poultry Equipments Systems, Balıkesir, Türkiye.
mustafa.dulger99@gmail.com

Received/Geliş Tarihi: 13.08.2024 Revision/Düzeltme Tarihi: 15.02.2025 doi: 10.5505/pajes.2025.63838
Accepted/Kabul Tarihi: 20.03.2025 Research Article/Araştırma Makalesi

Abstract

This study examines the effect of forming (bending and folding) procedures on the corrosion behavior of galvanized sheet steel in poultry manure. It also aims to compare the corrosion behavior in poultry manure with salty and atmosphere environments. To achieve this objective, samples were prepared by laser cutting DX51D galvanized sheets. These samples were then subjected to various bending processes, including V, L, U, and Z-bendings, as well as multiple bending, folding, and folding+bending techniques. The samples underwent salt spray testing to determine the percentages of white and red rust on their surfaces. The samples, including laser cut, V-bendings, multiple bending, and folding, were exposed to the atmosphere and poultry manure settings for 28 days. The corrosion rates in these environments were calculated by measuring the mass losses every seven days. In the salt spray test, 60° bent samples exhibited the most corrosion resistance compared to the other forms, showing minimum percentages of white (56%) and red (4%) rust. The frame-cut sample showed a maximum corrosion rate of 0.00152 mm/year in the atmosphere. Bending and folding processes had no detrimental effect on the galvanized coating, such as peeling or flaking the coating. However, corrosion affected the bent and folded regions negatively by decreasing the coating thickness.

Keywords: Galvanized steel, Bending, Salt spray test, Corrosion rate.

Öz

Bu çalışma şekillendirmenin (eğme ve katlamanın) galvanizli çelik sacın tavuk gübresindeki korozyon davranışını incelemektedir. Aynı zamanda çalışma, tavuk gübresindeki korozyon davranışını tuz sisi ve atmosfer ortamları ile karşılaştırmayı hedeflemektedir. Bunun için DX51D galvanizli çelik lazer yöntemiyle kesilerek numuneler elde edilmiştir. Daha sonra bu numunelere değişik formlarda eğme işlemleri uygulanmıştır. Bunlar V, L, U, ve Z-eğme ile çoklu eğme, katlama ve katlama artı eğme işlemleridir. Numuneler tuz sisi deneyine tabi tutularak yüzeylerinde oluşan beyaz ve kırmızı pas oranları belirlenmiştir. Lazer kesim, V-eğme, çoklu eğme ve katlama ile şekillendirilen numuneler atmosfer ve tavuk gübresi ortamlarında 28 gün bekletilmişlerdir. Bu ortamlardaki korozyon hızları numunelerin her yedi günde ortamdan alınarak kütle kaybı ölçümlerinden hesaplanmıştır. Tuz sisi deneyinde 60° eğme ile şekillendirilen numuneler %58 beyaz pas ve %4 kırmızı pas oranları ile diğer şekillendirmelere göre en yüksek korozyon direnci göstermişlerdir. Atmosfer ortamında çerçeve kesim numuneleri 0.00152 mm/yıl değeri ile en yüksek korozyon hızı göstermişlerdir. Eğme ve katlama işlemlerinin galvaniz kaplamaya, kaplamanın soyulması veya pul pul dökülmesi gibi zararlı bir etkisi olmamıştır. Ancak korozyon kaplama kalınlığını azaltarak eğilen ve katlanan bölgeleri olumsuz yönde etkilemiştir.

Anahtar kelimeler: Galvanizli çelik, Eğme, Tuz sisi testi, Korozyon hızı.

1 Introduction

Galvanizing is a very efficient method for safeguarding Fe-based alloys from corrosion. It provides long-lasting durability, economic advantages, and dependable application performance. Zinc coatings by galvanizing are protected against corrosion in three different ways: the environmental barrier effect of the zinc layer, the secondary barrier effects of zinc corrosive products that occur over time, and the cathodic protection of the steel by sacrificing itself when there is an inconsistency in the coating [1],[2]. Galvanizing offers extensive protection, encompassing corners, edges, and recessed places that may be difficult by alternative coatings. The galvanizing process forms a strong metallurgical link between zinc and steel, guarantees exceptional adhesion, and prevents peeling or flaking [3]. Galvanizing is a versatile process that may used on a diverse array of steel goods and structures, making it well-suited for several industries such as building, automotive, farming, petrochemical, electrical, and marine industry [4].

The zinc coating obtained by the hot dip galvanization process consists of a series of Fe-Zn intermetallic phases of different thicknesses and properties, increasingly enriched in Fe from the coating surface to the substrate material. The zinc coating consists of the intermetallic Fe-Zn compounds called eta (η-%0.03 Fe) and zeta (ξ-%6-7 Fe), delta (δ-%8-13 Fe), and gamma (Γ-%18-31 Fe) phases, with increased Zn content towards the outer surface. Fe-Zn alloy layers are less tough and

*Corresponding author/Yazışılan Yazar

fragile and have limited mechanical shaping abilities. The pure zinc layer is softer and more resistant to this type of mechanical stress [2].

Galvanized steels typically require shaping into different forms using various processes such as bending, drawing, stamping, and roll forming. The galvanized steel can be formed because the zinc is soft and ductile. For instance, compressive stresses can easily occur by press forming without peeling off in galvanized steel sheets [5]. But still, forming techniques should be applied with great attention to prevent any cracking or flaking of the coating. When forming, it is important to consider the thickness of the coating and its brittleness. Increased coating thickness can make the surface more susceptible to breaking, especially at low temperatures, where the zinc coating may become brittle. Certain precautions, such as lubricating the forming tool, using appropriate tools and zinc coating, and processing at a reasonable temperature, are essential to ensure non-damaged formed coatings. If the galvanized surface has sustained damage despite using these safeguards, it is possible to repair it. If the extent of the damage is significant, the affected portion can undergo a process of re-galvanization. For tiny damages, it is possible to apply thermal spraying, painting with zinc-rich paints, and soldering with a zinc-alloy stick [6].

