ANALYSIS OF COATED STEEL SHEETS' RESISTANCE TO CORROSION AFTER PLASTIC DEFORMATION

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The automotive industry is influenced by customers' requests, including safety and lifetime improvement, weight and emissions decreasing. The paper presents corrosion resistance improvement of car-body components by steel sheets coated with Zn-Al-Mg coating. Specimens coated with GI and Zn-Al-Mg coatings have been deformed by stretching (Erichsen test) and 3-point bending tests to 90 and 180. After deformation they have been tested in aggressive corrosion atmosphere of salt spray in corrosion chamber. Reached results showed better corrosion resistance of Zn-Al-Mg coatings when compared to standard Zn coating GI.

KEYWORDS

coated steel sheet, Zn coating, Zn-Al-Mg coating, corrosion

1 INTRODUCTION

The vehicle life is largely limited by the car-body lifetime. An effort of car producers is to prevent both types of the car-body corrosion: the perforation one until 10 years and cosmetic one until 5 years. In order to fulfil these requirements, polyfunctional coatings of zinc, tin, aluminium, lead, nickel and chromium are developed. These are combined with organic coatings in many cases as well. Considering both, the customers' demands fulfilling and price of coatings, zinc based coatings are irreplaceable within the coated steels for automotive applications [Hagarova 20131, Chovancova 2010]. These are produced either by hot dip galvanizing (GI) or electro-galvanizing (EG) - Fig. 1 and Fig. 2. Changing the chemical composition of coating allows of better corrosion protection when Fe-Zn (galvannealed - GA) or Zn-Al-Mg coatings are made [Graban 2008, Kolnerova 2001].

Fe-Zn coatings are made by a few minutes annealing of Zn coated steel sheets at the temperature 500-565° C in the chamber placed at the end of the production line [Evin 2011, Evin 2014].

Zn-Al-Mg coatings are made by hot dip galvanizing in zinc alloy with 0.8÷1.0 % Mg and 0.8÷1.0 % Al and these elements make the protection and stabilization layer at the surface. Thus, the natural protection of the coated material is reached and corrosion speed is decreased. Fe-Zn and Zn-Al-Mg coatings show better properties when compared to the Zn coatings, i.e. they are harder, scratch resistible, better weldable, with better formability and good spraying properties. Moreover, reduced zinc usage is reached. [Tanaka 2001, Tsujimura 2001, Graban 2008, Evin 2011]. Weldability and formability properties are important mainly for tailored welded blanks, used as new structures applied in some car-body parts [Schrek 2016].

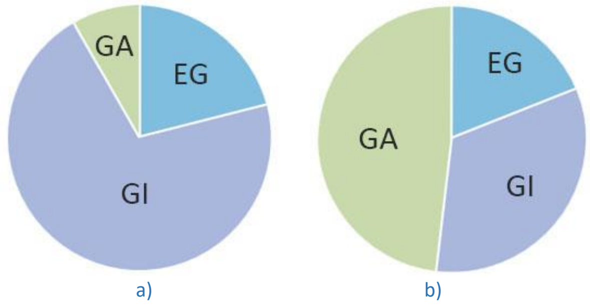


Figure 1. Share of zinc coatings used at the car-body production [Rouet 2014]
a) in Europe, b) in NAFTA states (North America Free Trade Agreement)
GA – annealed, EG – electrogalvanized, GI – hot dip galvanized

There is a worse protection of the coating when produce the car-body parts – roof, door, trunk lid, fender, deck – by bending, stretching or deep-drawing from Zn coated steel sheets, since the plastic deformation makes

- thinning the both, base material and coating,
- failure the coating integrity at the tool-steel sheet surface contact,
- cracks formation in coating when it is not enough plastic,
- flaking the coating when imperfect adhesion to the base material.

