1. Introduction

Hot-dip galvanizing (HDG) is a widely used technique to protect structural steel, due to its inherent capacity to long-lasting without requiring any maintenance.1–7

Such a technique consists in the formation of a protective layer of zinc on the surface of steel. In turn, zinc oxidizes but with a rate much lower with respect to uncoated steel. As a matter of fact, the zinc-consumption rate in a normal urban environment is of the order of 1 μm per year (up to 2 μm per year in the case of polluted environment) and this is equivalent to state that the duration of the protection by HDG would be even beyond 50 years, considering an average zinc thickness which is often times higher than the minimum one prescribed by the UNI EN ISO 1461 standard.8–10

Therefore, a zinc coating protects steel with a double mechanism,10 that is, 1) by a barrier effect, interposing itself between the steel surface and the aggressive atmosphere (passive protection) being perfectly continuous and impact resistant; 2) by a cathodic protection, corroding itself instead of steel, due to the different electromechanical potential of these two materials (active protection). It is worth noting that the 2) effect ensures that, in the case of nicks, scratches, and small uncoated regions, the surrounding zinc corrodes itself instead of steel. Moreover, the corrosion products tend to seal the above defects, preventing oxygen and other aggressive elements of coming into contact with uncoated steel, holding up the degradation process. By the way, the zinc in atmosphere tends to cover itself with a thin stable layer of oxides and carbonates (passivation layer) that protects it from dissolution, determining the long duration of steel protection.

When the steel is dipped in the zinc bath (molten zinc at a temperature equal to about 450 °C), a series of zinc-iron alloy layers (intermetallic phases) are formed with different chemical compositions of the above two metals. This is not a chemical reaction but, instead, a physical process or metallurgical reaction. As a matter of fact, the growth of a HDG coating is due to the interdiffusion of zinc and iron atoms between the zinc melting sphere (passive protection) being perfectly continuous and impact resistant; 2) by a cathodic protection, corroding itself instead of steel, due to the different electromechanical potential of these two materials (active protection). It is worth noting that the 2) effect ensures that, in the case of nicks, scratches, and small uncoated regions, the surrounding zinc corrodes itself instead of steel. Moreover, the corrosion products tend to seal the above defects, preventing oxygen and other aggressive elements of coming into contact with uncoated steel, holding up the degradation process. By the way, the zinc in atmosphere tends to cover itself with a thin stable layer of oxides and carbonates (passivation layer) that protects it from dissolution, determining the long duration of steel protection.

The intermetallic phases that grow during the dipping in the zinc bath are well characterized and recognizable both in terms of chemical composition and morphology of microstructure.10

As a matter of fact, each of them corresponds to one of the homogeneous phases in the zinc-iron phase diagram (Figure 1), where the content of zinc in the coating increases by moving from the inner zone to the outer zone, whereas the iron content decreases by moving from the inner zone to the outer zone.

In a typical zinc coating, the following intermetallic phases are recognizable10 and, by starting from the steel substrate, they are (Figure 2): 1) the fcc phase, consisting in a layer of about 1 μm in thickness, characterized by a zinc (Zn) content of about 70%; by
chemical compositions and morphologies of microstructure

Figure 2. Zinc-iron phase diagram.

Figure 2. Typical zinc coating intermetallic phases: $\Gamma$, $\delta$, $\zeta$, and $\eta$ phases.

weight and an iron (Fe) content ranging between 26.8% and 31.1% by weight. The phase is characterized by a face-centered cubic atoms arrangement: 2) the $\delta$ phase, characterized by an iron content of the order of 10% by weight and by a hexagonal crystal structure; 3) the $\zeta$ phase, characterized by an iron content of about 7% by weight. It is an isomorphous phase, characterized by a monoclinic unit cell and an atomic structure that contains a Fe atom and a Zn atom, surrounded by 12 Zn atoms at the vertices of a slightly distorted icosahedron. Such icosahedra are linked together to form chains, organized in a hexagonal array. 4) the $\eta$ phase, characterized by a chemical composition quite similar to that of the bath, with a maximum iron content up to 0.03% by weight. When the bath consists of a technological zinc alloy (e.g., by adding tin and nickel), such a phase will be influenced by the presence of the above chemical elements.