Several types of corrosion on the formed galvanized steels can occur in time according to the service environment, such as white rust, red rust, and pitting corrosion. Damages during forming, coating thickness (beneficial in corrosion resistance but detrimental in forming due to brittleness), moisture, and external mechanical damages, such as scratches, abrasions, and cuts, are primary factors affecting the corrosion behavior of formed galvanized steels. Forming type and deformation modes can also affect the corrosion behavior of galvanized surfaces. Vagge et al. [5] reported that the biaxial deformation mode caused low resistance to corrosion in the hot-dip galvanized steel sheets. Ploypech et al. [7] studied crack formation and propagation in galvanized steel under loads at four-point bending conditions. They found that longitudinal cracks formed in the δ layer due to thermal stresses resulting from cooling, and the cracks spread outwards with increasing bending forces. In the other study [8], the fracture toughness of the galvanized low and medium-carbon steels was investigated using three-point bending. The authors concluded that the low carbon (0.08%) steel showed higher resistance to fracture compared to the medium carbon (0.24%) steel after galvanization. Camurri et al.[9] examined the effect of static (three-point bend) and dynamic (fatigue bending) stresses on hot dip galvanized SAE 1020 steel. They concluded that the zinc bath composition should be adjusted to minimize the thinner brittle layers to achieve good fatigue resistance. They succeeded in this with the Zn-Fe-Ti-0.012%Al and Zn-Fe-Ti-0.01%Al-0.037%Ni bath compositions. Forming methods have primarily been utilized on standard test samples under controlled laboratory circumstances, as evidenced by the previously mentioned research and numerous more. Nevertheless, many laboratory conditions cannot replicate the same situations seen in the real world.

This study is organized to investigate the effect of forming methods that have equivalents in the poultry industry on galvanized steel in terms of corrosion. In this industry, many chemicals, such as nitrates, sulfates, chlorides, hydrogen sulfide, and ammonia, induce corrosion [10]. Oyewole et al. [10] searched the surface degradation of galvanized steel used in farm structures in poultry dung, pig dung, and urea solutions using an inhibitor, rice straw extract. The phytochemical analysis verified the good inhibition effect of rice husk. They achieved the highest inhibition efficiency of 88.59% by the passive film formation, which was attributed to the adsorption via rice straw extract.

This study aims to investigate the effect of actual forming processes (V, L, U, Z-bendings, multiple bending, and folding) on the corrosion behavior of galvanized steel sheets (DX51D) commonly used in chicken farms. The corrosion behavior of the formed galvanized sheets in the poultry manure has been compared with the corrosion behaviors in salt spray and atmospheric conditions.

2 Materials and method

The chemical composition of 1 mm thickness galvanized DX51D sheet steel supplied from Gökmetal A.Ş is given in Table 1.

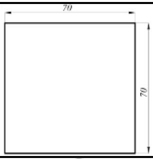
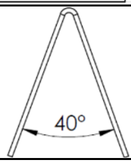
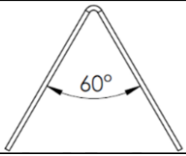
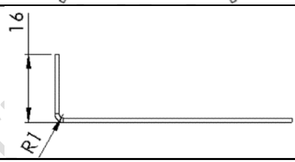
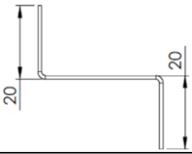
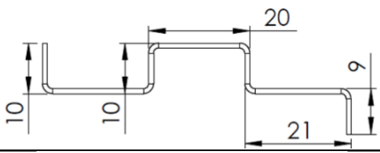
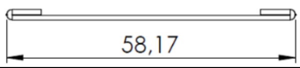
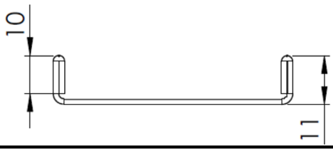
Table 1. Chemical composition of DX51D steel (wt.%).

C:	0.0451	Cr:	0.0284
Si:	0.0226	Al:	0.0466
Mn:	0.1720	Cu:	0.0290
P:	0.0180	Zn:	0.0022
S:	0.0069	Fe:	balance

The galvanized coating thickness was determined by Fisherscope X-Ray XDL and XDLM X-ray fluorescence spectrometer following ISO 3497 standard. Three measurements were done and averaged as 6,64 µm for coating thickness. A Hitachi M-1000 scanning electron microscope (SEM) was used to view the galvanized coating thickness.

Galvanized sheet steels were cut with a Mekotek FLO-1530 model fiber laser machine in dimensions of 70x70 mm^2. The cutting speed was set to 6 m/min, and the distance between the cutting tip and the sheet was 1 mm. Following the cutting procedure, the samples were shaped using the forming techniques, which involved V, L, U, and Z bendings, multiple bending, folding, and folding+bending processes. The Durmazlar brand press brake machine was utilized for the shaping procedure. The blade used is EURAM-1012/A35/1 type. The CKB brand D2088/88/V6/H80 model lower mold was used for L-bending. The bending load for L bending is 800 kg. CKB brand D2030/30/V8/H80 model was used as the lower mold in 40° and 60° V bendings. In folding+bending, the D3001/35/6/H90 model of the CKB brand was used as the lower mold. Sample codes are given in Table 2 per their shaping methods. After the bending and folding processes, no cracks, peeling, flaking, or any failure on the galvanized surfaces of samples were observed by the visual inspection.

