Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 99 (2021) 266–271

www.elsevier.com/locate/procedia

14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '20

Deformation behavior of pre-painted steel sheets

Daniele Ciccarelli[a], Archimede Forcellese[a], Luciano Greco[a], Tommaso Mancia[a], Massimiliano Pieralisi[a], Michela Simoncini[b*], Alessio Vita[a]

[a]*Dipartimento di Ingegneria Industriale e Scienze Matematiche, Università Politecnica delle Marche, Via Brecce Bianche, 60100 Ancona, Italy*
[b]*Università degli Studi eCampus, Via Isimabrdi 10, 22060 Novedrate (CO), Italy*

* Corresponding author. Tel.: +39 071 2204443. *E-mail address:* michela.simoncini@uniecampus.it; m.simoncini@staff.univpm.it

Abstract

The present work aims at studying the tensile behaviour of a hot-dip galvanized Z100 steel sheet, coated with a silicone-modified polyester resin. To this purpose, the pre-painted steel sheet was subjected to interrupted tensile tests at different strain levels in order to evaluate the elongation capability of both paint coating and steel sheet. The occurrence of superficial damages on paint coating was detected and the damage evolution before the sample fracture was analyzed. Furthermore, the thinning of each layer of the pre-painted sheet was also evaluated as a function of strain levels. Before the onset of necking, the degree of thinning on the different layers is almost uniform, whilst, once the necking was reached, a noticeable reduction in the thickness of both paint and steel sheet can be observed in the central zone of tensile sample.

Peer-review under responsibility of the scientific committee of the 14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 15-17 July 2020.

Keywords: Pre-painted steel sheets; Uniaxial tensile test; Superficial damage; Thin-film coatings; Coating thinning

1. Introduction

In the manufacturing processes of household appliances, thin steel sheets are widely used for the obtaining of external covers of equipment, such as boilers, washing machines, ovens, air conditioners and outdoor units, due to the good elongation capability with a poor thinning attitude before fracture shown by steel sheets [1]. The conventional approach in the manufacturing of these components requires the performing of a sequence of metal forming and cutting processes in order to give to the parts the desired final shapes; then, the steel panels undergo a painting operation which firstly provides the obtaining of a coating on both sides by means of a primer able to improve the protection against corrosion, then the deposition of a finishing top layer, generally white, in order to give the coating a glossy surface finish and, at the same time, a good scratch resistance [2,3].

During the last few years, the technological innovations developed by the coating industries, in terms of new recyclable materials, innovative surface pre-treatments and painting cycles, led to significant changes in the production processes of appliances, due to the use of pre-painted steel sheets, i.e steel sheets that were film-coated prior to the forming and cutting processes. The elimination of the painting process offers several advantages, such as the strong reduction of volatile organic compounds or hydrocarbons harmful to health and atmospheric pollution [3], and the rise in the efficiency of production, as demonstrated by Escobar-Saldívar et al. [4]. As a matter of fact, pre-painted sheets can be very economic for household appliance manufacturers because they can obtain savings due to the elimination of costs associated with both the painting operation and stringent disposal requirements for paint chemicals. Furthermore, the manufacturers can buy pre-painted sheets from external suppliers without the need of an in-plant painting process.

In spite of these advantages, the use of pre-painted sheets in manufacturing processes was restricted by the occurrence of damages in the coating and adhesive bond between coating, primer, and metal sheet, that arise during the metal forming processes, and that make the component useless [3,5]. Then, in a metal forming process it is essential to ensure both that the steel substrate is deformed without fractures during the forming

2212-8271 © 2021 The Authors. Published by Elsevier B.V.

Peer-review under responsibility of the scientific committee of the 14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 15-17 July 2020.
10.1016/j.procir.2021.03.039

process, and that the integrity of the paint coating on the underlying steel layer is preserved [6]. To this purpose, the knowledge of coating elongation capability before the occurrence of aesthetic damages is fundamental in processes in which plastic deformation plays a significant role.