The fact that coating is composed by layers with different chemical compositions and morphologies of microstructure produces a variability of the mechanical properties along the coating thickness. As a matter of fact, the elastic modulus ranges from 75 GPa (in correspondence to $\eta$ phase) to 140 GPa (in correspondence to $\delta$ phase), whereas the microhardness ranges from 70 VHN ($\eta$ phase) to 280 VHN ($\delta$ phase). Therefore, the outer phases are characterized by ductility and high attitude to plastic deformation, whereas the inner phases are characterized by lower ductility. Moreover, the $\eta$ phase is soft and able to absorb impact, whereas the more inner phases, characterized by a high microhardness, give to galvanized steel advantages in terms of wear resistance and toughness.

Moreover, it is worth noting that the adherence of the coating to the steel support is guaranteed by the formation mechanics, that is, the interdiffusion of Zn atoms and Fe atoms. Such a mechanics produces evident benefits with respect to other anti-corrosive treatments that employ metals overlapping (as, e.g., in the electroplating and metallization processes) or organic coating (as, e.g., liquid or powder paints).

In the last years, there has been an increasing research on zinc coatings, in order to optimize the phases thickness and the mechanical and physical performances. Such a research has to inevitably take into account the factors that influence the formation mechanics, and more precisely: 1) the temperature and bath composition; 2) the dipping time; 3) the composition and the superficial state of the steel.

About the bath temperature, the operation conditions are usually between 440 and 460 °C. However, for technical zinc-based coatings, high-temperature baths, up to 550 °C, are possible. The formation of the $\zeta$ phase does not take place, and therefore the coating is composed by $\delta$ and $\eta$ phases. At such high temperatures, thicknesses greater than 100 μm are difficult to be reached.

About the bath composition, generally the zinc bath is pure at 98% (as required by the UNI EN ISO 1461 standard). A very small amount of other metals can be present, added as technological components of the alloy or as zinc impurities. In the context of technological zinc alloys, mainly nickel, aluminum, strontium, tin, bismuth, and magnesium are added. For example, the addition of nickel into the bath delays the growth of $\delta$ phase. Thus, zinc-based coating holds superior performance in terms of corrosion resistance, weldability, adherence, uniform thickness, and good paintability with respect to pure zinc coating. On the other hand, corrosion resistance and adherence can be improved by strontium addition.

About the dipping time, it is generally between 1.5 and 5 min. In the first minutes, the greatest growth of the coating thickness occurs. Clearly, the steel thickness plays a decisive role to determine the dipping time inside the bath.

About the composition of the steel, the addition of other elements to iron and carbon in the alloy leads to an increasing or decreasing of the growth of coating thickness. More precisely, the additions that strongly influence such a growth are the silicon and the phosphorus. As a matter of fact, it was experimentally observed that a content of silicon between 0.03% and 0.12% in weight (sandelin range) or higher than 0.25% in weight (hyper-sandelin steels) is able to accelerate the Zn–Fe diffusion, resulting in coatings characterized by high thickness. Moreover, the combined effect of silicon and phosphorus amplifies the sandelin effect.
Also, the steel state can influence the coating thickness, and more precisely its surface roughness, due to both the carryover effects and the increased specific surface.

In the present article, the bending behavior of a HDG hot-rolled hyper-sandelin steel is numerically simulated by considering both a pure zinc coating and a zinc-based coating with 3% Sn addition in weight, that is, a technological coating. More precisely, the proposed numerical models aim to simulate some experimental bending tests available in the literature,[24–27] performed by considering, for each of the aforementioned baths, five different dipping time values. The numerical models, developed by using the finite element method (FEM), exploit the experimental observations of the longitudinal section of the specimens at the end of the bending tests, performed by light optical microscope, in terms of intermetallic phase thickness, morphology, and damage.