2 MATERIALS AND METHODS OF EXPERIMENT

Experimental research has been done using specimens GA1 and GA2 with zinc-aluminium-magnesium coating and specimens GI with conventional zinc hot dip galvanized coating. Specimens marked GA1 contained 1.53 % Al and 1.26 % Mg in the coating, they were passivated by Cr^{3+} (40÷50 mg/m^2) and one side surface weight of Zn coating was 70 g/m^2. Specimens marked GA2 contained 1.85 % Al and 1.68 % Mg in the coating, they were passivated by Cr^{3+} (40÷50 mg/m^2) and one side surface weight of Zn coating was 68 g/m^2. Specimens marked GI were passivated by Cr^{3+} (40÷50 mg/m^2), they contained 0.63 % Al and one side surface weight of Zn coating was 82 g/m^2.

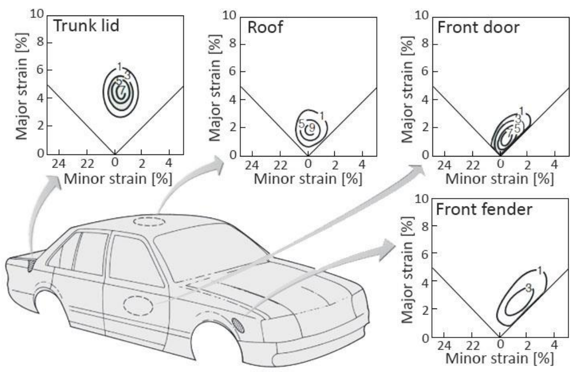


Figure 2. Strain schemes at car-body parts production

When produce car-body parts by bending and stretching, tensile stresses act – Fig. 2 – and thinning and abrasion of coating, cracks in the coating as well as flaking of coating may occur. The specimens stressing by stretching has been modelled by Erichsen test – Fig. 3d, stressing by bending has been modelled by 3-point bending to 90°and 180° - Fig. 3 b,c.

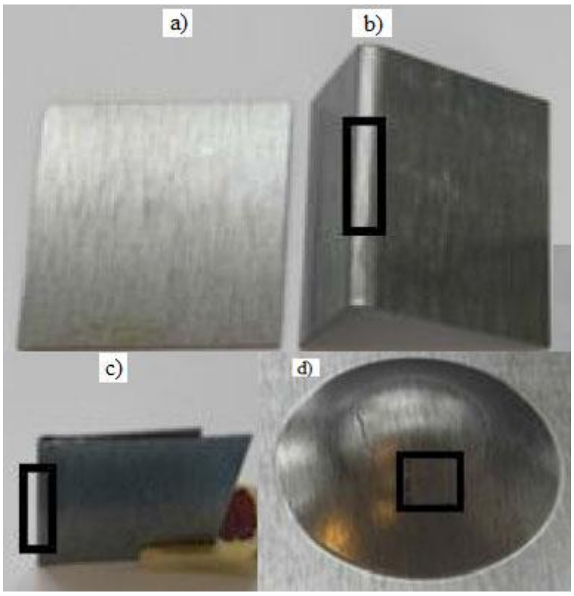


Figure 3. The specimens shape after plastic deformation
a) no deformation, b) bending 90°, c) bending 180°, d) stretching by Erichsen test

Corrosion resistance of the specimens before and after deformation has been tested according to STN EN ISO 9227 in corrosion chamber using salt spray (sodium chloride solution of 50 g/l concentration) at the temperature of 35°C. The specimens have been fastened in the corrosion chamber not being directly sprayed by the sodium chloride solution. Corrosion resistance of the coating has been researched in dependence on:

- time to appearance of red corrosion,
- area of corroded surface after 24, 48, 72, 120, 144, 216, 312, 408, 624, 724, and 864 hours spent in corrosion chamber.