To date, many studies on mechanical properties, formability and thinning attitude of metal sheets were performed [7–11], whilst few investigations are available on the occurrence of coating damages in pre-coated sheet subjected to metal forming processes. Ueda et al. [12] studied the rheological properties of polyester/melamine paint systems with different molecular weights and glass transition temperatures of polyester resin and various weight ratios of polyester/melamine, to investigate the formability of paint film in deep drawing process. They obtained that the paint films, characterized by the polyester with high glass transition temperature and high contents of the melamine resin, are not easily deformed. Moreover, the damage to paint films of pre-painted sheet after deep drawing decrease with a rise in the molecular weight of polyester resin, with a decrease in glass transition temperature of polyester resin and with a decrease in the weight ratios of melamine resin. Prosek et al. [13] analyzed the behavior of various polymer-based paints subjected to accelerated tests in corrosive environments and a connection between the internal tensile stress in topcoat paints and the blister density on full paint systems was shown. Sorce et al. [14] analyzed the influence of different crosslinker contents on the mechanical properties of free-film polyester coatings, demonstrating that a higher crosslinker content produces a more brittle material with a reduced strain to failure, while samples with a lower crosslinker content exhibit a greater strain to failure. Forcellese et al. [15] studied the formability of steel sheets pre-painted using a silicon modified polyester resin. They observed that the degree of damage to the paint coating depends on the loading conditions; in particular, under biaxial balanced stretching condition the paint coating is characterized by a limiting dome height, that is the dome height at which paint is damaged due to the occurrence of debonding at the coating–sheet interface, lower than that of steel sheet, demonstrating that the deformation limit of the pre-painted sheet is defined by the elongation capability of the coating rather than the formability of the steel sheet. Behrens and Gaebel [16] investigated the formability of an anti-fingerprint clear coating on satin stainless steel sheet and defined the coating specific forming limit curve. Thus, more research on the deformation capability of paint used as finishing top coating is needed.

In this framework, the present work aims at investigating the tensile behavior of a pre-painted steel sheet under uniaxial stretching condition. Interrupted tensile tests were until different strain levels in order to evaluate the elongation capability of both paint coating and steel sheet. At each strain level, superficial damages on the paint coating were detected and thinning of the different layers of pre-painted sheets was evaluated and analyzed.

2. Material and Experimental Methods

2.1. Material

A pre-painted steel sheet, schematically represented in Fig. 1, was investigated in the present work. It was composed by the low carbon steel sheet Z100 for cold forming (885 μm in thickness), zinc-coated on both sides by means of continuously hot-dip coating process, according to the ASTM A653/A653M-19a and EN 10346:2015 standards [17,18]. The hot-dip galvanized steel sheet was subjected to a degreasing and washing phases for removing the surface impurities. Subsequently, a pre-treatment was performed using immersion iron-phosphating technology to provide a good resistance to corrosion and scratching to the sheets and to prepare the surfaces to the coating application. After the passivation process, lasting about 40 seconds, and the phosphating process, the plates were dried at a temperature of around 130°C to be ready for the next painting phase. The cycle includes the lay down of two layers of 5 μm thick epoxy-polyester resin, as top and back primers, to improve the anticorrosion function. Finally, a silicone-modified polyester layer, about 35 μm in thickness, was applied as finishing top coating.

The final thicknesses of the dry pre-painted sheet were about 0.920 mm. Tolerances of the pre-coated steel are in accordance with the EN 10143:2006 standard guidelines [19].

2.2. Uniaxial tensile test

Uniaxial tensile tests were performed at room temperature on the pre-painted steel sheet (Fig. 2), according to ASTM E8/E8M [20], using the servo-hydraulic testing machine MTS 810® supplied of a 250 kN load cell, at a constant crosshead speed of 0.1 mm/s. An extensometer clamped down on the sample surface was used to measure the instantaneous strain

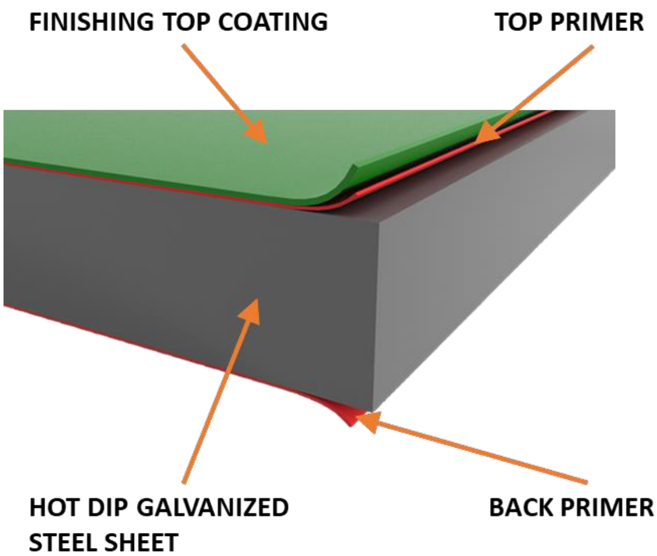

Fig. 1. Scheme of the pre-painted steel sheet.

developed during tests.

