GALVANISED SHEET STEEL FOLDING CHARACTERISTICS AND CORROSION RESISTANCE

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Abstract. The paper deals with the effects of geometric, physical and mechanical characteristics of hot-galvanised steel sheets on the technological characteristics and corrosion resistance of parts made of the steel sheets. The paper identified the changes in zinc coating layer thickness during the process of folding steel sheets, the effects of geometric parameters of punches and matrixes on the bend radius value and the corrosion resistance of samples exposed to acetic acid. It found that the corrosion resistance of folded parts made of galvanised steel sheets was associated with the relative elongation, thickness and bend radius of the steel sheets and zinc coating.

Key words: hot-galvanised steel, steel sheet, folding, corrosion resistance, acetic acid.

Introduction

Corrosion resistant products can be produced in two ways: first, galvanised steel sheets are used; second, the product is made and after it is galvanised. The cheapest way is the first one, while the application of it is constrained by the physical and mechanical characteristics of zinc galvanised steel sheets. The layer of zinc, the hardness of which, on average, is only HB35, can be damaged or in some spots it does not completely coat a steel sheet if mechanically impacting the zinc galvanised steel sheet, shaping its form and splitting it into separate elements. In the result, favourable conditions emerge for faster chemical or electrochemical corrosion of the parts. It is important to manufacturers that guarantee their product quality, including corrosion resistance, to know what technical characteristics of their product they can guarantee.

The paper focuses on the problems that emerge if folding zinc galvanised steel sheets at a relatively small bend radius. Theoretical calculations and experimental research were done on materials, the base element of which is a 2 mm non-alloy steel sheet. Folding the sheet results in tensile forces in the zinc coating on the outside of bend that deform the zinc layer. As known from the literature [1-3], the extent of deformation depends on the thickness of a material to be folded and the bend radius. The thickness of a zinc galvanised material is mainly determined by the thickness of a steel sheet. It is important to know the minimum bend radius for a steel sheet on which a layer of zinc is coated. The standard EN 10025-2-2004 [1] prescribes that, for example, for non-alloy S235J2 steel sheets 1.5-2.5 mm in thickness the minimum allowable inside bend radius applied both parallel and perpendicular to the direction of flat rolling shall be 2.5 mm. The standard EN 10250-2 [2] specifies that the minimum relative elongation for S235J2 steel sheets has to be 17%. The authors calculate the minimum relative elongation to ensure that the surface of the base material remains undeformed. The thickness of a steel sheet, h_t, and the neutral axis bend radius, R_n, have to be known to perform the calculations. The relative elongation for a steel sheet on the outside of bend in the tensioned zone A, as %, may be calculated by the equation $A = (h_t/2 \cdot R_n^{-1})$. After placing h_t = 2 mm and R_n = 3.5 mm in the equation, one can acquire a result that A = 28.6 %. The outside bend radius R_{out} at which the bent surface of a 2 mm thick S235J2 steel sheet is not going to crack, given that A = 17 %, is equal to $R_{out} = R_n(1+A)$ =3.5(1+0.17)= 4.1 mm. The allowable bend radius depends on the relative elongation of a material. For structural steel having low carbon content, for example, C10, the minimum relative elongation A = 31 %. For DX51D+Z600 steel sheets with a carbon content of 0.05 %, which are intended for cold shaping and hot-galvanisation with zinc, the minimum relative elongation A = 22 % [4]. It means that cracks are going to appear on the surface bent outwards if folding such a 2 mm thick steel sheet at an outside bend radius of 4.27 mm or less.

The aim of the present research is to identify whether micro-cracks could appear in the zinc layer if deforming 2 mm thick sheets of steel appropriate for galvanisation with zinc. The second problem relates to whether such micro-cracks create the risk of corrosion.

Materials and methods

To verify whether the theoretical calculations are correct, tests were done on samples of a DX51D+Z600 steel sheet. The samples were cut out of the 2 mm hot-galvanised steel sheet, which had a coating of zinc spread evenly at a rate of 600 g per m^2, by means of a punching machine TruPunch 3000. The samples, 100 mm in length and 20 mm in width, were folded by means of the machine at a bend angle of 90º. The folding involved punches with radiuses R = 0.6, 2.0 or 3.0 mm. The matrixes had V = 12, 16 or 20 mm holes.