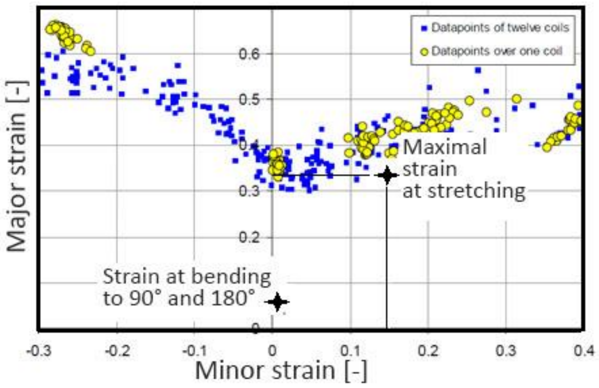


Figure 4. Strains shown in the Forming Limit Diagram for base material DX54D

Different strain schemes appear when produce the car-body parts by forming. Limit strains in the plane at different strain schemes are defined by Forming Limit Diagrams and it is shown in Fig. 4 for base material DX54D. As it flows out from numerical simulations (Fig. 5), localised deformation, followed by fracture is given by the tensile strains and stresses which take part in the critical section. Combination of major and minor strains in this section reaches the limit strains - $\varepsilon_1 = 0.33$ and plastic properties have been totally utilized. As it flows out from numerical simulations of bending – Fig. 6 and Fig. 7 – low strains have been reached when bending to 90° and 180° - $\varepsilon_1 = 0.07$ within the uniform deformation and plastic properties have been utilized only to 23 % approx. However, the wider area has been deformed when bending to 180°.

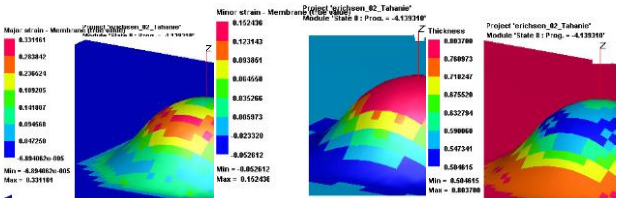


Figure 5: Strains calculated by numerical simulation when stretching by Erichsen test – critical major/minor strains [0.33; 0.15]

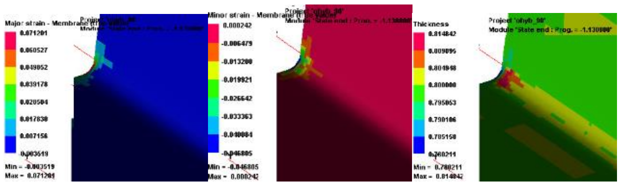


Figure 6. Strains calculated by numerical simulation when bending to 90° – critical major/minor strains [0.07; 0.0002]

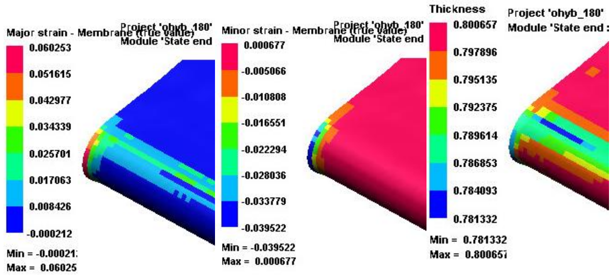


Figure 7. Strains calculated by numerical simulation when bending to 180° – critical major/minor strains [0.07; 0.0007]

3 REACHED RESULTS AND DISCUSSION

The corrosion resistance of specimens GA1 and GA2 coated with Zn-Al-Mg have been compared to the corrosion resistance of specimens GI coated with conventional zinc coating. Specimens taken out of the chamber have been washed off from salt sediments. The corroded area of the specimens has been evaluated by standardised images and photos at different angles. During the tests, time to initial red rust and area of corroded surface in % have been evaluated after 24, 48, 72, 120, 144, 216, 312, 408, 624, 724 and 864 hours spent in corrosion chamber.