The experimental nominal stress (s) values were plotted as a function of the nominal strain (e). The s-e curves allowed to detect the mechanical properties of the pre-painted steel sheet, such as the yield strength (YS), ultimate tensile strength (UTS), uniform elongation (e_u) and total elongation (e_t). Furthermore, the nominal stresses vs. nominal strain curves were converted to true stress (σ) vs. true strain (ε) curves in the region of uniform plastic deformation (until the onset of necking); the flow curve allowed the evaluation of the strain hardening exponent (n) and strength coefficient (K), according to the ASTM E646 standard guidelines [21]. Interrupted tensile tests were also carried out at different strain values in order to monitor the coating appearance and to detect the presence of surface defects as a function of strain level. To this purpose, the Leica EZ template 4D stereomicroscope was used to identify the occurrence of coating defects. The thinning attitude of the different layers of the pre-painted sheet was also investigated by means of periodic acquisitions of the cross-section of the samples deformed at different strain values. The image analysis system Leica Application Suite was used for the measurement of the thicknesses of both coatings and steel sheet layers (Fig. 3). Finally, the results of the interrupted tensile tests at an elongation of 15%, in the region of uniform deformation, were used to measure the normal anisotropy R, equal to the ratio between true strain in the width direction (ε_w) and true strain in the thickness one (ε_t) of the sample [22]. At least three tensile tests were performed under each process condition in order to assure the repeatability of experimental results.

Fig. 2. Tensile test of pre-painted steel sheet.

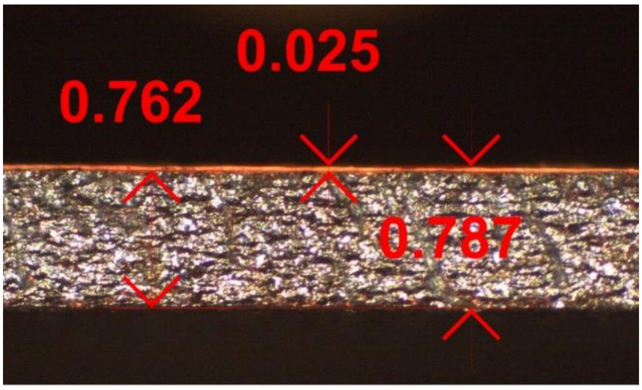

Fig. 3. Steel sheet and coating thickness measurement method along a typical cross-section of a deformed pre-painted sheet.

3. Results and discussion

3.1. Mechanical behavior of pre-painted steel sheet

Fig. 4 shows typical pre-painted steel samples before and after tensile test. It can be observed that the pre-painted sheet exhibits a wide deformation capability. Such behaviour is confirmed by the typical s-e curve obtained by tensile test performed on the pre-painted steel sheet, shown in Fig. 5. The pre-painted sheet is characterized by an elastic region in which the nominal stress linearly rises with the nominal strain, until reaching the yield strength value equal to 145 MPa. Then, the nominal stress rises with a non-linear behavior until reaching the ultimate tensile strength of about 266 MPa, at an ultimate elongation value of 0.27. The pre-painted steel sheet exhibits a wide post-necking region, equal to about 32.5% of the total elongation to failure.

The strain hardening exponent of the material, that is the measure for how quickly the material gains strength when it is being deformed, and strength coefficient, equal to the true stress value at a true strain of 1, were obtained as slope and intercept of the best line fit to true stress versus true strain data in the region of homogeneous plastic deformation, plotted on a logarithmic scale [22].

In order to assess the normal anisotropy (R) of the pre-painted steel sheet, uniaxial tensile tests were carried out until reaching an elongation of 15% [22]. The painted sheet is characterized by a high value of normal anisotropy, equal to 3, indicating that the pre-painted sheet exhibits a very high attitude to be deformed without necking. The high R value justify the high post-necking deformation shown in Fig. 5.

Table 1 summarizes the mechanical properties, evaluated by means of uniaxial tensile tests, of both pre-painted steel sheet and, as a comparison, the hot deep galvanized Z100 steel, used as base material for the pre-painted steel sheet. As expected, no significant discrepancies in terms of mechanical properties can be seen between the pre-painted steel sheet and Z100 steel sheets, denoting the negligible contribution of coating resins on the mechanical properties of pre-painted material.