**Table 1.** Chemical composition of the steel support (wt%).

| Element | C  | Si  | Mn  | P  | S  | Al  | Fe   |
|---------|----|-----|-----|----|----|-----|------|
|         | 0.090 | 0.167 | 0.540 | 0.010 | 0.004 | 0.051 | Bal. |

**Table 2.** Thickness of the intermetallic phases: pure zinc bath and technological bath by varying the dipping time.

| Dipping time [s] | Phase | Pure Zn bath [μm] | Technological bath [μm] |
|------------------|-------|-------------------|------------------------|
| 15               | δ     | 13                | 15                     |
|                  | ζ     | 4                 | 20                     |
|                  | η     | 9                 | 22                     |
| 60               | δ     | 17                | 16                     |
|                  | ζ     | 10                | 20                     |
|                  | η     | 43                | 25                     |
| 180              | δ     | 11                | 13                     |
|                  | ζ     | 75                | 36                     |
|                  | η     | 16                | 27                     |
| 360              | δ     | 18                | 15                     |
|                  | ζ     | 140               | 52                     |
|                  | η     | 22                | 31                     |
| 900              | δ     | 12                | 34                     |
|                  | ζ     | 150               | 76                     |
|                  | η     | 28                | 47                     |

**Figure 3.** Geometrical configuration of the steel specimen. Sizes in mm.

**Figure 4.** Nonstandardized device employed to perform the bending tests.
The article is organized as follows. Section 2 is dedicated to the experimental campaign description, in terms of specimens, baths composition, dipping times, testing machine used, and obtained results. Section 3 is aimed to the numerical models description. Numerical results are presented in Section 4 and compared with the experimental ones. Conclusions are summarized in Section 5.

2. Experimental Campaign

The experimental tests\textsuperscript{[24–27]} were performed on HDG specimens under constant bending moment, applied by means of a nonstandardized device.\textsuperscript{[13]} The longitudinal sections of the specimens were experimentally observed by a light optical microscopy (LOM) to measure both the phases thicknesses (before testing) and the level of damage (after testing).\textsuperscript{[28,29]}

The specimens, manufactured from hot-rolled hyper-sandelin steel plates, had the geometrical configuration shown in Figure 3.

The chemical composition is reported in Table 1.

The galvanized process was preceded by the preparation of steel support. More precisely, first, the surface was degreased and rinsed by using alcohol. Then, the specimen was pickled in an aqueous solution of hydrochloric acid (50\%) for 10 min at room temperature, washed in fresh water (20 °C), and fluxed in an aqueous solution of zinc chloride (280 g L\(^{-1}\)) and ammonium chloride (220 g L\(^{-1}\)) for 2 min at room temperature. Finally, the specimen was dried (50 °C) for 10 min.

The coating was performed at 460 ± 2 °C by using two different baths: 1) a pure zinc bath; 2) a technological bath, obtained by employing a tin addition (3\% Sn in weight).

Five different dipping times were considered, that is, 15, 60, 180, 360, and 900 s.

The experimental observations of coating sections performed by LOM allowed to identify the coatings kinetic and to measure the thickness of each intermetallic phase, as reported in Table 2. More precisely, as the intermetallic phases tend to interpenetrate, that is, their boundaries cannot be perfectly defined (as it is shown in Figure 2), dividing lines that best approximate their thickness were drawn and the thickness of each phase measured by means of a suitable imaging software. For each dipping time examined, 26 metallographic images were analyzed, where the thickness values listed in Table 2 are the average values of such measurements.

The bending tests were performed by the nonstandardized device shown in Figure 4, represented by a double symmetrical articulated mechanism. The specimen, containing two holes (Figure 3), was clamped by two gripping heads. The tests were performed under the displacement control of the crosshead. The force \( F \) and the bending angle were measured and registered during testing. The feature of such a device was to apply a constant bending moment along the calibrated length of the specimen (Figure 3). The test was stopped at a crosshead displacement equal to 35 mm.

The curve of bending moment against half-bending angle is reported in Figure 5 for each dipping time and for the two coatings employed.

For both coatings it can be observed that, for a given value of the half-bending angle, the bending moment increases by increasing the dipping time (up to 11\% for the pure zinc coating and to 15\% for the zinc-based coating, with respect to a dipping time equal to 15 s) and that, for a given value of dipping time, the reached bending moment, in the case of technological coating, was greater with respect to the pure zinc coating.

After the testing, the longitudinal section of the specimen was observed by means of the LOM, where the specimen was metallographically prepared and etched by using nital at 1\% for 1 s.