Table 2. Sample codes and shaping methods.

Codes	Process	View
FC	Frame Cutting (70 mm ×70 mm)	
40VB	40° V Bending	
60VB	60° V Bending	
LB	L Bending	
UB	U Bending	
ZB	Z Bending	
MB	Multiple Bending	
F	Folding	
FB	Folding+Bending	

Salt spray tests were carried out at Uzman Katoferez (Bursa). The salt spray test was performed under the BS EN ISO 9227:2006 requirements. Sodium chloride is dissolved in deionized water with a conductivity of 0.2 µS/cm at 25°C to a concentration of 50 g/l for obtaining a 5% salt solution according to the standard. The specific weight of the solution at 25 °C is 1,032gr/cm³. The salt test cabin's pH is set to 6.9. The pH was adjusted by adding sodium hydroxide into the salt solution. The temperature in the cabin was fixed at 35°C ±3°C utilizing heaters. Salt mist spraying was carried out in the range of 1.5±0.188 bar. The devices used for placing samples in the cabin have phosphorized surfaces and are subsequently painted and baked with electro-static powder paint. No corrosion occurred in these devices in the test cabin. The samples had been kept in the salt spray testing cabin for 72 hours. Then, the samples were digitally photographed.

The red and white rust percentages on the samples were determined via the template method. In this method, a square of size 70 x 70 mm² is drawn on an acetate paper. Twenty-five equal squares are drawn inside the drawn square. Each small square corresponds to 4%. The template is placed on the samples, and the red and white rust falling inside the squares is evaluated in terms of % rust. Since the formation of red rust will occur after the formation of white rust, the occurrence of red and white rust in the same frame is counted as two ratios.

Under these conditions, the red rust rate in galvanized parts cannot be higher than the white rust.

After salt spray tests, red and white rust formations were scraped from the surfaces and placed in separate closed containers. These samples were analyzed with the ICP-OES device, and the Fe and Zn ratios in the rust content were analyzed. The given samples were dissolved in acid cocktails (HNO_3, HCl, HF, $HClO_4$), the solutions were placed in pressurized containers, and the content was determined by stimulating them with Ar gas. This test was carried out according to standard SM 3120 B. Furthermore, white and red rusted sites were investigated with a Fisherscope X-ray device for coating thickness and elemental analysis.

Some forms of the galvanized sheets were tested in the atmospheric and poultry manure environments between 25.04.2024 and 23.05.2024 dates. The samples were placed on a 10 cm × 10 cm grooved wooden wedge for the atmospheric corrosion tests. Atmospheric conditions include rain, dew, sun, temperature difference, humidity, and wind. The samples were left in an open area with constant sunlight and nightfall during the day.
Products used in the poultry industry are produced from galvanized sheets. Sheets are exposed to various compounds in poultry manure. Therefore, the samples were buried in the poultry manure, using a container of 26.5cm×17cm×3.5cm in dimension. Constituents of poultry manure are given in Table 3. The samples, held in the atmosphere and poultry manure, were taken from the corrosive environments every seven days, and their surfaces were gently cleaned and dried. After that, weight measurements were made with a Denver Instrument SI-234 Summit analytical balance with 0.1 mg sensitivity. Using the weight losses, corrosion rates were determined by Equation 1, where W is mass loss (mg), D is density (g/cm^3), A is area (cm^2), and T is duration (h) [11].

Table 3. Constituents and pH of a poultry manure [12].

pH:	6.95	NO_3-N:	%0.02
N:	%0.96	Ca:	%1.34
OC:	%4.67	K:	%0.13
P:	%0.27	Na:	%0.026
NH_4-H:	%0.42	Cu:	6.89 ppm

$$R_{corr.} = \frac{87.6 \times W}{D \times A \times T} \quad (1)$$

3 Results and discussion

The cross-section view of the galvanized coating obtained by SEM is given in Figure 1. The zinc coating is measured at 6 µm in this figure, corresponding well with the X-ray measurement (6.64 µm).

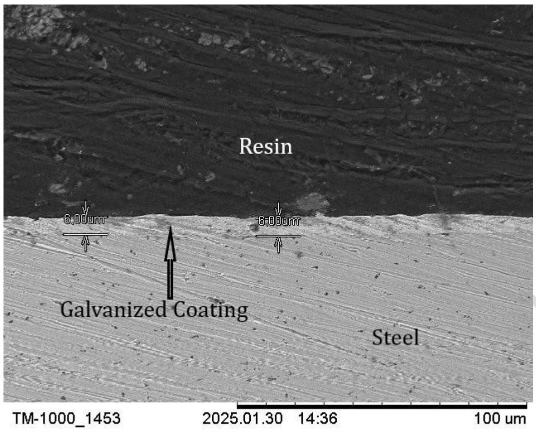


Figure 1.The cross-section of the galvanized coating.

Figure 2 illustrates the identification of white and red rust rates by the template method for the frame-cut (FC) sample with no forming process tested in the salt spray. Due to the flexibility of acetate paper, this measurement technique was applied to all-formed samples easily, even if too complex forms.

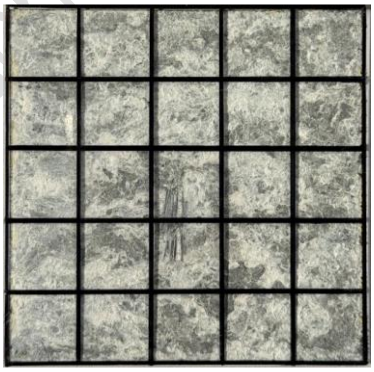


Figure 2. White and red rust rate identification for the FC sample via the template method.