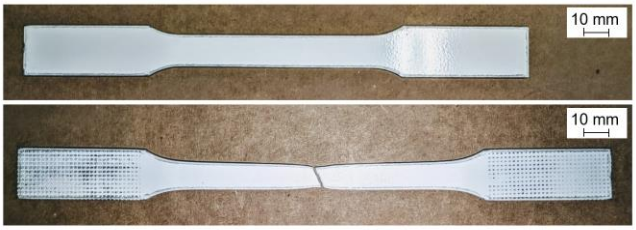

Fig. 4. Tensile samples in pre-painted steel sheet before and after tensile tests.

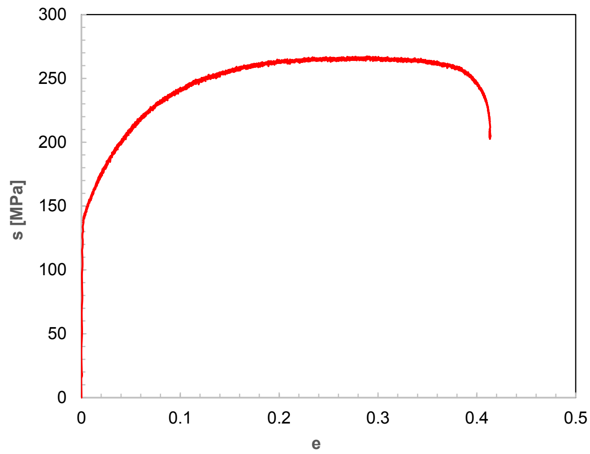

Fig. 5. Typical nominal stress vs. nominal strain curves of pre-painted steel sheet.

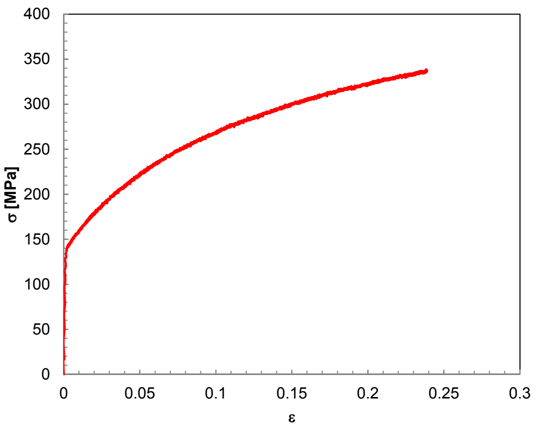

Fig. 6. Typical true stress vs. true strain curves of pre-painted steel sheet.

Table 1. Mechanical properties of pre-painted steel sheet and base Z100 steel evaluated by means of uniaxial tensile tests.

Sheets	YS [MPa]	UTS [MPa]	e_u	e_t	n	K [MPa]	R
Z100 Steel	148	267	0.28	0.41	0.25	501	2.8
Pre-painted steel	145	266	0.27	0.40	0.28	505	3

3.2. Analysis of the superficial damage of paint coating

As the paint coating applied to the steel sheet before the deformation process is subjected to significant deformation during the sheet forming, it is fundamental that the paint is characterized by the strength and toughness to withstand the applied deformation without the occurrence of premature defects before the underlying steel sheet fracture. In order to study the elongation capability of the paint coating during tensile tests, interrupted tests were carried out at different strain levels, and magnifications of deformed painted surface were analyzed by means of stereomicroscopy investigation.

Fig. 7 shows magnifications of the paint coating layer of tension-tested samples at different strain levels. In particular, it can be observed that in the region of uniform elongation (Fig. 7a), the paint coating is characterized by an orange peel finish and a loss of glossiness, without the occurrence of wrinkles or fractures on the coating surface. Such a surface finish appears up to a nominal strain value of 0.34, therefore inside the post-necking area of the steel sheet (Fig. 7b), when the first defects appear on the painted surface (Fig. 7c).

Failure on the paint coating develops perpendicularly to the loading direction, while, in the transverse direction, wrinkles are caused by significant stresses due to the difference in the rate of expansion of the surface of the coating and body of the coating [5] (Fig. 8). The degree of paint coating damage rises with strain level up to the failure of the steel sheet sample and, consequently, of the paint coating (Fig. 7d). However, the primer exhibits a good adhesion capability since it is able to remain adherent both to the underlying hot-dip galvanized steel sheet and to the top finishing coating, thus allowing the paint to remain almost adherent to the metal sheet also near the fracture surface.