The metallographies obtained at the end of the testing are reported in Appendix for each dipping time and for both the coatings examined (see Figure A1 and A2). Due to the fact that the compressive side was characterized by a negligible damage, only the tensile side is reported in Appendix for each specimen examined. Mainly radial cracks were observed on such a side, both for the pure zinc and the technological coating, and more precisely, it was observed that the cracks nucleated at the coating-support interphase. Then, different crack paths were followed, that is, 1) crack propagated in \( \delta \) phase and arresting at the \( \delta-\zeta \) interphase; 2) crack propagated both in \( \delta \) and \( \zeta \) phases, arresting in \( \zeta \) phase; 3) crack propagated both in \( \delta \) and \( \zeta \) phases, arresting in \( \zeta-\eta \) interphase. It is worth noting that no crack propagation

![Figure 5. Bending moment versus half-bending angle for each dipping time examined, in the case of: a) pure zinc bath and b) technological bath.](image-url)
was observed in η phase. Only for high values of dipping time, the presence of some longitudinal cracks was observed.

In order to quantify the damage inside the intermetallic phases, the radial cracks density (cracks no./length) was calculated by counting the number of cracks present on the tensile side, and measured along a length equal to 1 mm. This operation was repeated six times on each metallography examined. In Figure 6, the radial cracks density at the end of the testing is plotted against the dipping time for both the pure zinc bath and the technological bath.

It can be observed that the mechanical behavior of the specimens coated by using a technological bath is more ductile with respect to those coated by a pure zinc bath for each dipping time examined, due to the ductility of all the intermetallic phases that characterize the zinc-based coating. Moreover, the best galvanizing condition was obtained for a dipping time equal to 60 s for both baths.

3. Numerical Models

The FEM is used to numerically simulate the behavior of coated specimens, tested according to the procedure described in Section 2. A commercial FE modeling software package (Straus 7, G + D Computing, Sydney, Australia) is used.

Two numerical models are developed, and more precisely: 1) model A, used to simulate the specimens galvanized by a pure zinc bath; 2) model B, used to simulate the specimens galvanized by a zinc-based bath with an addition of 3% by weight of tin.

The difference between the above models consists in the laws used to simulate the behavior of intermetallic phases, due to the fact that in the technological coating all phases experimentally showed a ductile behavior, whereas in the pure zinc coating only the η phase showed a ductile behavior.
The geometry of the steel specimen is reported in Figure 3, although for the sake of modeling only the calibrated length is considered, and equal to 50 mm. Each intermetallic phase, observed during the experimental campaign, is modeled as a single layer, whose thicknesses are listed in Table 2. Perfect adherence is assumed between each layer, due to the fact that mainly radial cracks were experimentally observed.

As each specimen is in a plane strain condition, a 2D FE model is developed and, due to the symmetry of the problem, only one-half of the specimen is modeled (Figure 7). The boundary condition applied on the symmetric axis consists in displacement along $x_1$ axis and the rotation around $x_3$ axis equal to zero for all nodes on such an axis (Figure 7). In order to simulate the testing condition, represented by the imposed displacement of the crosshead of testing machine, an imposed rotation along the border line of the model, characterized by $x_1 = 25$ mm, is applied (Figure 7). The aforementioned boundary conditions allow to achieve a constant bending moment in all sections of the numerical model, that is, the same loading condition characterizing the tested specimens.

The discretization employed is shown in Figure 7. The type and the number of the FEs used are listed in Table 3

