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Improved Zn-based coatings for ipersandelin steel products

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Abstract

The protection of iron-based alloy products against corrosion is fundamental to preserve their mechanical properties in aggressive environments. Hot-dip galvanizing process represents one of the most used techniques to make protective coatings for such products. In order to improve both mechanical and chemical properties of coating, metallic elements may be added to the traditional zinc bath.

In the present paper, two types of improved zinc-based coating are proposed:

- (i) A coating obtained employing a tin addition (3% in weight);
- (ii) A coating obtained employing aluminium (5% in weight), tin (1% in weight) and copper (0.5% in weight) additions.

Firstly, the performance of such two types of coatings is experimentally investigated through bending tests on ipersandelin steel plate specimens, treated through different bath dipping times. The intermetallic phase thicknesses of coatings are measured for each dipping time, in order to evaluate the kinetic formation. Then, a Finite Element (FE) model is proposed in order to simulate the bending behaviour of the above specimens, both employing the measured phase thickness and implementing the loading and boundary conditions of the experimental tests. A numerical non-linear static analysis is performed.

A quite satisfactory agreement between experimental and numerical results is observed, especially under plastic behaviour regime.

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1. Introduction

The protection of metallic materials in aggressive environments has a fundamental role in many fields, especially in the industrial one, from both esthetical and mechanical point of view. Hot-Dip Galvanizing (HDG) represents one of the most common techniques aiming to protect metallic materials, in particular iron-based alloy, against corrosion and, consequently, to preserve their mechanical properties through the time (Carpio et al. (2010), Marder (2000)).

The interdiffusion between the atoms of the substrate and those of the zinc bath generates a layered coating, the so-called intermetallic phase, with different chemical composition (Culcasi et al. (1999), Massalski (1986)). In particular, the outer zone is rich of zinc, while iron is predominant in the inner zone. Each intermetallic phase is characterised by different thickness and mechanical properties, which are mainly influenced by bath temperature and immersion time, since such environmental conditions act on the interdiffusion phenomenon. In order to optimise both mechanical and chemical properties of coating, alloys of metallic elements may be added to the galvanizing bath (Di Cocco (2012), Di Cocco et al. (2014), Katiforis and Papadimitriou (1996), Natali et al. (2015), Shibli et al. (2007)).

In the present work, two different types of improved Zn-based coatings are analysed, by considering an addition of both (i) tin and (ii) aluminium, tin and copper.

First of all, the mechanical behaviour of the two aforementioned coatings is experimentally analysed by performing bending tests on galvanized ipersandelin steel plate specimens. In particular, three different dipping times of the support into the bath are examined and, for each of them, the intermetallic phase thicknesses are measured in order to evaluate the kinetic formation.

Then, a 2D Finite Element (FE) model is implemented in order to simulate the above experimental tests. The bending behaviour (in terms of bending moment against half-bending angle) is numerically investigated by implementing into the model both intermetallic phase thicknesses, experimentally measured, and loading and boundary conditions applied during tests.

2. Materials, method and experimental results

Two series of rectangular 80x25x3mm specimens are obtained from two hot-rolled ipersandelin plates (named Base 1 and Base 2 in the following). Then, they are polished and pre-treated, as is described in detail in Di Cocco et al. (2014). Each base is galvanized in different baths, by employing two types of coating:

- (i) An addition of tin (3% in weight) to the traditional Zn-coating, deposited on the Base 1 (Series 1 specimens);
- (ii) An addition of aluminium, tin and copper (5%, 1% and 0.5%, respectively) to the traditional Zn-coating, deposited on the Base 2 (Series 2 specimens).

For each series, three dipping times, equal to 60, 180 and 360s, are examined. It has experimentally been observed that dipping time has an influence on both coatings, in terms of phase thicknesses and intermetallic phases formation. In particular, there are two common phases in each galvanized series, that is:

- A δ phase, characterized by high content of iron (equal to about $7\pm 12\%$ in weight), located in the inner zone of the coating;
- An η phase, characterized by low content of iron (less than 5-6% in weight), located in the outer zone of the coating.

After the measurement of intermetallic phase thicknesses for each specimen, performed by means of an Optical Light Microscope (LOM), experimental bending behaviour is investigated. In particular, the abovementioned hot-dip galvanized specimens are tested on a non-standard device, as is described in Di Cocco et al. (2014). Such a device does not allow them to roll, and ensures a constant bending moment in all specimen sections. The two series are tested under bending angle control, up to a half bending angle equal to 35 degrees, which corresponds to a residual half bending angle of the related ungalvanized specimen equal to about 30 degrees.