3.3. Thickness distribution of the different layers of the pre-painted sheet

In order to investigate the thinning attitude of the different layers of deformed pre-painted sheet, the thicknesses of the paint coating and Z100 steel sheet were measured along the gage length of the tensile sample at different strain levels.

Fig.s 9 and 10 show the influence of strain on the thickness distribution vs. the distance from the half length of the sample gage in top finishing coating and steel sheet, respectively.

Irrespective of the layer taken into account, for a nominal strain of 0.2, within the uniform deformation region, thicknesses of both steel sheet and paint coating layers are almost constant along the gage length of the tensile sample. In particular, a thickness reduction of about 13% and 5.5% can be measured for paint coating and steel sheet, respectively.

In the post-necking region (e=0.3), a non-uniform thickness distribution along the gage length can be observed, with a significant reduction in thickness in the central zone of gauge length, due to the occurrence of necking. Such behavior is more marked for paint coating than for steel sheet, with a thickness reduction with respect to initial thickness value of about 40% and 16% for the paint coating and steel layer, respectively, in half length of the tensile sample gage.

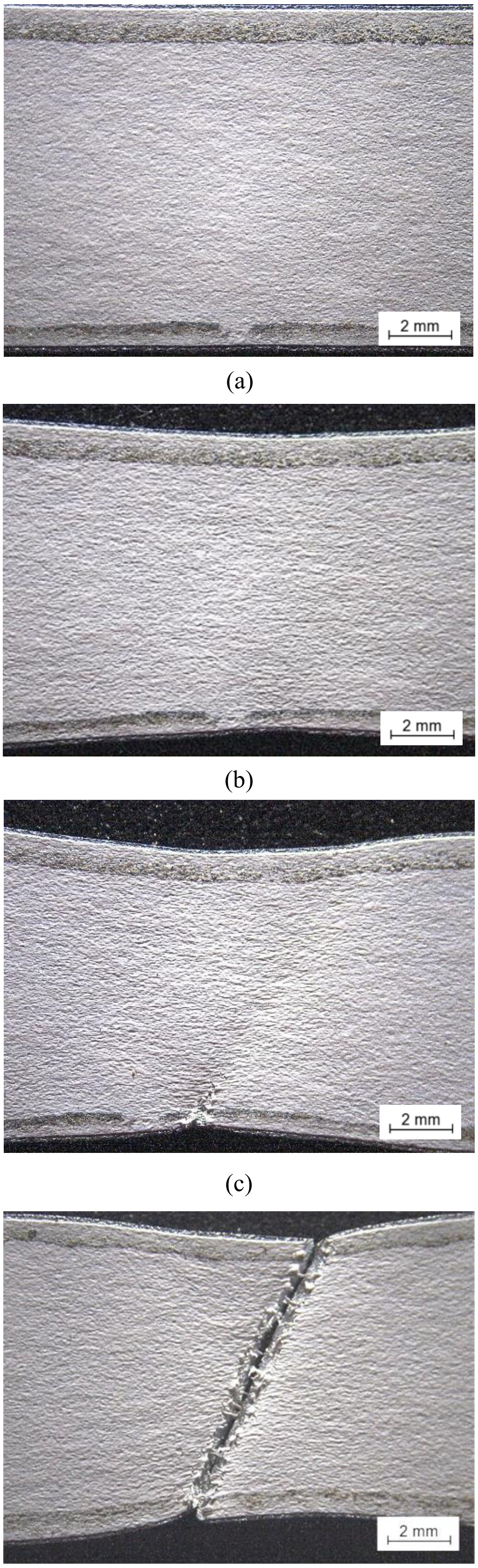

Fig. 7. Painted surface of tension - tested samples at different strain levels: (a) 0.13, (b) 0.29, (c) 0.36 and (e) 0.40.

