Fatigue Damaging Mechanisms in a Hot-Dip Zinc Coated Steel

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ABSTRACT. *Hot-dip galvanizing is one of the most used methods to apply zinc-based coatings on steels, in order to provide sacrificial protection against corrosion over all the steel surface. The efficiency of the protection is affected by the coating mechanical response to loading: cracking and coatings delamination during forming and/or during service could decrease the corrosion resistance and could allow the contact between the environment and the substrate (the steel). In this work, fatigue damaging mechanisms of hot dip zinc coated steel plates were investigated by means of a non-standard fatigue-bending test performed considering high strain levels. Fatigue damaging micromechanisms were investigated by means of LOM (light optical microscope) analysis of metallurgically prepared longitudinal section of tested specimens, considering different applied cycle numbers (from 1 up to 1000).*

INTRODUCTION

Hot-dip galvanizing is one of commercially most important protection method of steel surfaces. Zinc and the zinc-based coatings provide a sacrificial protection against corrosion (in the galvanic protection zinc is less noble to steel at ambient condition), and play the role of a barrier to external environments [1].

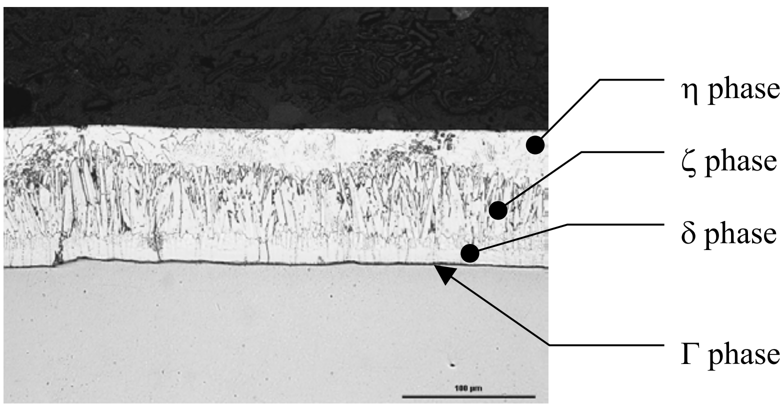


Figure 1: Zinc coating phases distribution

Zinc-based coating layer formation is obtained by diffusion of zinc atoms in iron and vice-versa. It is governed by physical parameters (bath temperature, immersion time, pre-galvanizing surface temperature, etc.) and chemical parameters (bath and steel chemical compositions, flux chemical composition, etc.) [2]. The result of the zinc coating is a multilayer system usually constituted by four phases (Fig. 1), characterized by different chemical compositions, thickness and mechanical properties. Outer layer is a ductile η phase with maximum Fe content up to 0.03%. The subsequent layer is named as ζ phase, wìch is isomorphous with a monoclinic unit cell and an atomic structure that contains a Fe atom and a Zn atom surrounded by 12 Zn atoms at vertices of a slightly distorted icosahedron. The icosahedra link together to form chains and the linked chains pack together in a hexagonal array [3]. δ phase is a brittle one with a Fe content up to 11.5 wt%, with an hexagonal crystal structure. The last phase is a very thin layer named Γ phase and is characterized by a Fe content up to 29 wt% (fcc).

In the last years, there has been an increase in zinc coatings research, focusing both coating procedures and mechanical behaviour characterization, in order to optimize Zn layer thickness and mechanical performances [4].

In this work, cyclic bending resistance of a zinc coated steel was investigated considering different bath chemical compositions (four different Pb content), analysing the damaging mechanisms by means of metallographic procedures.

MATERIAL AND EXPERIMENTAL METHODS

For all the investigated Zn-based baths, 3 mm thick commercial carbon steel plates were considered. Steel chemical composition is shown in Table 1; Zn and Zn/Pb baths were Fe saturated.

Table 1. Galvanized steel chemical composition (wt%).

C	Si	Mn	P	S	Al
.090	.167	.540	.010	.004	.051

Prior to galvanizing, steels samples were degreased and rinsed with alcohol. Subsequently specimens were pickled in an aqueous solution 20% H_2SO_4 at 50°C for 10 minutes, washed in fresh water, fluxed in an aqueous solution containing 280 g/l $ZnCl_2$ and 220 g/l NH_4Cl at laboratory temperature for 2 minutes and then dried for 10 minutes at 50°C. After this procedure, specimens were dipped for 1 minute considering four galvanizing baths (460 ± 2 °C), characterized by different Pb content (0, 0.1, 0.5, 1.0 wt%) [5].