The percentages of white and red rusts of all salt spray tested samples are given in Figure 3. White rust is a prevalent type of corrosion that initially occurs on galvanized steel when it comes into contact with moisture and oxygen. Corrosion frequently occurs during the initial phases of exposure to a corrosive atmosphere, such as in a salt spray test. The white, chalky deposit is visible on the surface of the galvanized coating. Although white rust may impact the visual aspect of galvanized steel, it often does not substantially diminish the zinc coating's protective qualities. Red rust forms as the steel beneath the coating erodes by depletion of zinc coating. This suggests the zinc coating has been compromised or fully corroded in specific regions [13]. The reddish-brown rust observed is characteristic of iron oxide, indicating the oxidation of the steel substrate. Red rust occurs when the integrity of the zinc coating is damaged, enabling moisture and oxygen to penetrate the steel and start the corrosion process. Red rust is a more severe issue than white rust since it signifies the failure of the protective zinc coating in those specific regions. This results in the corrosion of the steel, which may threaten the structural stability and durability of the material [14].

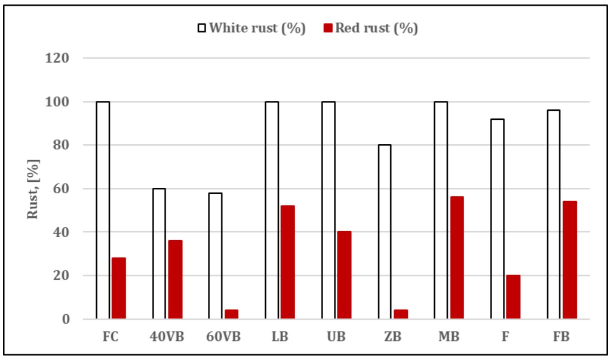


Figure 3. White and red rust percentages after salt spray tests.

After the inspection of the rust analysis by the ICP-OES device, it was found that the white rust had 70.5% Zn, while the red rust contained 34.8% Fe. The amount of Fe in the gamma (Γ), the coating's bottom and adjacent phase layer to the steel, is reported between 18-31% in the literature [2]. This result confirms that the galvanized coating disappeared before the red rust formed and rust reached the steel base, showing a problematic situation in terms of corrosion of sheet steel.

The white rust percentages are higher for all samples, as expected. The minimum red rust percentage is obtained in 60° V (60VB) and Z-bent (ZB) samples as 4% (Figure 4a). The highest red rust percentage is in the multiple-bent (MB) sample at 56% (Figure 4b). The 60VB sample showed minimum percentages of both white and red rust. The red rust percentages of the three samples (L-bent, multiple-bent, and folded+bent) are higher than 50%. Generally, the white rust is recognized in all shaped samples by the duration of 72 h in the salty environment. This result is consistent with the literature. Haiducu et al. [15] observed white rust formation on steel galvanized at various batch temperatures and durations within 48 h of exposure in salt spray testing.

Figure 4. After the salt spray test, a) ZB sample with minimum red rust, b) MB sample with maximum red rust.

The X-ray of the MB sample, showing the highest red rust after the salt spray test, is given in Figure 5, depicting the elemental analysis of the white and red rust in this sample. By examining the white rust, the galvanized coating thickness is averaged by three measurements as 4.20 µm, an acceptable coating thickness for corrosion resistance (Figure 5a). On the other hand, the zinc coating thickness in the red rust region was 1.4 µm by averaging five measurements (Figure 5b). There were coating thickness values below 1 µm, indicating destroyed coating and vulnerable to corrosion. This result is confirmed by the Zn amounts, where red rust has rather less Zn than white rust. Inversely, the Fe amount is higher in red rust, meaning that the zinc coating disappeared and the red rust containing iron oxides formed. The chromium (Cr) element was also identified in the galvanized coatings. According to the literature [16], the Cr element comes from the passivation treatment, applied after galvanizing to form a dense protective film for extending the service life of the galvanized coating. The film produced by the passivation prevents the formation of white rust or delays the onset of white rust, maintaining the appearance of the coating.

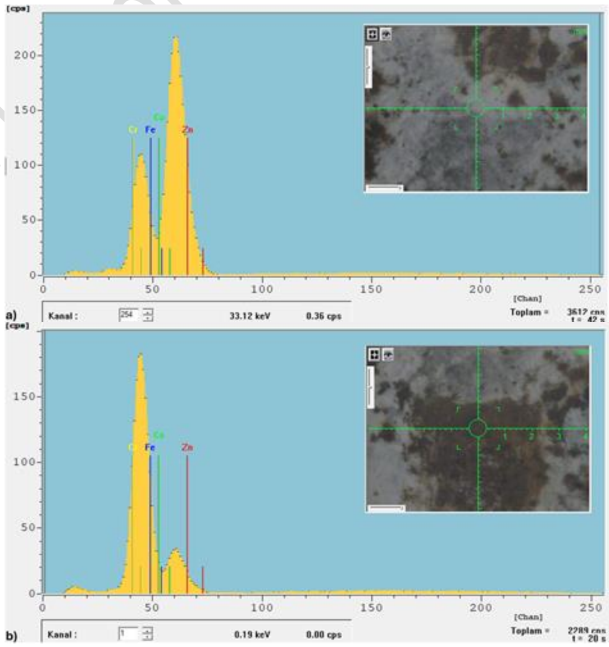


Figure 5. X-ray analysis of a) white rust, and b) red rust in salt spray tested MB sample.