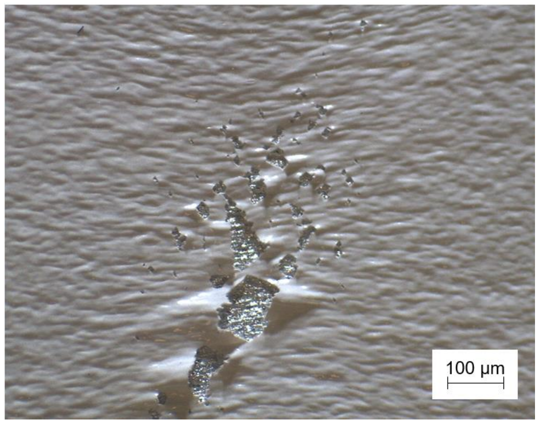

Fig. 8. Magnification of a damage on the paint coating surface of a deformed tensile sample in pre-painted steel sheet.

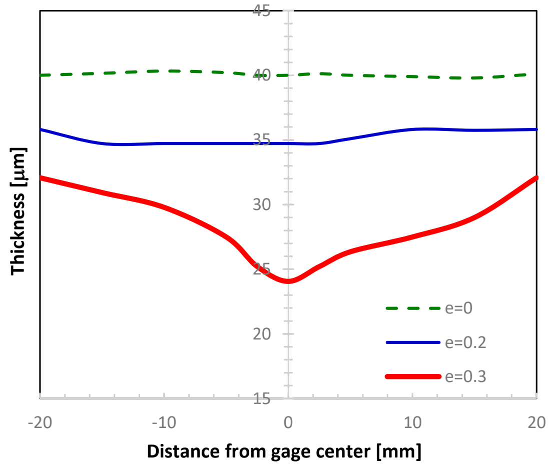

Fig. 9. Effect of strain level on the thickness distribution of the coating of deformed pre-painted sheet vs. distance from the half length of the tensile sample gage.

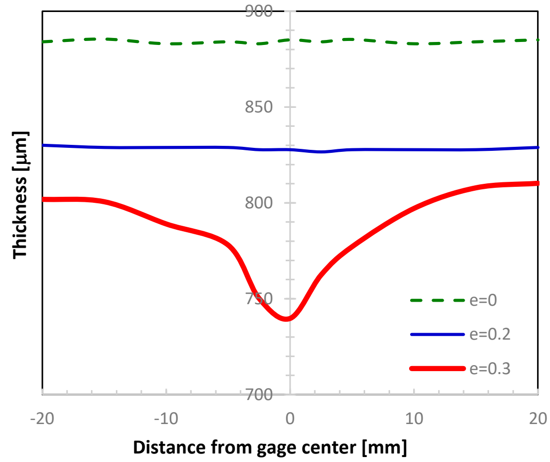

Fig. 10. Effect of strain level on the thickness distribution in the steel sheet layer of deformed pre-painted sheet vs. distance from the half length of the tensile sample gage.

4. Conclusions

The present investigation aims at studying the deformation behavior of a pre-painted steel sheets, commonly used in household appliances, under uniaxial stretching condition. The material is constituted by a Z100 galvanized low carbon steel sheet, film-coated on both sides with an epoxy-polyester resin. A further layer in silicone-modified polyester resin was used as finishing top coating. Interrupted uniaxial tensile tests were carried out on the pre-painted steel sheet samples in order to evaluate the elongation capability of both paint coating and steel sheet. Furthermore, the effect of strain level on both the superficial damages of paint coating and thickness distribution in the different layers was investigated. The main results can be summarized as follows:

- the pre-painted steel sheet exhibits a wide post-necking deformation due to the high normal anisotropy of steel;
- in the uniform elongation region of the steel sheet, the paint coating is characterized by an orange peel finish, without the appearance of wrinkles or fractures on the surface of the coating
- at a nominal strain value of 0.34, inside the post-necking area of the steel sheet, the first defects appear on the painted surface; the degree of paint coating damage increases with strain level up to the failure of the steel sheet sample;
- the primer is characterized by a good adhesion capability since it allows the paint to remain adherent to the underlying hot-dip galvanized steel sheet also near the fracture surface;
- in the uniform deformation region of steel sheet, thicknesses of both steel sheet and paint coating layers are almost constant along the gage length of the tensile sample; in the post-necking region, a non-uniform thickness distribution appears due to the occurrence of necking. Such behavior is more marked for paint coating than for steel sheet.

References

[1] Kubo Y, Hanya K, Kodama S. Steel sheet for the better human life (application for household electrical appliances, OA equipment). Nippon Steel Tech Rep 2012:48–56.