Both static (1 cycle) and cyclic bending tests were performed considering a non-standard device (Figure 2, on the left) and repeated four times for each investigated coating bath.

Tests were performed using an electromechanical 100kN testing machine, considering a crosshead displacement range between 9 and 11 mm, that corresponds to a bending angle range between 9° and 11° (figure 2b) [6 - 9]. Finally, in order to identify the damaging mechanisms for each investigated coating bath, longitudinal sections of the bended specimens were metallografically obtained and observed by means of an optical microscope (LOM). Damage level was evaluated in terms of "radial cracks density" (cracks number/length) considering 6 images for each specimen (damage level is obtained as the mean value of 24 measurements, with a very high repeability). Crack paths were also evaluated analysing their interactions with Zn-based intermetallic phases. As a consequence, damage evaluation was considered as strongly connected with cracks nucleation: authors are conscious of the limit of this definition that do not take into account the crack growth in the different phases.

Damage and crack path analysis were performed considering different specimens after respectively 1, 10, 100, 1000 cycles.

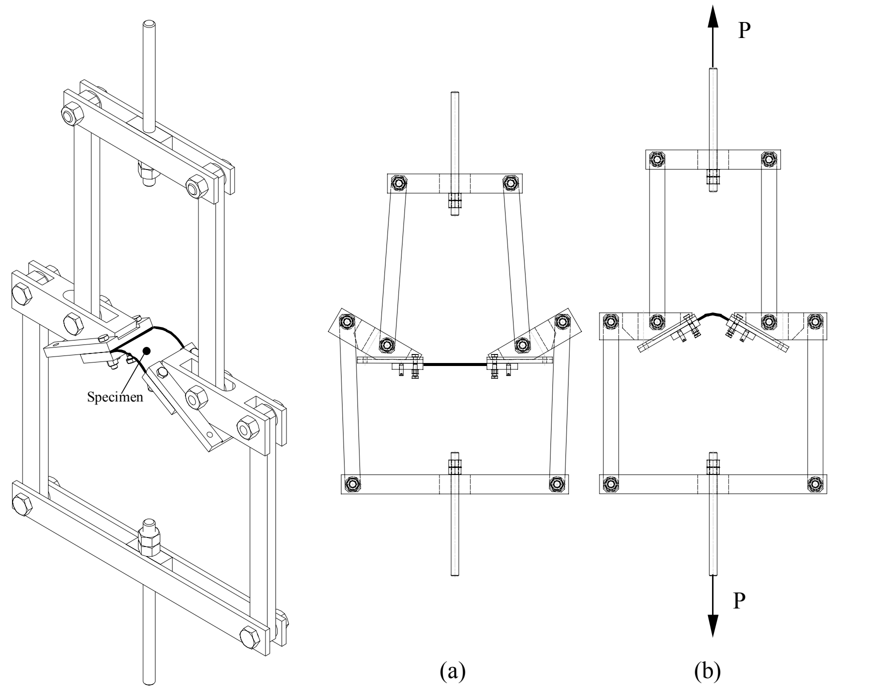


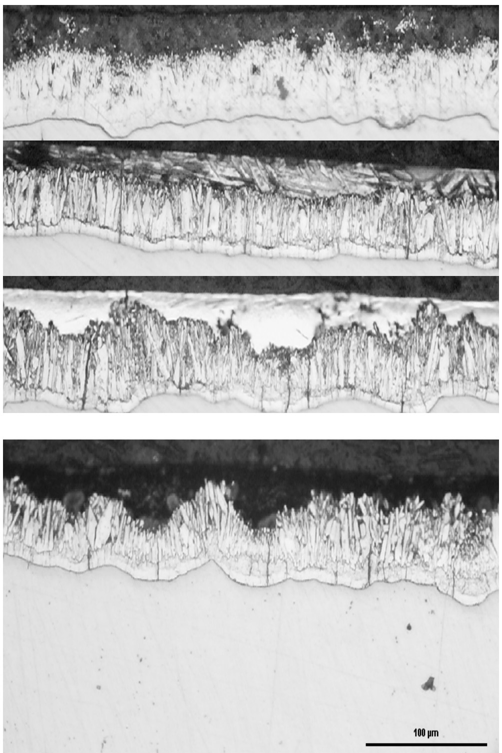
Figure 2: Clamping system for bending test (on the left). Different clamping configurations (on the right): a) starting position; b) generic position [10].