2.1. Experimental results for Series 1 specimens

For Series 1, LOM analysis shows the presence of an additional intermetallic phase named ζ phase, situated between δ - and η -phase. It is characterized by medium content of iron (equal to about 5 to 6% in weight) and,

increasing dipping time, such a phase experimentally shows a crystal redistribution leading to a non-orientated structure. Such a microstructural behaviour strongly influences the mechanical behaviour of ζ phase, resulting in a dipping time-dependent phase.

In Table 1, the measured intermetallic phase thicknesses related to Series 1 specimens are listed for each dipping time examined.

Table 1. Thicknesses of intermetallic phases for Series 1 and Series 2 specimens.

	Dipping time (s)	Intermetallic phase thickness (μm)			
		δ	ζ	lamellar	η
Series 1	60	16	20	-	25
	180	13	36	-	27
	360	15	52	-	31
Series 2	60	4	-	130	-
	180	20	-	120	210
	360	22	-	210	220

2.2. Experimental results for Series 2 specimens

As is observed for Series 1 specimens, LOM analysis on Series 2 specimens shows the presence of a third phase which is lamellar, situated between δ - and η - phase. Intermetallic phases at compressed side of a Series 2 specimen, corresponding to a dipping time equal to 360s, are shown in Figure 1.

In Table 1, the measured intermetallic phase thicknesses related to Series 2 specimens are listed for each dipping time examined.

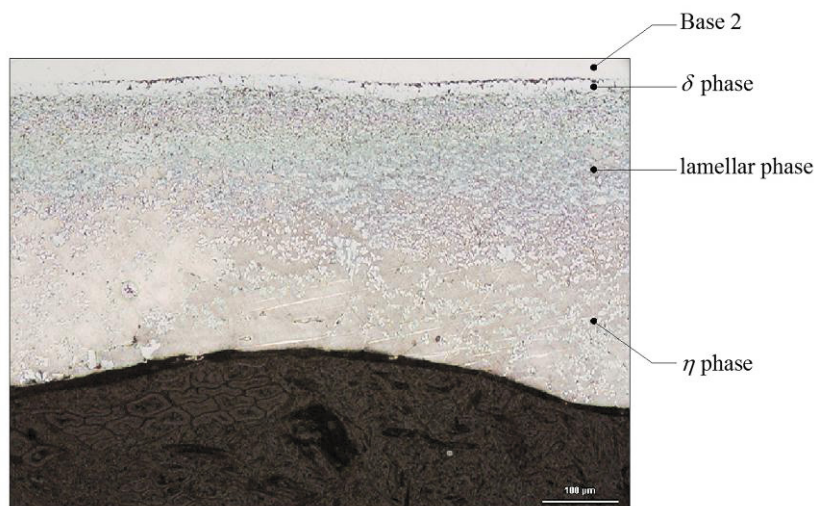


Figure 1: Intermetallic phases located at the compressed side of a Series 2 specimen, corresponding to a dipping time equal to 360s.

3. Numerical model and results

A Finite Element (FE) model is herein proposed in order to simulate the bending behaviour of each galvanized series of specimens, by varying the dipping time. Such a numerical model is developed by employing the commercial finite element software Straus7, G+D Computing, Sydney, Australia. A schematic representation of both the base and the intermetallic phases is shown in Figure 2. Note that the total length of each specimen is assumed to be equal to 50mm, corresponding to the specimen calibrated length.

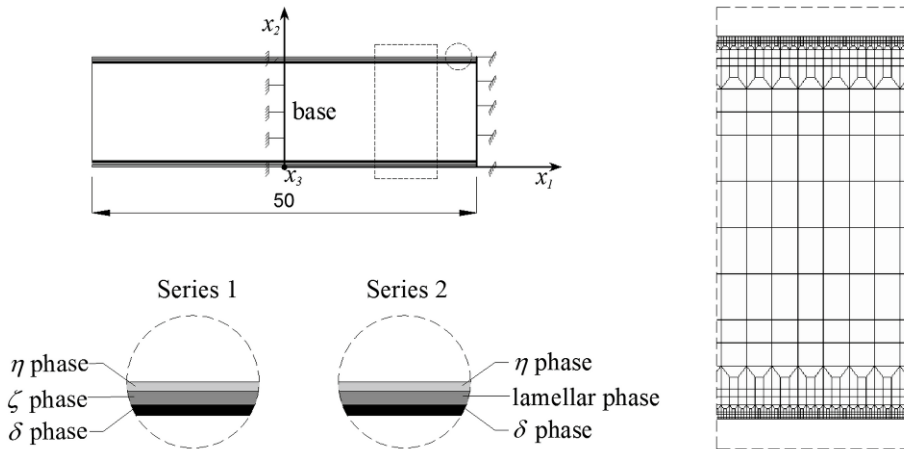


Figure 2: Schematic representation of the base and the intermetallic phases for Series 1 and Series 2 specimens.