Figure 6 illustrates the corrosion rates of some samples (FC, 40VB, 60VB, MB, and F) over 28 days in the atmosphere, measuring mass losses at the end of every 7 days. After the seventh day, while the F sample showed a maximum corrosion rate of 0.00204 mm/year, the 40VB one had a minimum value of 0.00086 mm/year. The F sample's corrosion rates decreased gradually towards day 28. In inverse, the 40VB sample's corrosion rate increased by duration. After the end of the 28th day, the F sample's corrosion rate was lower than that of the 40VB. These two samples showed nearly the same corrosion rates at the end of the 14th day.

The corrosion rates of the 60VB sample on the 7th and 28th days are close to each other. This sample showed a relatively stable corrosion rate throughout the period, with a slight peak around the 21st day. When the corrosion rates of a material are stable, it means that the material has established a consistent state in its association with the corrosive environment. Based on the findings of the present study, it can be inferred that the 60VB sample is more trustworthy for extended periods of use in atmospheric situations.

In the FC sample, the second high corrosion rate is inferred on the 7th day, showing a decrease in the next seven days, then increasing for the remaining duration. At the end of the 28th day, the frame cut sample had the highest corrosion rate of 0.00152 mm/year.

The MB sample's corrosion rate showed a maximum peak value of 0.00227 mm/year on the 14th day, then decreased relatively rapidly at the end of the next seven days (the 21st day), continuing to decline but more slightly. After 28 days, its corrosion rate is below the frame-cut sample's.

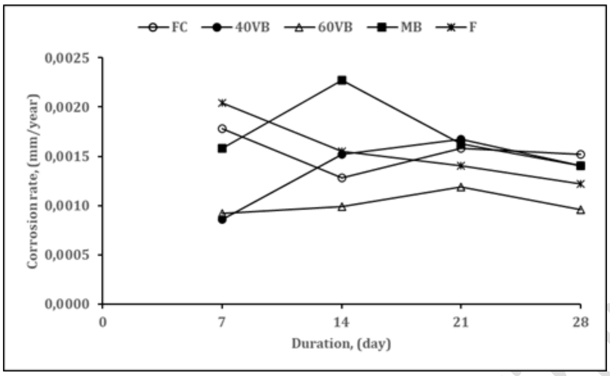


Figure 6. Corrosion rates of some samples in the atmosphere.

The corrosion rates of the samples held in the atmosphere are given in Figure 7 for the poultry manure environment. In this environment, after the 7 days of corrosion, while the frame-cut sample showed a maximum corrosion rate of 0.04810 mm/year, the 60VB sample had a minimum value of 0.02208 mm/year, below nearly half of the FC sample value.

The corrosion rates of the 60VB and MB samples show relatively stable behavior, suggesting better corrosion resistance in poultry manure in 28 days. The FC and 40VB samples' corrosion rates are decreased gradually by the duration time. The folded (F) sample has a peak value of corrosion rate (0.05730 mm/year) on the 14th day, then decreases after that. Despite this decrease, the highest corrosion rate is determined for the F sample as 0.03234 mm/year at the end of 28 days. All samples, except for the F, showed nearly similar corrosion rates after 28 days in the poultry manure environment. The decrease in corrosion rates over time is in line with the development of protective layers and the stabilization of corrosion rates. Decreases in corrosion rates with elapsed time were explained by Hernandez-Alvarado et al.[17] with the formation and growth of an adherent, white corrosion layer composed of zinc hydroxychloride and zinc hydroxide.

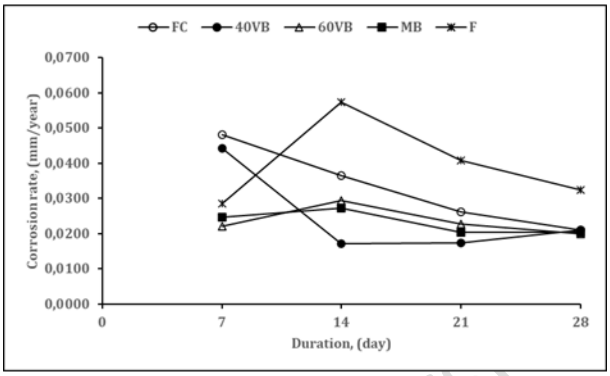


Figure 7. Corrosion rates of some formed samples in a poultry manure environment.

All obtained corrosion rates, even those measured in the poultry manure environment, are acceptable. According to the literature [17], corrosion rates between 25-100 µm/year are considered excellent per widely used classifications.

Comparing the corrosion rates of the same formed samples in two environments (atmosphere and poultry manure), the 60VB sample showed the most stable behavior by showing little corrosion rate differences between the 7th and 28th days. In addition, the corrosion rates of all samples are very high in poultry manure. The corrosion rates for FC, 40VB, 60VB, MB, and F samples are respectively 14, 15, 21, 17, and 23 times higher in poultry manure after 28 days of corrosion. This result suggests that poultry manure is a more corrosive medium than the atmosphere due to many chemicals (Table 2). When used in natural atmospheric conditions, galvanized sheets have a thin passive zinc carbonate layer that begins to form immediately after production and continues slowing down. This layer, which is the product, partially protects the sheet from severe corrosion that may occur later, but this natural barrier is insufficient for many strong corrosive environmental conditions. The mechanism of formation of this corrosion layer is as follows [18]:

$$Zn + \frac{1}{2}O \rightarrow ZnO$$
$$ZnO + H_2O \rightarrow Zn(OH)_2$$
$$Zn(OH)_2 + CO_2 \rightarrow ZnCO_3 + H_2O$$