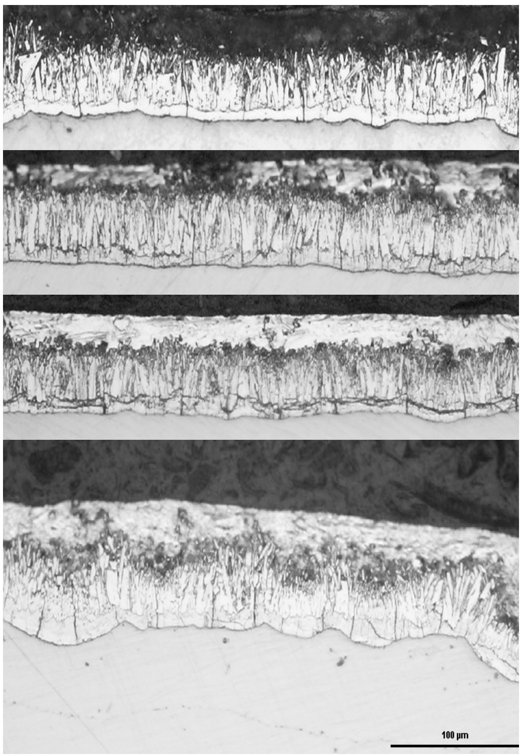
RESULTS AND DISCUSSION

Crack path analysis is shown in Figs. 3-6. Zn based intermetallic phases are characterized by different growing kinetics, implying an increase of their thickness as a function of the increase of the Pb content. Furthermore, morphological differences are evident between microstructures obtained with a Pb content equal to 1% and the other values. In fact, for Pb wt% up to 0.5, ζ phase is characterized by a columnar structure and corresponding to Pb wt% equal to 1.0, ζ phase looses its columnar character. Microstructure analysis performed on the tested specimens does not allow to observe an evident Γ phase and does not show either radial or longitudinal cracks in η phase (the external one, almost pure Zn).

Longitudinal and radial cracks are observed as a function both of the bath chemical composition and of the loading conditions. Longitudinal cracks are not observed for Pb wt% equal to 0, for all the investigated cycles number. The increase of the Pb content implies the presence of longitudinal crack after 100 cycles, preferentially at δ - ζ interfaces. For Pb wt% equal to 1, longitudinal cracks are also observed inside δ phase.

All radial cracks nucleate at Γ - δ interface and propagate in δ phase. A number of them could also propagate in ζ phase, up to the η – δ interface, where they definitevely stop. Radial cracks are considered to evaluate the damage level (Fig.7 and 8, mean values). Both δ and ζ phases are characterized by an increase of the damage level with the increase of the cycles number, with an evident influence of the Pb content up to a Pb wt% equal to 0.5, with the lowest rate obtained with Pb wt% equal to 0.