Under the hypothesis of plain strain condition, a 2-dimensional model is implemented and, because of the symmetry, only one half of specimen is modelled. The discretisations of bases and intermetallic phases are obtained by employing 4-node plates.

In order to adequately simulate experimental tests, non-linear static analysis is performed by employing the following boundary conditions:

- (1) For $x_1=0\text{mm}$ (see Fig.2), the displacements along both x_1 - and x_2 -axis and the rotation around x_3 -axis are kept equal to 0;
- (2) For $x_1=25\text{mm}$ (see Fig.2), a rotation around x_3 - axis is applied, by increasing the half bending angle from 0 to 35 degrees.

3.1. Numerical results for Series 1 specimens

The assumed stress-strain curve for Base 1 is typical for ductile steels, with the mechanical properties listed in Table 2. The stress-strain curves for δ - and η - phase are typical of elastic-plastic materials, with the mechanical properties listed in Table 2. The assumed stress-strain curve for ζ phase is:

- (i) For the dipping times equal to 60s, the same as that of δ - and η - phase;
 - (ii) For the dipping times equal to 180 and 360s, the stress-strain curve shown in Figure 3(a);
- whereas the curves for δ - and η - phase are assumed to be dipping time-independent.

A comparison between experimental and numerical results, in terms of bending moment against half-bending angle, is shown in Figure 4(a)-(b), for dipping times equal to 60 and 360s, respectively. A satisfactory agreement between such results can be noticed, especially in plastic region (that is, for half-bending angle higher than 7 degrees). As can be observed, the phase thickness increasing with dipping time leads to appreciably higher bending moment bearing. The dashed lines in Figure 4 represent a scatter band equal to ± 1 degrees, corresponding to the accuracy of the testing machine.

Table 2. Mechanical properties of bases and intermetallic phases for Series 1 and Series 2 specimens.

		E (MPa)	$f_{y,H}$ (MPa)	$f_{y,L}$ (MPa)	f_{max} (MPa)	f_u (MPa)
Series 1	Base 1	190000	450	400	588	533
	δ, ζ, η phase	73000	210	-	-	-
Series 2	Base 2	150000	450	-	-	350
	$\delta, \text{lamellar phase}$	73000	210	-	-	-
	η phase	73	0.210	-	-	-