Table 1. Time to initial red corrosion appearance for different strain schemes

	Time [hours]		
	GI	GA1	GA2
Undeformed samples	216/2	624/1	864/1
Samples after bending to 90°	72/2	624/3	864/2
Samples after bending to 180°	72/4	408/2	724/1
Samples after stretching (Erichsen test)	48/2	72/3	216/2

Results of tests – time to initial red corrosion are shown in Tab. 1. Percentage of corroded area depending on time spent in corrosion atmosphere is shown in Fig. 8, Fig. 10 and Fig. 12. These also show the kinetics of red corrosion growth for undeformed and deformed specimens. The surface appearance after 72 hours and 864 hours is shown in Fig. 9, Fig. 11 and Fig. 13.

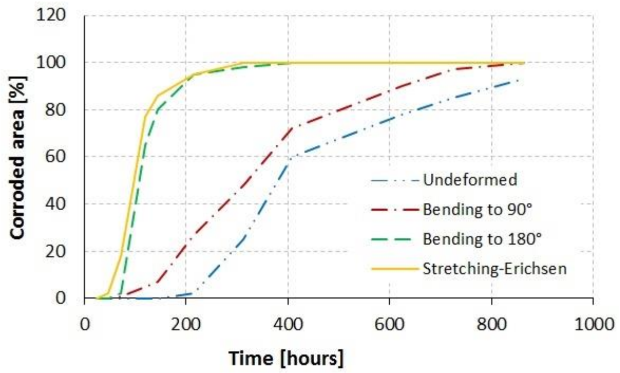


Figure 8. Corroded surface-Time dependence for GI samples with Zn coating

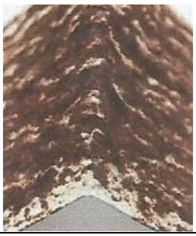
Time [hours]	72	864
Undeformed		
Bending to 90°		
Bending to 180°		
Stretching (Erichsen)		

Figure 9. Surface of samples with zinc coating GI after 72 and 864 hours spent in corrosion atmosphere

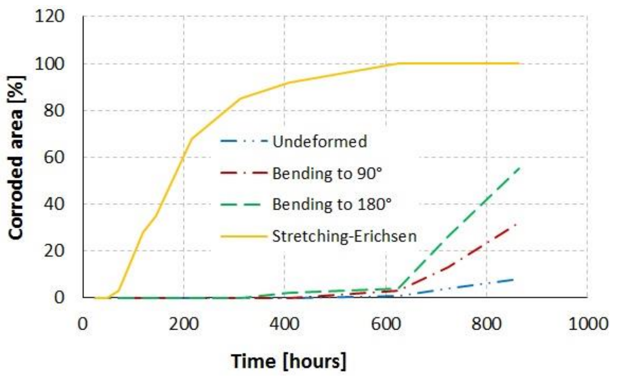


Figure 10. Corroded surface-Time dependence for GA1 samples with Zn-Al-Mg coating

Time [hours]	72	864
Undeformed		
Bending to 90°		
Bending to 180°		
Stretching (Erichsen)		

Figure 11. Surface of samples GA1 with Zn-Al-Mg coating after 72 and 864 hours spent in corrosion atmosphere

As it flows out from Fig. 8 and Fig. 10, the kinetics of red corrosion growth present S-curve shape. There are shown three phases: slow red corrosion growth up to 10 % of corroded area in the first phase, more intensive red corrosion growth in the second phase when 10 to 80 % of corroded area have appeared and the third phase up to 80 to 100 % of corroded area.

Fig. 9 shows, for undeformed samples GI with zinc coating, the initial red corrosion appears on 2 % of the surface after 216 hours spent in corrosion chamber. Increasing the time from 216 to 408 hours spent in corrosion chamber, more intensive red corrosion growth from 2 % to 60 % of the surface is observed. When time increases from 408 to 864 hours, the intensity of red corrosion is gradually relaxed. The similar tendency has been observed for samples after plastic deformation. Samples bent to 90° and 180° have shown the initial red corrosion growth after 72 hours, while corroded surface for specimens bent to 90° was 2 % and for specimens bent to 180° it was 4 %.