The sample placement in a sheet and a devise for measuring zinc layer thickness are presented in Figure 1.

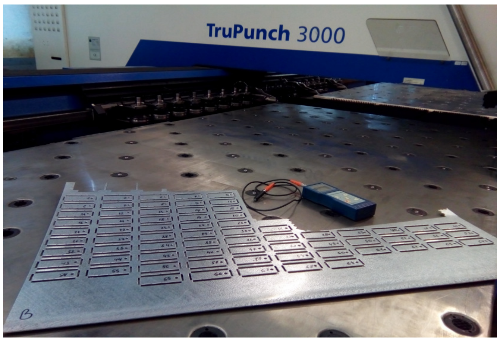

Fig. 1. **Sample placement in a sheet and a devise for measuring zinc layer thickness**

The zinc layer thickness was measured on both sides of the samples using a coating thickness digital meter CM-8822. The measurements revealed that the average zinc layer thickness was 55 ± 6 µm. The inside and outside bend radiuses of the folded samples were measured by a digital microscope VHX-100K.

Results and discussion

The results of measurements of inside and outside bend radiuses for the samples are summarised in Table 1.

Table 1

Outside bend radiuses of the samples depending on the punch and matrix parameters

Punch radius, *R* and matrix hole, *V*, mm	R 0.6 V 12	R 0.6 V 20	R 2 V 12	R 2 V 16	R 2 V 20	R 3 V 16
Average outside bend radius, R_{out}, mm	3.30 ±0.24	4.10 ±0.21	3.54 ±0.27	3.84 ±0.3	4.32 ±0.31	4.37 ±0.26

The results show that an increase in the matrix hole V, with the punch radius R being constant, affects an increase in the outside bend radius R_{out} more significantly than an increase in the bend radius of a punch, with the matrix hole size being the same.

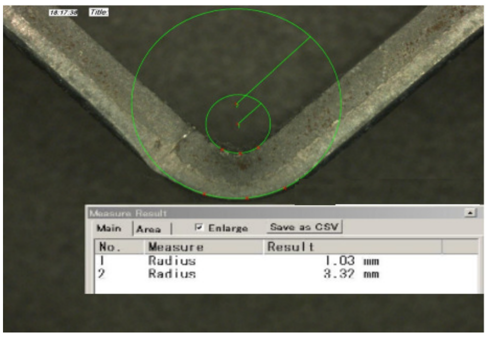

Fig. 2. **Bend radius measurements for Sample No. 20**

Surface defects on the outside of bend of a sample are captured at a preset magnification and the width of cracks in the zinc coating is measured at an accuracy of 0.01 µm. A table in Figure 3 shows that in a sample, which was folded to a radius of 3.32 mm by means of a punch R 0.6 and a matrix

V = 12, the widest zinc coating crack on the outside of bend was 104.22 μm in width; besides, the crack, just like a number of other ones, were oriented at an angle from the direction of folding. A photograph of the bent zone of Sample No. 30 is presented in Figure 3.

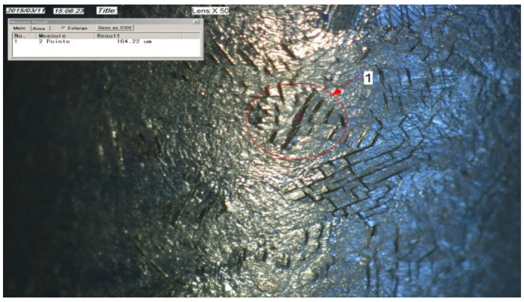

Fig. 3. **Cracks in the zinc coating for a sample folded by means of a punch R = 0.6, a matrix V = 16 (50x magnification)**

Further, using the options provided by the digital microscope, one can determine the width of cracks per unit of length in the bent surface of the samples. Based on the results, the relative crack width B, as a percentage, can be calculated employing the equation $B = \Sigma l_i / L$, where: l – width of the crack, mm; L – length of the area of measurements, mm.