Figure 8 illustrates the corroded surfaces of FC and MB samples after 28 days of corrosion in the atmosphere and poultry manure. It is inferred from the figure that poultry manure showed a more severely corrosive effect, showing clear surface degradations on both sample surfaces (Figure 8c and d). In the atmosphere condition (Figure 8a and b), in parallel with the low corrosion rates, generally smooth and unaffected surfaces are seen, showing the protective layer effect of the zinc coating. Few local degradations can be seen, especially near the cut edges, showing laser cutting has a detrimental effect on corrosion resistance. This result can be attributed to the generated high temperatures, above the melting point of zinc, and burning galvanized coating in and near the cut sections by laser cutting. Therefore, the galvanized layer's protective effect may have been compromised in these specific places, leading to its accelerated deterioration due to increased reactivity with the corrosive environment. No visible reddish-brown rust formation is recognized in the FC, MB, and other sample surfaces (40VB, 60VB, and F) in the poultry manure after 28 days. However, the coating thicknesses were measured below 1 µm, as 0.634 µm and 0.427 µm, respectively, too low for corrosion resistance at dark-colored corroded surfaces of MB and F samples. This suggests that the red rust formation may begin, even if not visible to the naked eye, due to the low coating thickness in these places.

During the galvanized coating in the atmosphere, a film of zinc compounds, highly insoluble in water, such as ZnO and $ZnCO_3$, occurs. This film protects the zinc coating by isolating the sensitive substrate from an aggressive environment. However, this film is affected by certain ions, such as chlorine and sulfate ions, which react with the protective film and form soluble compounds, decreasing the corrosion resistance and forming red rust on the surface [19]. The absence of aggressive ions in the atmosphere according to salty and poultry manure environments, smooth and non-corroded surfaces are seen in atmospheric condition by comparing Figures 4 and 8.

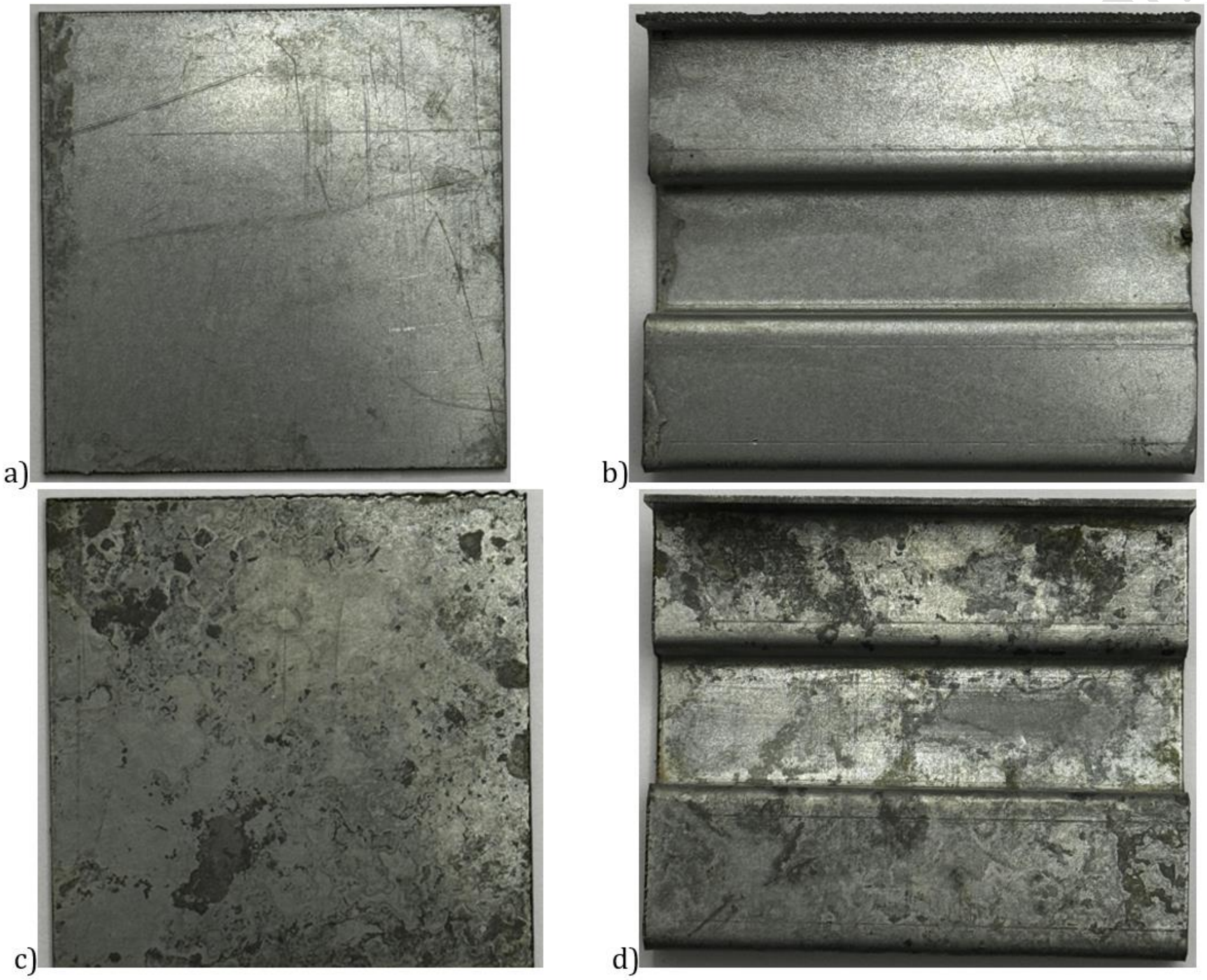


Figure 8. Corroded surfaces of FC (a, c) and MB (b,d) samples after 28 days of exposure to atmosphere (a,b) and poultry manure (c,d).