In the second phase, for time spent in the chamber from 144 to 408 hours, more intensive corrosion growth has been observed for samples bent to 180° and samples stretched at Erichsen test. The corroded surface of 100 % was found after 312 hours for samples stretched at Erichsen test, after 408 hours for samples bent to 180°, after 864 hours for samples bent to 90° and not all surface has been corroded after 864 hours for undeformed samples. It has been found out, the corrosion resistance of zinc based coating GI depends on time, deformation and deformed surface for similarly same coating thickness.

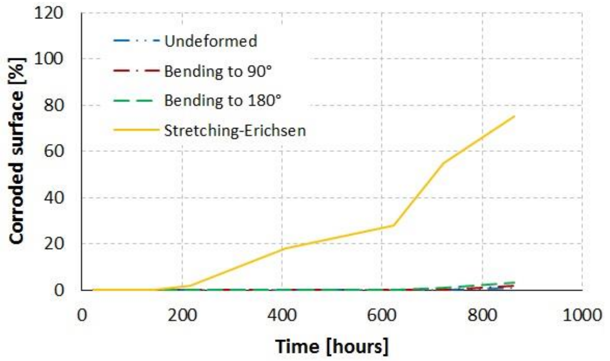


Figure 12. Corroded surface-Time dependence for GA2 samples with Zn-Al-Mg coating

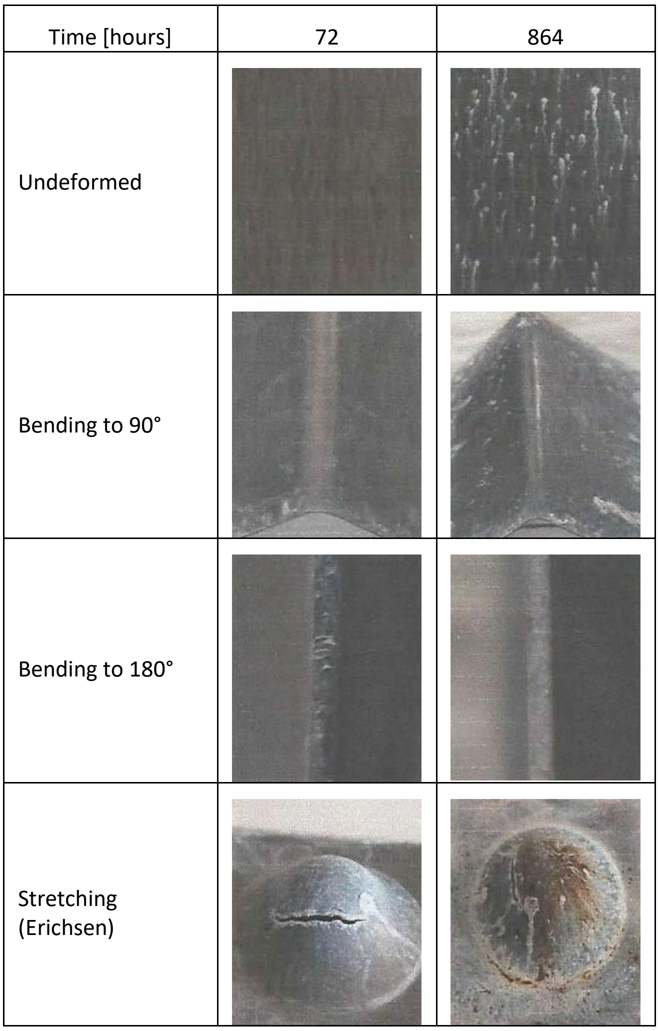


Figure 13. Surface of samples GA2 with Zn-Al-Mg coating after 72 and 864 hours spent in corrosion atmosphere

As it is shown in Fig. 10, the onset of red corrosion for undeformed samples GA1 with Zn-Al Mg coating has been found on 2 % of corroded surface after 624 hours spent in corrosion chamber. Increasing time from 624 to 864 hours, more intensive red corrosion growth from 2 % to 8 % is observed. The similar tendency has been found for samples bent to 90° and 180° with a slight difference for samples bent to 180°, where more intensive red corrosion growth has been found when compared to samples bent to 90°. Samples stretched at Erichsen test have shown the onset of red corrosion after 72 hours, while 100 % of corroded surface was observed after 624 hours.