| Model A | Dipping time [s] | FE type | FE no. | Nodes no. | Minimum FE size [mm] |
|---------|------------------|--------|--------|-----------|----------------------|
| Steel   | –                | Quad4  | 6252   | 7351      | $2.31 \times 10^{-2}$ |
| $\delta$ phase | 15          | Quad4  | 2160   | 4324      | $1.30 \times 10^{-2}$ |
|        | 60               |        | 2160   | 4324      | $1.67 \times 10^{-2}$ |
|        | 180              |        | 2160   | 4324      | $1.10 \times 10^{-2}$ |
|        | 360              |        | 4320   | 6482      | $9.17 \times 10^{-3}$ |
|        | 900              |        | 2160   | 4324      | $1.18 \times 10^{-2}$ |
| $\zeta$ phase | 15          | Quad4  | 2160   | 4324      | $4.00 \times 10^{-3}$ |
|        | 60               |        | 2160   | 4324      | $9.75 \times 10^{-3}$ |
|        | 180              |        | 10000  | 12 972    | $1.50 \times 10^{-2}$ |
|        | 360              |        | 21 600 | 23 782    | $1.40 \times 10^{-2}$ |
|        | 900              |        | 25 920 | 28 106    | $1.25 \times 10^{-2}$ |
| $\eta$ phase | 15          | Quad4  | 2160   | 4324      | $9.00 \times 10^{-3}$ |
|        | 60               |        | 8640   | 10 810    | $1.08 \times 10^{-2}$ |
|        | 180              |        | 2160   | 4324      | $1.58 \times 10^{-2}$ |
|        | 360              |        | 4320   | 6482      | $1.10 \times 10^{-2}$ |
|        | 900              |        | 4320   | 6482      | $1.40 \times 10^{-2}$ |

Table 4. Model B: type and no. of FEs, no. of nodes and minimum size of the FE employed for each dipping time examined.

| Model A | Dipping time [s] | FE type | FE no. | Nodes no. | Minimum FE size [mm] |
|---------|------------------|--------|--------|-----------|----------------------|
| Steel   | –                | Quad4  | 6252   | 7351      | $2.31 \times 10^{-2}$ |
| $\delta$ phase | 15          | Quad4  | 2160   | 4324      | $1.49 \times 10^{-2}$ |
|        | 60               |        | 2160   | 4324      | $1.63 \times 10^{-2}$ |
|        | 180              |        | 2160   | 4324      | $1.29 \times 10^{-2}$ |
|        | 360              |        | 2160   | 4324      | $1.49 \times 10^{-2}$ |
|        | 900              |        | 4320   | 6482      | $1.70 \times 10^{-2}$ |
| $\zeta$ phase | 15          | Quad4  | 4320   | 6482      | $9.73 \times 10^{-3}$ |
|        | 60               |        | 2160   | 4324      | $2.01 \times 10^{-2}$ |
|        | 180              |        | 6480   | 8648      | $1.21 \times 10^{-2}$ |
|        | 360              |        | 6480   | 8648      | $1.73 \times 10^{-2}$ |
|        | 900              |        | 10 800 | 12 972    | $1.52 \times 10^{-2}$ |
| $\eta$ phase | 15          | Quad4  | 4320   | 6482      | $1.08 \times 10^{-2}$ |
|        | 60               |        | 2160   | 4324      | $2.31 \times 10^{-2}$ |
|        | 180              |        | 4320   | 6482      | $1.35 \times 10^{-2}$ |
|        | 360              |        | 4320   | 6482      | $1.56 \times 10^{-2}$ |
|        | 900              |        | 6480   | 8648      | $1.56 \times 10^{-2}$ |
model A and in Table 4 for the model B, together with the nodes no. and the FE minimum size.

The FE analysis is a nonlinear static one.

3.1. Model A: Constitutive Laws

The stress–strain curve for the steel under tension is typical of an elastoplastic with strain hardening material, whereas under compression is elastic (Figure 8a).

The stress–strain curve for the \( \delta \) phase is typical of an elastic material, with a tension cutoff (Figure 8b).

The stress–strain curve for the \( \eta \) phase is typical of an elasto-perfectly plastic material under tension, whereas under compression is elastic (Figure 8c).

The parameters characterizing such stress–strain curves are listed in Table 5.

3.2. Model B: Constitutive Laws

The stress–strain curve for the \( \zeta \) phase is typical of an elastic material, with a tension cutoff (Figure 8b).

The stress–strain curve for the \( \eta \) phase is typical of an elasto-perfectly plastic material under tension, whereas under compression is elastic (Figure 8c).

The parameters characterizing such stress–strain curves are listed in Table 5.

**Figure 8.** Stress–strain curves employed in the numerical modeling: a) elastoplastic with strain hardening, b) elastic material with cutoff, and c) elasto-perfectly plastic.