Figures 9 a and b show the corroded surface morphologies in the atmosphere for the 60VB and FC samples, respectively. A relatively uniform corrosion with evidence of small pittings is seen in both figures. These pittings are more on the 60VB's surface. Figures 9 c and d illustrate the corroded surfaces of the 60VB and F samples in the poultry manure. Contrary to Figures 9 a and b, these surfaces depict severe localized corrosion with clear irregular corrosion products. The aggressive constituents of the poultry manure, such as ammonia and organic acids, could have caused these products. The surfaces appear rougher with deeper pittings due to higher corrosion rates in the poultry manure, as verified by Figure 7.

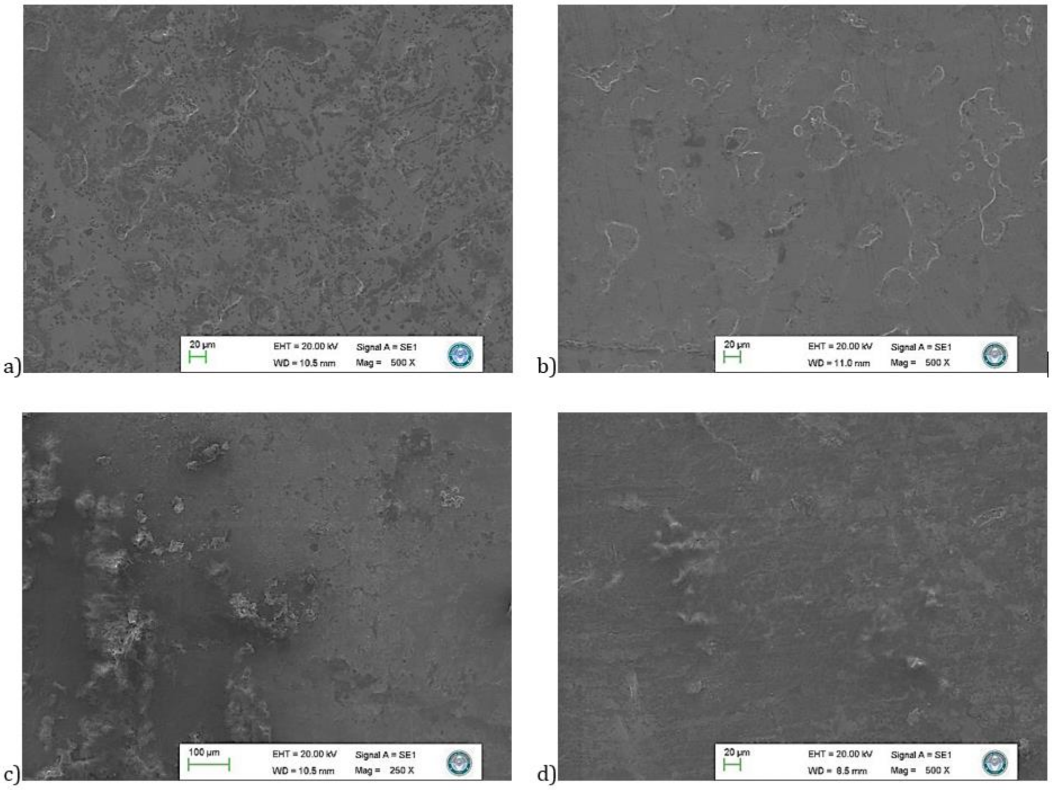


Figure 9. Corroded surfaces of) 60VB and b) FC samples in the atmosphere and c) 60VB and d) F in the poultry manure.

Evaluating salt spray, atmosphere, and poultry manure corrosive environments, 60VB samples showed the highest corrosion resistance with the minimum white and red rust percentages in salt spray tests and steady and lowest corrosion rates at 28 days of duration in the atmospheric and poultry manure environments. In the salt spray testing, the multiple-bent (MB) sample has higher white and red rust percentages. While this sample showed high corrosion rates in the atmosphere in line with the salt spray testing result, it had low and steady corrosion rates in the poultry manure. This result shows that the corrosion environments do not show a parallel effect on the same formed galvanized sheets. This result can be attributed to the different corrosion product formations on the galvanized surface by various corrosive environments.

After the corrosion tests, the bent and folded regions of samples were macro-investigated by a digital camera. This inspection detected no cracks, peeling, flaking, or any other failure on the formed galvanized coating. Only the corrosion phenomenon affected adversely these formed surfaces by depleting or thinning the galvanized coating. For instance, the 60VB sample had 1,97 µm and 5,11 µm coating thicknesses at the critic surface (upper of the angle) in the poultry manure and atmosphere, respectively. The coating thicknesses of the plane surfaces of this sample had relatively higher values, meaning that the critic surfaces were prone to corrosion sensitivity. This effect may be attributed to the residual tensile stresses on the outer surface that occur by bending. Yang et al.[20] reported that tensile stress may increase active, reactive sites, increasing the zinc dissolution rate and resulting in the depletion process of zinc coating.

4 Conclusions

The corrosion behavior of DX51D galvanized steel sheets was examined in three environments (salty, atmosphere, and poultry manure) with frame-cut and V, L, U, Z-bent, multiple bent, folded, and folded+bent samples. According to the results, the following conclusions can be drawn:

- In the salt spray test, 60° bent samples (60VB) exhibited the most corrosion resistance compared to the other forms, showing minimum percentages of both white (56%) and red (4%) rust. After the salt spray tests, white and red rusts had 70.5% Zn and 34.8% Fe atoms, respectively.
- After 28 days, while the frame-cut (FC) sample showed a maximum corrosion rate of 0.00152 mm/year in the atmosphere, the folded (F) sample exhibited the highest corrosion rate (0,03234 mm/year) in the poultry manure. The 60VB samples are the most corrosion-resistant form in the salty, atmosphere, and poultry manure.
- The poultry manure was a more corrosive medium, showing 14-23 times higher corrosion rates for the same formed samples than the atmosphere, due to having many chemicals.
- While the reddish-brown corrosion products had not been observed in the poultry manure for 28 days, the zinc coating thickness decreased below 1 µm, which is sensitive to corrosion.
- Cutting the edges by laser technique is not recommended because of burning zinc coating at and near the cut edges due to high temperatures when cutting. These burned edges could be priority locations for the beginning corrosion.