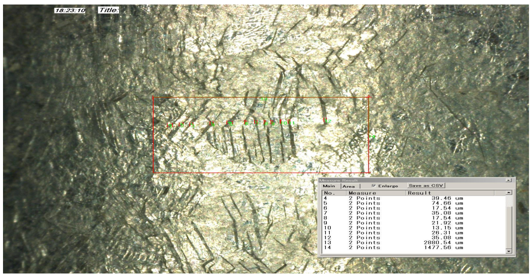

Fig. 4. **Identification of the relative width of cracks in a sample bent at a R_{out} = 3.32 mm (50x magnification)**

The calculations revealed that the relative width of cracks in the bent zone B for samples with a bend radius R_{out} ranging from 3.30 mm to 4.36 mm could reach 20-30 %. The results acquired indicate that the theoretical calculations on the probability of emergence of cracks in the zinc coating proved to be practically true.

Therefore, a question arises how the cracks in the zinc coating affect the corrosion resistance of zinc galvanised steel. As known from the literature [5], under medium corrosion risk conditions, a zinc coating of 0.042 mm in thickness provides the corrosion resistance of zinc galvanised steel for 20 years. This assertion is approximate, as no structure, homogeneity and relative elongation of the zinc coating have been specified. The literature [6] states that depending on the way and technology of production, the relative elongation of zinc at room temperature can range from 0.34 to 84%. If one wants to forecast the corrosion resistance of bent parts made of zinc galvanised steel sheets, it is required to know the way and technology of production of the zinc coating. The amount of zinc applied per m^2 is usually specified in grams and included in the product mark. In our case, the amount of zinc applied per m^2 is 600 g. The thickness of a zinc coating, h_c, could be calculated by the following equation if the amount of zinc applied per m^2 is known:

$$h_c = V_c/S_c = m_c/\rho_c/2S_c; \quad (1)$$

where V_c – zinc volume, m^3;
S_c – zinc coating surface area, m^2;
m_c – amount of zinc applied per $1m^2$;
ρ_c – zinc density, $kg \cdot m^{-3}$.

For example, if m_c = 0.600 kg, then h_c = 0.600/7140/2 = 0.000042 m = 0.042 mm = 42.1 μm. If m_c = 0.400 kg, h_c = 28.0 μm.

The relative deformation of a zinc coating in the tensioned zone is calculated by the equation:

$$A=(h_t/2+h_c)/R_n)\cdot 100, \quad (2)$$

where h_t – the thickness of a steel sheet, mm;
h_c – the thickness of a zinc coating, mm.

If a steel sheet is 2 mm thick, a zinc coating is 0.042 mm thick and a bend radius R_n is 2.5 mm, then the relative deformation A = 41.7%. According to the literature [4], the relative deformation of a zinc coating for a hot-galvanised steel sheet is approximately 45 %. One can conclude that with such parameters, the zinc coating should be undeformed and no cracks should emerge. It is likely that the zinc coating cracks because the base material – steel – cracks at such parameters. It is indirectly indicated by the experimental data on the values of relative crack width B. This assumption is also confirmed by the result obtained when examining the corrosion resistance of zinc galvanised samples in a 5 % acetic acid solution [7]. In the experiment, the samples were weighed and placed into a 5 % acetic acid anhydride solution, so that one half of them was in the solution, whereas the other half was in the air that was saturated with vapours of this acid. The first set of the samples was exposed to the acid for 24 h, the second – 48 h, the third – 72 h and the fourth – 96 h. After the samples were taken out of the solution, rinsed and dried out, they were again weighed at an accuracy of 0.0001 g. The intensity of corrosion in time was determined by the difference in the samples' weights. The results are presented in Figure 5.

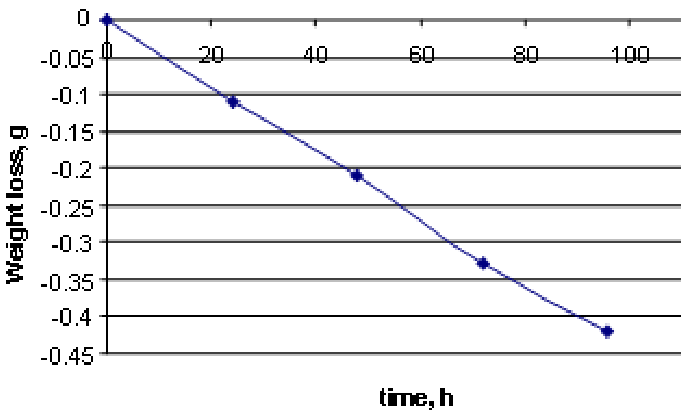

Fig. 5. **Weight losses of the zinc galvanised samples exposed to a 5 % acetic acid anhydride solution**