### Table 5. Mechanical parameters of the steel and intermetallic phases for both model A and B.

| Material/phase | Reference | \( E \) [GPa] | \( \sigma_{y,H} \) [MPa] | \( \sigma_{y,S} \) [MPa] | \( \sigma_{y,H} \) [MPa] | \( \sigma_{u} \) [MPa] | \( \varepsilon_{0} \times 10^{3} \) | \( \varepsilon_{S} \times 10^{3} \) | \( \varepsilon_{i} \times 10^{3} \) | \( \varepsilon_{r} \times 10^{3} \) | \( \varepsilon_{u} \times 10^{3} \) | \( \varepsilon_{c} \times 10^{3} \) |
|---------------|-----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Steel         | [27]      | –              | 450            | 400            | 588            | 533            | 2.76           | 5.60           | 2.16           | 5.92           | 1.11           | –              |
| \( \eta \) phase | [12]     | 75             | 210            | –              | –              | –              | –              | –              | –              | –              | –              | –              |
| Model A       |           |                |                |                |                |                |                |                |                |                |                |                |
| \( \delta \) phase | [12]    | –              | 450            | –              | –              | –              | –              | –              | –              | –              | –              | 3.21           |
| \( \zeta \) phase | [27]     | –              | 210            | –              | –              | –              | –              | –              | –              | –              | –              | 2.25           |
| Model B       |           |                |                |                |                |                |                |                |                |                |                |                |
| \( \delta \) phase | [12]    | 140            | 450            | –              | –              | –              | –              | –              | –              | –              | –              | –              |
| \( \zeta \) phase | [27]     | 93             | 450            | –              | –              | –              | –              | –              | –              | –              | –              | –              |
The stress–strain curve for the $\delta$, $\zeta$, and $\eta$ phases is typical of an elasto-perfectly plastic material under tension, whereas under compression is elastic (Figure 8c).

The parameters characterizing the mechanical behavior of the steel and intermetallic phases are listed in Table 5.

4. Results and Discussion

In Figure 9, the contour plot of the Von Mises stress in the tensile side of the model A is reported for a bath characterized by a dipping time equal to 180 s. The region in the plot is that across the symmetric axis over a length equal to about 1 mm. Different values of the half-bending angle are considered and more precisely: $1^\circ$, $2^\circ$, $4^\circ$, $6^\circ$, $12^\circ$, $20^\circ$, $25^\circ$, and $32^\circ$. In Figure 10, such a contour plot is reported for the model B. The following values of the half-bending angle are considered and more precisely: $1^\circ$, $2^\circ$, $4^\circ$, $6^\circ$, $11^\circ$, $21^\circ$, $25^\circ$, and $33^\circ$.

Figure 9. Pure zinc coating (dipping time 180 s). Von Mises stress field at different values of the half-bending angle, that is, a) $1^\circ$, b) $2^\circ$, c) $4^\circ$, d) $6^\circ$, e) $12^\circ$, f) $20^\circ$, g) $25^\circ$, and h) $32^\circ$. The contour plot is related to the region across the symmetry axis and over a length equal to about 1.0 mm.

Figure 10. Zinc-based coating (dipping time 180 s). Von Mises stress field at different values of the half-bending angle, that is, a) $1^\circ$, b) $2^\circ$, c) $4^\circ$, d) $6^\circ$, e) $11^\circ$, f) $21^\circ$, g) $25^\circ$, and h) $33^\circ$. The contour plot is related to the region across the symmetry axis and over a length equal to about 1.0 mm.
Relatively to the pure zinc bath simulation (Figure 9), it can be observed that: 1) for very low values of half-bending angle, both the steel support and the intermetallic phases experience an elastic behavior, with stress values occurring in $\delta$ phase higher than those in $\zeta$ and $\eta$ phases; 2) for half-bending angle equal to $4^\circ$, $\sigma_{y,H}$ is reached in the steel support, and the elastic limit is exceeded in the intermetallic phases; 3) for half-bending angle higher than $11^\circ$, the steel support is characterized by a hardening behavior.