1 cycle

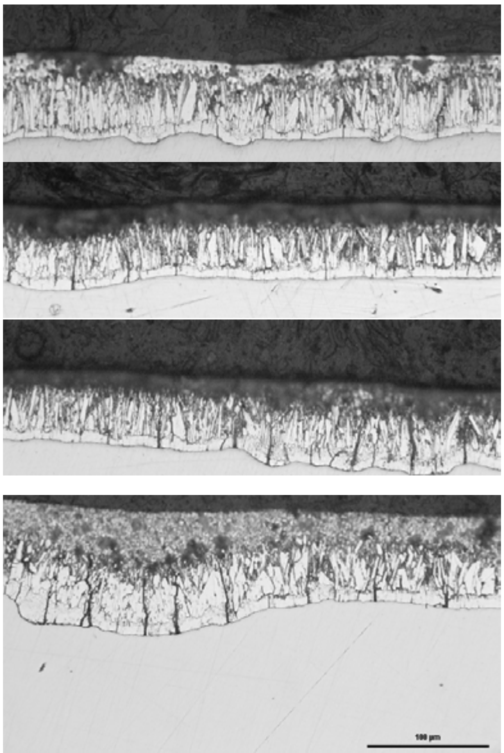
10 cycles

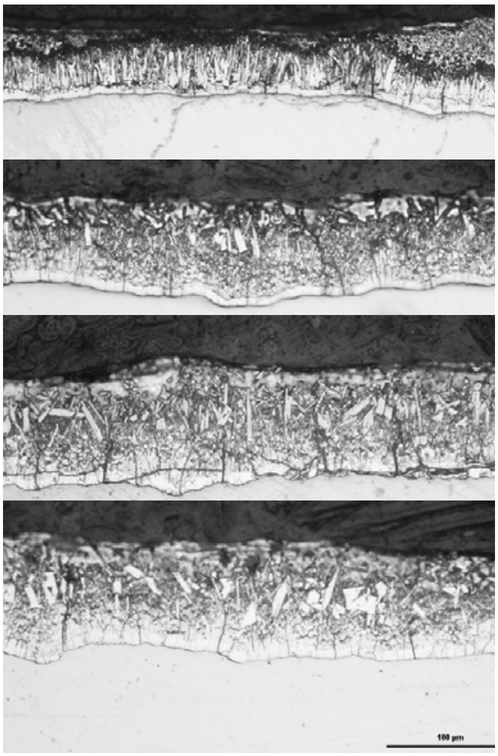
100 cycles

1000 cycles

Figure 3. Crack path analysis. 0% Pb

Figure 4. Crack path analysis. 0.1% Pb





1 cycle
10 cycles
100 cycles
1000 cycles

Figure 5. Crack path analysis. 0.5% Pb   Figure 6. Crack path analysis. 1% Pb

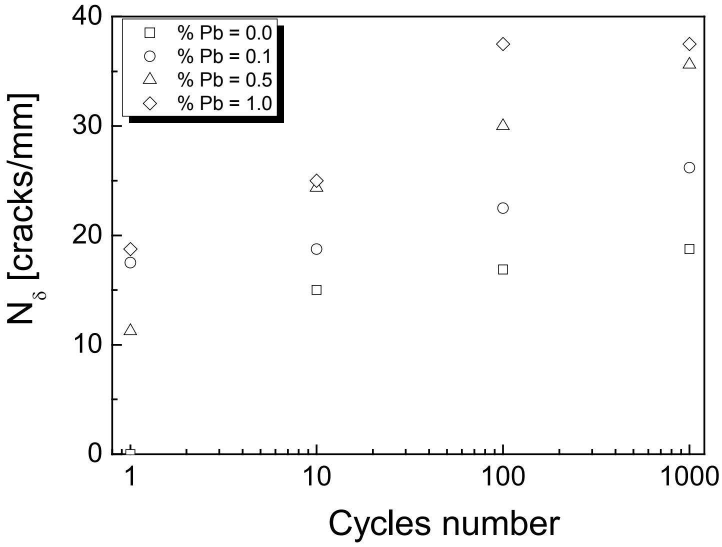


Figure 7. Damage level (δ phase).

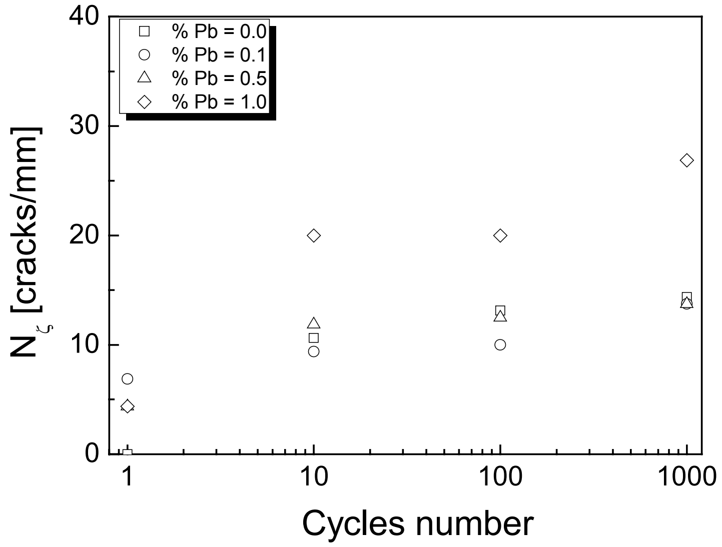


Figure 8. Damage level (ζ phase).