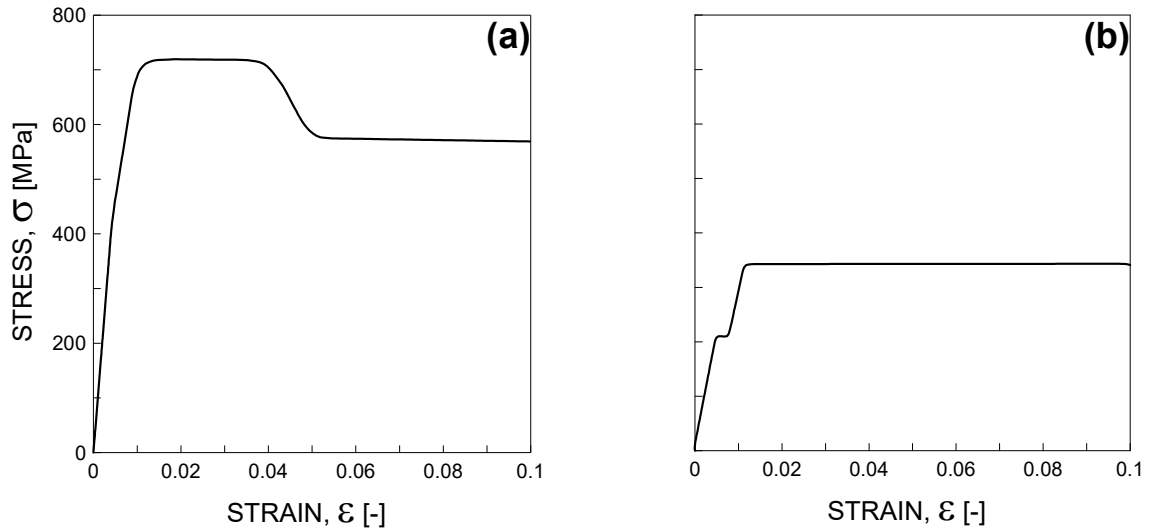


Figure 3: Stress-strain curve of: (a) ζ phase, for the dipping time equal to 180 and 360s ; (b) lamellar phase, for dipping time equal to 360s.

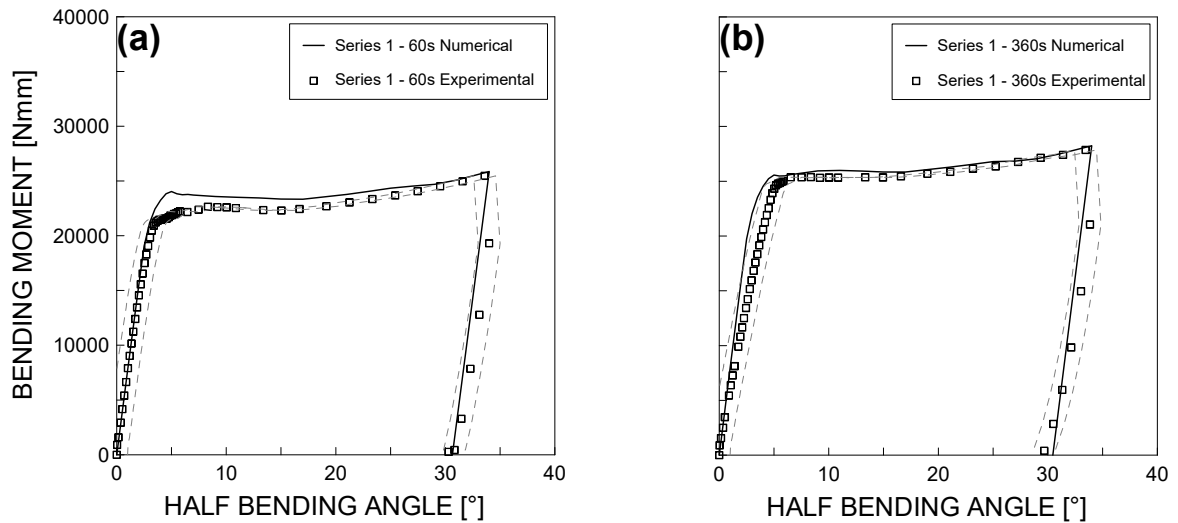


Figure 4: Experimental and numerical results related to Series 1 specimens for the dipping time equal to: (a) 60s ; (b) 360s.

3.2. Numerical results for Series 2 specimens

The assumed stress-strain curve of Base 2 is typical for cast irons, with mechanical properties reported in Table 2. The stress-strain curves of δ - and η - phase are typical of elastic-plastic materials. Nevertheless, η phase shows a much lower both yield stress and elastic modulus respect to those of δ phase, giving a very small contribution to mechanical behaviour and strength. Their mechanical parameters are reported in Table 2. Such stress-strain curves are assumed to be dipping time-independent, whereas the stress-strain curve of lamellar phase is:

- (i) For the dipping times equal to 60 and 180s, the same as that of δ phase;
- (ii) For the dipping time equal to 360s, the stress-strain curve shown in Figure 3(b).

A comparison between experimental and numerical results, in terms of bending moment against half-bending angle, is shown in Figure 5(a)-(b), for dipping times equal to 60 and 360s, respectively. A satisfactory agreement between experimental and numerical results can be noticed, showing a stronger influence of phase thickness on mechanical behaviour in the case of Series 2 specimens with respect to the Series 1 specimens.