Relatively to the technological bath simulation (Figure 10), it can be observed that: 1) for very low values of half-bending angle, both the steel support and the intermetallic phases experience an elastic behavior, with stress values occurring in $\delta$ phase higher than those in $\zeta$ and $\eta$ phases; 2) for half-bending angle equal to $4^\circ$, $\sigma_{y,H}$ is reached in the steel support, the elastic limit is exceeded in the $\delta$ phase, and $\zeta$ and $\eta$ phases exhibit an elastic behavior; 3) for half-bending angle equal to $6^\circ$, $\sigma_{y,S}$ is reached in the steel support, and the intermetallic phases experience a plastic behavior; 4) for half-bending angle higher than $21^\circ$, the steel support is characterized by a hardening behavior.

In Figure 11, the results obtained by using the model A, in terms of bending moment against the half-bending angle, are...
shown for each bath examined and compared with the experimental results, whereas the results obtained from model B are shown in Figure 12.

Note that, in such figures, the dashed lines define an error equal to ±5% computed with respect to the value of the experimental bending moment, whereas the dash-dotted lines define an error equal to ±10%.

Relatively to the pure zinc bath simulations, it can be observed that: 1) for a given value of the half-bending angle, the numerical bending moment overestimates the corresponding experimental one in the elastic regime; 2) the numerical bending moment does not exceed the ±10% of the corresponding experimental value from half-bending angles greater than about 4°, that is, in the plastic regime.

Relatively to the technological bath simulations, it can be observed that: 1) for the dipping times equal to 15 and 60 s, the slope of the elastic branch is quite well simulated by the numerical model B; 2) for the dipping times equal to 180, 360, and 900 s, and for a given value of the half-bending angle, the numerical bending moment overestimates the corresponding experimental one in the elastic regime; 3) the numerical bending moment does not exceed the ±10% of the corresponding experimental value from half-bending angles greater than about 3°, that is, in the plastic regime.

Figure 12. Numerical bending moment versus half-bending angle in the case of the technological coating simulation at the dipping time of: a) 15 s, b) 60 s, c) 180 s, d) 360 s, and e) 900 s. The experimental data are also reported.
5. Conclusions

In the present article, the bending behavior of a HDG hot-rolled hyper-sandelin steel has been numerically simulated. Two coating types have been considered and more precisely: a pure zinc coating and a zinc-based coating with 3% Sn addition by weight.

As it was experimentally observed, the above coatings are characterized by a different mechanical behavior under bending, with an increase in flexural strength in the case of technological coating, for each dipping time examined. As a matter of fact, although the tin addition influences the thickness of each intermetallic phases, the better performance in terms of flexural strength is due to the increased ductility of the intermetallic phases.

Therefore, the key of the numerical simulation has been to assume suitable constitutive laws to phase layers, by considering that only few mechanical parameters are available in the literature, especially for the technological coating here examined. Therefore, such an assignment has been derived mainly from considerations on both the physical phenomenon of the interdiffusion between Zn and Fe atoms, and on the metallographies of the tensile side of the specimens.

Such an approach has shown quite satisfactory results. As a matter of fact, in general, although for a given value of the half-bending angle the numerical bending moment overestimates the corresponding experimental one in the elastic regime, such a moment does not exceed the ±10% of the corresponding experimental value from half-bending angles greater than about $3\textdegree-4\textdegree$, that is, in the plastic regime.

The numerical models developed have been able to capture also the experimental finding that only $\delta$ and $\zeta$ phases were damaging, whereas the $\eta$ phase did not show any radial cracks.

Such an approach can be promising as a numerical tool to be used by HDG industry, being quite simple but quite accurate to estimate flexural strength and damaging of Zn-based coated steels.

Appendix

The metallographies obtained at the end of the testing are reported in Figure A1 and A2 for each dipping time and for both the coatings examined. Due to the fact that the compressive side

![Figure A1](image)

Figure A1. Tensile side of the specimen in the case of the pure zinc bath at the dipping time of: a) 15 s, b) 60 s, c) 180 s, d) 360 s, and e) 900 s.
was characterized by a negligible damage, only the tensile side is reported for each specimen examined.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords

bath, dipping time, hot-dip galvanizing (HDG), technological coating, zinc-based coatings

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