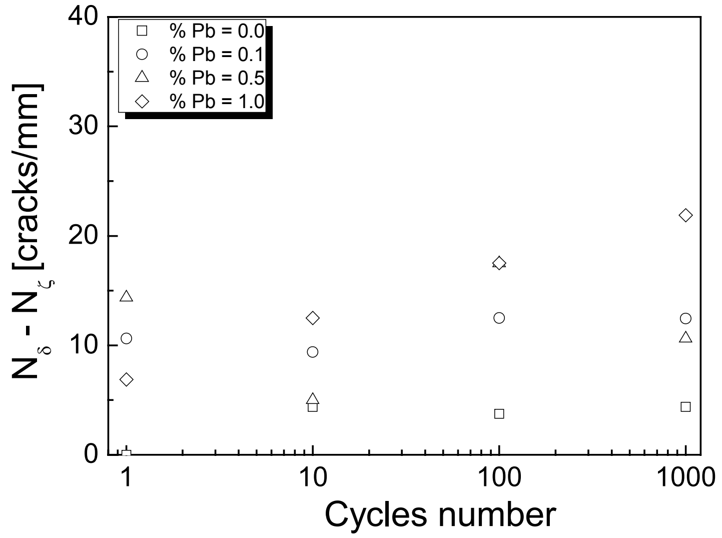


Figure 9. Cracks that do not propagate from δ phase into ζ phase.

For Pb wt% equal to 1, damage values are comparable or also lower than the values obtained for Pb% = 0.5. Damage evolution in the two considered phases is similar. This peculiar behaviour is probably due to different mechanisms: δ phase is characterized by an evident presence of longitudinal cracks, with a consequent decrease of the importance of the radial cracks nucleation; ζ phase looses its columnar character, and, consequentely, radial cracks are not still the preferential path. This mechanism is confirmed by the analysis of the evolution of the difference $N_\delta - N_\zeta$, that corresponds to the cracks number that do not propagate from δ phase into ζ phase (Fig. 9). For Pb% = 1, experimental values are linearly correlated with a very high correlation coefficient. This implies that crack propagation from δ to ζ phase is inhibited by the ζ phase morphology that does not presents preferential paths, and consequentely damage is concentrated as radial and longitudinal cracks in δ phase. For Pb% = 0 and 0.1, differences "$N_\delta - N_\zeta$" are pratically constant: cracks propagate from δ to ζ phase and find preferential path up to η phase.

CONCLUSIONS

In this work, cyclic bending resistance of a zinc coated steel was investigated considering different bath chemical compositions (four different Pb content from 0 up to 1.0 wt%), analysing the damaging mechanisms by means of metallographic measurements performed on longitudinal sections of tested specimens. Damage was identified as radial and longitudinal cracks and different damaging mechanisms were proposed considering the different phases distribution and mechanical properties.

Following results can be summarized:

- ductile η phase does not show any cracks;
- longitudinal cracks are evident only at δ-ζ interfaces (for Pb ≥ 0.1%) and in δ phase (Pb = 1.0%).
- radial cracks nucleate in δ phase and propagate in ζ phase, depending on the Pb content; for %Pb = 1, ζ phase peculiar morphology implies an increase of the difficulty for the crack propagation from δ phase, implying an increase of the importance of longitudinal cracks in δ phase.

Damage analysis based only on the consideration of radial cracks does not allow a complete characterization of the damaging mechanisms, especially considering higher Pb content.

REFERENCES

1. *ASTM Handbook Corrosion, Hot dip coatings* (1999) 13.
2. De Abreu, Y. Da Silva, A. Ruiz, A. Réquiz, R. Angulo, N. Alanis, R. (1999) *Surface and Coatings Technology* **120-121**, 682-697.
3. Marder, A.R. (2000) *Progress in Materials Science* **45**, 191-198.
4. Evangelos, T. Papadimitrou, G. (2001) *Surface and Coatings Technology* **145**, 176-188.
5. Reumont, G. Voct, J.B. Iost, A. Foct, J. (2001) *Surface and Coatings Technology* 1**39**, 265-277.
6. Duncan, J.L. Ding, S.-C. Jiang, W.L. (1999) *International Journal of Mechanical Sciences* **41**, 249-261.

7. Duncan, J.L. Ding, S.-C. Jiang, W.L. (1999) *International Journal of Mechanical Sciences* **41**, 261-277.
8. Kim, S.-R. Nairn, J.A. (2000) *Engineering Fracture Mechanics* **65**, 573-588.
9. Kim, S.-R. Nairn, J.A. (2000) *Engineering Fracture Mechanics* **65**, 595-609.
10. Natali, S. Di Cocco, V. Iacoviello, F. (2004) *La Metallurgia Italiana* **7-8**, 49-61.