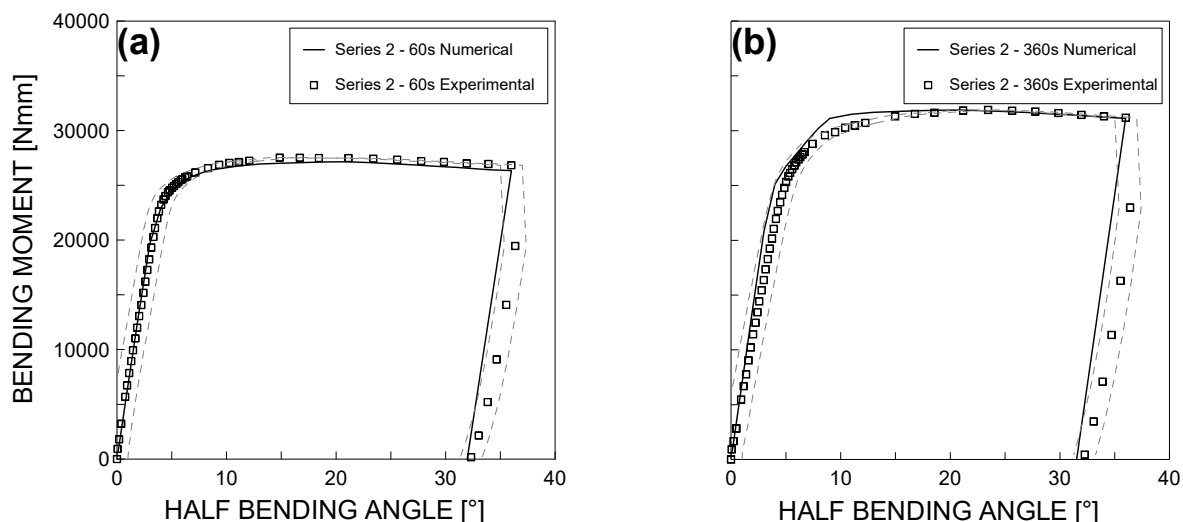


Figure 5: Experimental and numerical results related to Series 2 specimens for the dipping time equal to: (a) 60s ; (b) 360s.

4. Conclusions

In the present work, the mechanical behaviour of ipersandelin steel plate specimens, galvanized with two different types of improved zinc-based coatings, has been analysed. In particular, both a coating with an addition of tin and a coating with an addition of aluminium, tin and copper have been studied by considering three different dipping times in galvanization bath.

Experimental bending tests have been carried out by means of a non-standard device, which prevents specimens to roll and ensures them to have constant bending moment in all specimen sections.

Then, a Finite Element (FE) model has been developed in order to simulate bending behaviour of tested specimens, by performing a non-linear static analysis and implementing suitable boundary conditions.

The agreement between experimental and numerical results is quite satisfactory. Such results show how coating thickness can influence the mechanical behaviour of specimens due to kinetic formation and mechanical properties of intermetallic phases. In particular, this influence is more pronounced for Series 2 specimens, characterized by a zinc coating improved with aluminium, tin and copper.

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References

- Carpio, J., Casado, J.A., Álvarez, J.A., Méndez, D., Gutiérrez-Solana, F., 2010. Stress corrosion cracking of structural steels immersed in hot-dip galvanizing baths. *Engineering Failure Analysis* 17, 19–27.
- Culcasi, J.D., Sere, P.R., Elsner, C.I., Di Sarli, A.R., 1999. Control of the growth of zinc–iron phases in the hot-dip galvanizing process. *Surface and Coatings Technology* 122, 21–23.
- Di Cocco, V., 2012. Sn and Ti influences on intermetallic phases damage in hot dip galvanizing. *Frattura ed Integrità Strutturale* 22, 31–38.
- Di Cocco, V., Iacoviello, F., Natali, S., 2014. Damaging micromechanisms in hot-dip galvanizing Zn based coatings. *Theoretical and Applied Fracture Mechanics* 70, 91–98.
- Katiforis, N., Papadimitriou, G., 1996. Influence of copper, cadmium and tin additions in the galvanizing coatings. *Surface and Coatings Technology* 78, 185–195.
- Marder, A.R., 2000. Metallurgy of zinc-coated steel. *Progress in Materials Science* 45, 191–271.
- Massalski, T.B., 1986. Binary alloy phase diagrams (2nd Volume). American Society for Metals, Metals Park Ohio.
- Natali, S., Volpe, V., Zorzea, L., Burattini, C., Di Cocco, V., Iacoviello, F., 2015. Mechanical and Structural Characterization of Zn-Ti Colored Coatings. *Procedia Engineering* 109, 105–112.
- Shibli, S.M.A., Jayalekshmi, A.C., Remya, R., 2007. Electrochemical and structural characterization of the mixed oxides-reinforced hot-dip zinc coating. *Surface and Coatings Technology* 201, 7560–7565.