[2] Kaczmarczyk J. Modelling of guillotine cutting of a cold-rolled steel sheet. Materials (Basel) 2019;12. https://doi.org/10.3390/ma12182954.

[3] Vayeda R, Wang J. Adhesion of coatings to sheet metal under plastic deformation. Int J Adhes Adhes 2007;27:480–92. https://doi.org/10.1016/j.ijadhadh.2006.08.003.

[4] Escobar-Saldívar LJ, Smith NR, González-Velarde JL. An approach to product variety management in the painted sheet metal industry. Comput Ind Eng 2008;54:474–83. https://doi.org/10.1016/j.cie.2007.08.009.

[5] Ahmad Z. Coatings. Princ. Corros. Eng. Corros. Control, 2006, p. 382–437. https://doi.org/10.1016/B978-0-7506-5924-6.50008-8.

[6] Ueda K, Kanai H, Suzuki T, Amari T. Effects of mechanical properties of paint film on the forming of pre-painted steel sheets. Prog Org Coatings 2001;43:233–42. https://doi.org/10.1016/S0300-9440(01)00199-0.

[7] Ambrogio G, Bruni C, Bruschi S, Filice L, Ghiotti A, Simoncini M. Characterisation of AZ31B magnesium alloy formability in warm forming conditions. Int J Mater Form 2008;1. https://doi.org/10.1007/s12289-008-0027-y.

[8] Sasso M, Forcellese A, Simoncini M, Amodio D, Mancini E. High strain rate behaviour of AA7075 aluminum alloy at different initial temper states. vol. 651–653. 2015. https://doi.org/10.4028/www.scientific.net/KEM.651-653.114.

[9] Forcellese A, Gabrielli F, Simoncini M. Prediction of flow curves and forming limit curves of Mg alloy thin sheets using ANN-based models. Comput Mater Sci 2011;50. https://doi.org/10.1016/j.commatsci.2011.05.048.

[10] Forcellese A, Simoncini M. Mechanical properties and formability of metal–polymer–metal sandwich composites. Int J Adv Manuf Technol 2020;107:3333–49. https://doi.org/10.1007/s00170-020-05245-6.

[11] Banabic D. Formability of Sheet Metals. Sheet Met. Form. Process., Springer Berlin Heidelberg; 2010, p. 141–211. https://doi.org/https://doi.org/10.1007/978-3-540-88113-1_3.

[12] Ueda K, Kanai H, Amari T. Formability of polyester/melamine pre-painted steel sheets from rheological aspect. Prog Org Coatings 2002;45:267–72. https://doi.org/10.1016/S0300-9440(01)00255-7.

[13] Prosek T, Nazarov A, Olivier MG, Vandermiers C, Koberg D, Thierry D. The role of stress and topcoat properties in blistering of coil-coated materials. Prog Org Coatings 2010;68:328–33. https://doi.org/10.1016/j.porgcoat.2010.03.003.

[14] Sorce FS, Ngo S, Lowe C, Taylor AC. The effect of HMMM crosslinker content on the thermal-mechanical properties of polyester coil coatings. Prog Org Coatings 2019;137:105338. https://doi.org/10.1016/j.porgcoat.2019.105338.

[15] Forcellese A, Mancia T, Simoncini M. Tensile behavior and formability of pre-painted steel sheets. Metals 2020;10:1–14. https://doi.org/10.3390/met10010053.

[16] Behrens BA, Gaebel CM. Formability of an anti-fingerprint clear coating on satin stainless steel sheet metal. Prod Eng 2013;7:275–81. https://doi.org/10.1007/s11740-012-0434-2.

[17] ASTM A653 / A653M-19a, Standard Specification for Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process 2019. https://doi.org/10.1520/A0653_A0653M-19A.

[18] EN 10346:2015, Continuously hot-dip coated steel flat products for cold forming - Technical delivery conditions 2015.

[19] EN 10143:2006, Continuously hot-dip coated steel sheet and strip - Tolerances on dimensions and shape 2006.

[20] International A. ASTM E8 / E8M-16a, Standard Test Methods for Tension Testing of Metallic Materials 2016. https://doi.org/10.1520/E0008_E0008M-16A.

[21] International A. ASTM E646-16, Standard Test Method for Tensile Strain-Hardening Exponents (n -Values) of Metallic Sheet Materials, ASTM International, West Conshohocken 2016.

[22] Kalpakjian S, Schmid SR. Manufacturing Engineering & Technology. 8 edition. Pearson; 2019.