- Forming processes (bending and folding) had no detrimental effect on the galvanized coating layer. Additionally, no peeling or flaking occurred in the critic-shaped surfaces after corrosion tests. However, coating thicknesses decreased below 1 µm on these surfaces in the poultry manure due to residual tensile stresses generated by forming processes.

5 Authors' contribution

The authors contributed equally to the study.

6 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared. There is no conflict of interest with any person/institution in the article prepared.

7 References

[1] Ciubotariu AC, Istrate GG. “Corrosion rate of steels DX51D and S220GD in different corrosion environment”. *Scientific Bulletin of Naval Academy*, 19(1), 166-172, 2016.

[2] Şirin ŞY. “The effect of hot dip galvanizing process on the fatigue properties of hot rolled and quenched-tempered AISI 4340 steel”. *Pamukkale University Journal of Engineering Sciences*, 24(4), 626-634, 2018.

[3] Najafabadi EP, Heidarpour A, Raina S, Arashpour M, Zhao XL. “Effects of galvanization on the mechanical properties of high and ultra-high-strength steel tubes”. *ce/papers*, 4(2-4), 1606-1611, 2021.

[4] Singh JK, Mandal S, Adnin RJ, Lee HS, Yang HM. “Role of coating processes on the corrosion kinetics and mechanism of zinc in artificial seawater”. *Materials*, 14(23), 7464, 2021.

[5] Vagge ST, Raja VS, Narayanan RG. “Effect of deformation on the electrochemical behavior of hot-dip galvanized steel sheets”. *Applied Surface Science*, 253(20), 8415-8421, 2007.

[6] ArcelorMittal Europe “Corrosion protection of rolled steel sections using hot-dip galvanization”. https://sections.arcelormittal.com/repository2/Sections/10_Corrosion%20protection/5_10_02_Corrosion_EN.pdf (10.08.2024).

[7] Ploypech S, Boonyongmaneerat Y, Jearanaisilawong P. “Crack initiation and propagation of galvanized coatings hot-dipped at 450 C under bending loads”. *Surface and Coatings Technology*, 206(18), 3758-3763, 2012.

[8] Okafor IC, O’Malley RJ, Prayakarao KR, Aglan HA. "Effect of zinc galvanization on the microstructure and fracture behavior of low and medium carbon structural steels". *Engineering,* 5(8), 656-666, 2013.

[9] Camurri PC, Benavente GR, Roa SI, Carrasco CC. “Deformation and fatigue behavior of hot dip galvanized coatings”. *Materials Characterization*, 55(3), 203-210, 2005.

[10] Oyewole O, Smart P, Ajani D, Olorunfemi JB. “Effect of corrosion on surface degradation of galvanized steel in poultry dung, pig dung and urea solutions using rice straw as an inhibitor”. *Journal of the Mechanical Behavior of Materials*, 30, 95-102, 2021.

[11] Dülger M. “Investigating the effect of mechanical processes on corrosion behavior in galvanized DX51 and DX52 quality steels”. MSc Thesis, Balıkesir University, Balıkesir, Türkiye, 2024.

[12] Korkmaz AH, Sürücü A, Horuz A. “The utilization of rw-watered poultry manure as organic fertilizer in the agriculture”. *J. Agric. Fac. O.M.U.*, 11(2), 117–125, 1996.

[13] Moreira VB., Krummenauer A, Ferreira JZ, Veit HM, Armelin E, and Meneguzzi A, “Computational image analysis as an alternative tool for the evaluation of corrosion in salt spray test”. *Studia UBB Chemia*, LXV, 3, 45-61, 2020.

[14] Elewa RE, Afolalu SA, Fayomi OSI. “Overview production process and properties of galvanized roofing sheets”. *Journal of Physics: Conference Series* 1378, 022069, 2019.

[15] Haiducu M, Ghiban B, Ghiban N, Miculescu F, “ Corrosion resistance of some zinc galvanizing steels”. *U.P.B. Sci. Bull., Series B*, Vol. 75, 2013.

[16] Liu Q, Cao Y, Chen S, Xu X, Yao M, Fang J, Lei K, and Liu G, “Hot-dip galvanizing process and the influence of metallic elements on composite coatings”, *Journal of Composite Science,* 8, 160,2024.

[17] Hernandez-Alvarado LA, Hernandez LS, and Rodriguez-Reyna SL. “Evaluation of corrosion behavior of galvanized steel treated with conventional conversion coatings and a chromate-free organic inhibitor”, *International Journal of Corrosion*, Volume 2012, Article ID 368130, 8 pages.

[18] Karakaş Ö, Kanca E, Aydın Z. “Examination of the effects of the use of passivation agents and protective oils on corrosion formation”. *International Iron & Steel Symposium*, Karabük, Türkiye, 2012.

[19] Vourlias G, Pistofidis N, Stergioudis G, Pavlidou E, and Tsipas D, “ Influence of alloying elements on the structure and corrosion resistance of galvanized coatings”, *phys. stat. sol.* (a) 201, No. 7, 1518–1527 2004.

[20] Yang WJ, Yang P, Li XM and Feng WL, “Influence of tensile stress on corrosion behaviour of high strength galvanized steel bridge wires in simulated acid rain”, *Materials and Corrosion*, 63, No. 5, 401-407, 2012.