As it is shown in Fig. 12, the onset of red corrosion growth for samples GA2 with Zn-Al-Mg coating for undeformed samples and bent to 90° samples have been found after 864 hours spent in the corrosion chamber. The onset for samples bent to 180° has been found after 724 hours. When stretched by Erichsen test, the onset of red corrosion growth has been found after 216 hours and after 864 hours only 75 % of surface has been corroded. It means the corrosion resistance of Zn-Al-Mg coatings GA depends not only on time, deformation and deformed surface for similarly same coating thickness, but also on Al and Mg content in coating.

4 CONCLUSIONS

The influence of plastic deformation to corrosion resistance of samples with Zn coating and Zn-Al-Mg coatings with different content of Al and Mg have been tested in the aggressive corrosion atmosphere of salt spray according to the STN EN ISO 9227. Time to initial red corrosion as the first criterion has been evaluated when compare the corrosion resistance of coatings after plastic deformation by stretching (Erichsen) and bending to 90° and 180°. The second criterion to evaluate the samples has been corrodes surface after each cycles spent in the corrosion chamber – 24, 48, 72, 120, 144, 216, 312, 408, 624, 724 and 864 hours.

The results of experimental research have shown, due to plastic deformation the onset of the S-curves (kinetics of red corrosion growth) as well as time to the 100 % of corroded surface are shifted towards the shorter times spent in the corrosion atmosphere:

- the samples GI coated with Zn have shown a deterioration of corrosion resistance when bent to 90° and 180° about 67 % and 78 % when stretched at Erichsen test, compared to the undeformed samples GI,
- the samples GA1 coated with Zn-Al-Mg coating have shown a deterioration of corrosion resistance when bent to 180° about 35 % and 88 % when stretched at Erichsen test, compared to the undeformed samples GA1,
- the samples GA2 coated with Zn-Al-Mg coating have shown a deterioration of corrosion resistance when bent to 180° about 16 % and 35 % when stretched at Erichsen test, compared to the undeformed samples GA2.

Even more markedly has shown the increase of the corrosion resistance of Zn-Al-Mg coatings GA1 and GA2 when compared to the Zn coating GI at different strain states:

- the undeformed samples GA1 have improved corrosion resistance of 188 % and samples GA2 of 300 %,
- when bent to 90° the samples GA1 have improved corrosion resistance of 767 % and samples GA2 of 1100 %,

- when bent to 180° the samples GA1 have improved corrosion resistance of 467 % and samples GA2 of 905 %,
- when stretched at Erichsen test the samples GA1 have improved corrosion resistance of 50 % and samples GA2 of 350 %.

Based on mentioned it follows that the effect of the deformation degree has shown significantly less for samples with Zn-Al-Mg coating. More content of Al and Mg in the coating is, the higher corrosion resistance is shown. Different behaviour of Zn-Al-Mg coatings in corrosion environment when compared to the conventional Zn coating can be explained by the very stable, well-adherent thin layer of corrosion product of zinc aluminium carbonate hydroxide, $Zn6Al2(CO3)(OH)16{\cdot}4\ H_2O$ formed on the steel substrate. This layer provides enhanced corrosion resistance of Zn-Al-Mg coated steel sheets when compared to the conventional Zn coated steel sheets [Graban 2008, Newman 2010, Schurz 2011]. It means if engineers refrains multiple bends when design car-body components, then they minimize the number of places with limit deformation. Along with simultaneous use of Zn-Al-Mg coated steel sheets it is expected significant increase of corrosion resistance of the car-body components.

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