The results indicate that the weight of the samples placed in a 5 % acetic acid anhydride solution decreased linearly in proportion to the time the samples were exposed to the acid. Almost no changes in coating thickness, measured by the thickness meter, were observed for the sample half immersed in the acid. The coating thickness on the sample half being above the acid solution did not change as well. The corrosion could be best observed visually. A black line, the width of which increased with the time exposed to the acid, was specific to the transitional zone for all the samples. Similarly, corrosion signs increased near drill holes with the time exposed to the acid. The black coating's thickness ranged from 5 to 20 μm. The changes in zinc coating thickness in time are shown in Table 2.

The corrosion signs on the samples can be seen in Figure 6.

Table 2

Changes in zinc coating thickness in time

Duration of exposition to acid, hours	0	24	48	72	96
Zinc coating thickness, μm	56 ± 4 56 ± 4	56 ± 4 55 ± 3	56 ± 2.5 56 ± 3	47 ± 4 58 ± 4	54 ± 2.5 56 ± 2.5

An answer to the question how the zinc coating cracks in the bent zone affect the corrosion resistance of zinc galvanised steel is given by Figure 6. As seen in it, the samples having been immersed in the acetic acid anhydride solution for 48 h and longer had no zinc coating in the outside of bend; besides, the no-zinc coating zone increased with the time exposed to the acid.

Fig. 6. **Corrosion signs on the samples (sample No.4 was exposed to the acid for 24 h, No.20 – for 48 h, No.31 – for 72 h and No.37 – for 96 h)**

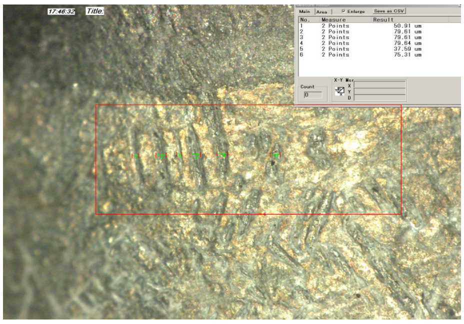

Fig. 7. **Sample folded at an outside bend radius of 3.32 mm (100x magnification)**

The cracks in the zinc coating are so deep that they reach the surface of steel and contribute to corrosion. The cracks on the surface of zinc galvanised steel sheets in the bent zone depends on the relative elongation. If replacing DX51D+Z600 steel sheets with DX56D+Z600 steel sheets, the relative elongation A is 39%, and the risk of surface cracking decreases 1.8 times.

Conclusions

1. Tensile strains, which can exceed the relative deformation value for the material to be zinc galvanised, emerge on the outside of bend during the process of folding zinc galvanised steel sheets. Consequently, the surface of steel cracks and contributes to the emergence of cracks in the zinc coating as well. The risk of cracks in the zinc coating of galvanised steel sheets increases with decrease in the bend radius and increase in the thickness of the base sheet.
2. Two mm thick DX51D+Z600 steel sheets with a relative deformation of 22 % and a zinc coating of 55 μm folded at an angle of 90º remain undeformed at a neutral axis bend radius of 3.5 mm if the outside bend radius is greater than 4.27 mm. Cracks in the zinc coating and changes in its thickness and shape contribute to the risk of corrosion.
3. Cracks on the surface of zinc galvanised steel sheets on the outside of bend depend on the relative elongation of the steel. If replacing DX51D+Z600 steel sheets with DX56D+Z600 steel sheets, the relative elongation A is 39 %, and the risk of surface cracking decreases 1.8 times.
4. Deformations emerging during the process of folding a zinc galvanised steel sheet are significantly affected by the geometric parameters of the punch and matrix. An increase in the matrix hole V, with the punch radius R being constant, affects an increase in the outside bend radius R_{out} more significantly than an increase in the bend radius of a punch, with the matrix hole size being the same. Defects on the surface of bent parts depend on the surface roughness of the moving parts – the punch and the matrix – and the precision of their production.
5. The corrosion resistance of bent parts made of zinc galvanised steel sheets depends on the thickness of the zinc coating on the bent surface. Compared with the unbent surface, a decrease in corrosion resistance in the bent zone is proportional to changes in the zinc coating's thickness.

References

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