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Design of Press Tools to Investigate the Hot Stamping Behaviour of Alternative Coatings for Press-Hardened Steel Parts

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Abstract. Due to oxidation and decarburization during heat treatment prior to hot stamping, various coating products have been developed in the last decades. Press-Hardened Steel (PHS) components for passenger cars are generally coated by aluminized or galvanized (GI) coatings. The aluminized coating presents a good formability at high temperature and permits forming and quenching components in the same press tools with a so called direct hot stamping method. Due to a strong cracking in the base material during direct hot stamping induced by liquid-metal embrittlement (LME), galvanized coated products must be pre-formed at low temperature and undergo heat treatment in separate press units. Moreover, the oxide scale formed on GI parts must be removed by abrasive blasting, whereas aluminized parts can be directly painted after hot forming. However, higher performance in corrosion resistance has been observed for galvanized parts, in particular in cosmetic and cut-edge corrosion. This increase is linked to the sacrificial effect or cathodic protection provided by the layer containing zinc. Daimler AG is investigating the possibility of improving performance of PHS body parts in terms of suitability for direct hot stamping and corrosion protection by developing new coating materials. In the following article, the main particularities and challenges involved in both current coating products will be introduced. The development of specific press tools for this study, as well as the corresponding simulation of hot forming will be presented. Finally, the hot forming behaviour and anticorrosive properties of both current products will be presented.

Introduction

Press-hardening permits obtaining steel components with a high stiffness and a total elongation of about 5% [1]. These mechanical properties are essential for structural body parts acting as anti-intrusion components, in particular in the passenger compartment. The high mechanical properties of the parts are obtained after a two-step microstructural transformation from ferrite-pearlite into austenite carried out by a heat treatment process, followed by quenching of the steel substrate in cooled press tools. The heat treatment is generally carried out in furnaces at a temperature range of 900-950°C for 3-10 min [2]. A cooling rate of 27°C/s is required for a complete martensite formation [3]. Direct hot stamping involves one forming step at high temperature carried out simultaneously with quenching, i.e. in the same press tools, permitting obtaining components with a low springback and a high geometrical accuracy.

Due to oxidation and decarburization of bare boron steels at high temperature during hot stamping and low corrosion protection of bare steel parts, steelmakers developed several protective coatings to improve performance of the products, their suitability for hot stamping and their subsequent manufacturing processes such as joining and painting. Two coating products are currently established at Daimler AG for press-hardened automotive components, namely aluminized and galvanized (GI) coatings. Their areas of application are mainly based on the degree of exposure to corrosive environments and their geometries. The aluminized coating consists of an Al/Si alloy with a near-eutectic composition containing 7-11wt% Si and permits manufacturing components by direct hot stamping with its good formability at high temperature [2]. GI liquid Zn baths generally contain 0.2% aluminum in order to avoid the formation of brittle Fe-Zn intermetallic phases at the substrate/coating interface during hot dipping process. A good formability at low temperature is thereby achieved due to the formation of a $Fe_2Al_{5-x}Zn_x$ inhibition layer [2].

Direct hot stamping of GI-coated parts induces strong cracking in the steel substrate, called liquid-metal embrittlement, or LME. A zinc-rich liquid phase diffuses from the protective coating into the base material during forming at high temperature and causes severe cracks. LME has been reported by Hensen et al. [4] to depend on the susceptibility of the material, the stress level applied during forming and the presence of a liquid phase in the coating. Various strategies have been proposed by [2] and [4] to suppress or at least reduce the cracking effect in the substrate. The most common method, called indirect hot stamping, consists of separating mechanical and thermal stresses by performing the total deformation of GI-coated parts at low temperature and carrying out heat treatment for austenitizing, followed by a calibration and quenching in another press unit. As stated in [5], an oxidizing atmosphere is required during heat treatment prior to hot stamping in order to avoid the loss of zinc material by vaporization. Oxide scale is formed on the surface of the hot formed parts. Since paintability and weldability of the final products are affected, the oxide layer is removed, generally by abrasive blasting.

In summary, manufacturing of GI parts involves higher costs due to the additional forming unit and press tools for cold forming, the specific heating equipments for pre-formed parts as well as abrasive blasting on final components. Nervertheless, indirect process with a cold forming step permits production of parts with complex geometries by carrying out several consecutive forming steps at low temperature. The cutting of the final geometries on pre-formed parts reduces the costs compared to press-hardened parts. Finally, GI-coated parts have shown better anticorrosive performance than aluminized parts in terms of cosmetic and cut-edge corrosion due to the presence of zinc, providing a sacrificial effect called cathodic corrosion protection [6]. Since direct hot stamping is the most cost-effective forming method for PHS components, current and alternative coated materials including the GI coating will be formed with this method for the present and future works.

Target Investigations

With the aim of developing alternative coating systems offering good suitability for direct hot stamping and cathodic corrosion protection, press tools were designed for investigating the forming behaviour of coating products. The specific press tools, leading to severe tensile deformation, will permit to study the adhesion of the deposited layers with the substrate, the formation of micro and macro-cracks, the peeling or flaking of the coatings and to evaluate the process-window of coated products during direct hot forming. The present work introduces the startup of the constructed tools and the forming behaviour of current coating products. The main investigation track selected for the development of alternative coatings is focused on the study of zinc-alloy coatings. The influence of the alloying elements on LME mechanisms and on suitability for direct hot stamping will be investigated in future works by considering the direct hot stamped GI product as a reference.

Simulation and Construction of Press Tools for Hot Stamping of Coated Products

Specifications for the Construction of Press Tools. During design of appropriate press tools for evaluating properties of current coated products and investigation of performance input of alternative coatings during direct hot stamping, several central themes have been taken into account. The first target was to obtain a wide range of thinning (up to 20%) on a unique specimen in order to evaluate the forming properties of the coating and to study the formation of micro and macro-cracks and the adherence of the formed interdiffusion layers with the steel substrate. Moreover, the use of a 2-part press tool was selected for good compatibility with the experimental press setup. It should be noted that the absence of blank holders leads to a reduction of the possible configurations and tool geometries. Sufficient space was necessary for investigating corrosion after electrochemical and cyclic corrosion tests and evaluating paintability of the hot stamped coated products.

Within the scope of depositing and investigating alternative coatings with various methods such as hot-dipping, electrodeposition or PVD-deposition processes, reduced dimensions, i.e. at most 200 x 200 mm², have been set for the specimens and press tools. Indeed, high costs for the deposition of new materials, more challenging setups and deposition parameters would be induced in the case of large scale investigations, for instance on body parts. Future studies could be dedicated to the investigation of the corresponding materials on a larger scale or on an industrial coating line for body components.

Simulation of Hot Stamping and Construction of Press Tools. Within the scope of designing specimens with geometries specific to this study and simulating hot stamping with the corresponding tools, numerous models have been developed and tested. An overview of several simulations is presented in Fig. 1. The first version of the simulations was based on linear U and V-punches distributed over the entire sample width. Some challenges in the identification of the areas presenting the target thinnings have been met. The simulation of similar geometries with a depth gradient increased the formation of a gradient of thinning on a radius, but a maximal thinning of 12% could not be exceeded.

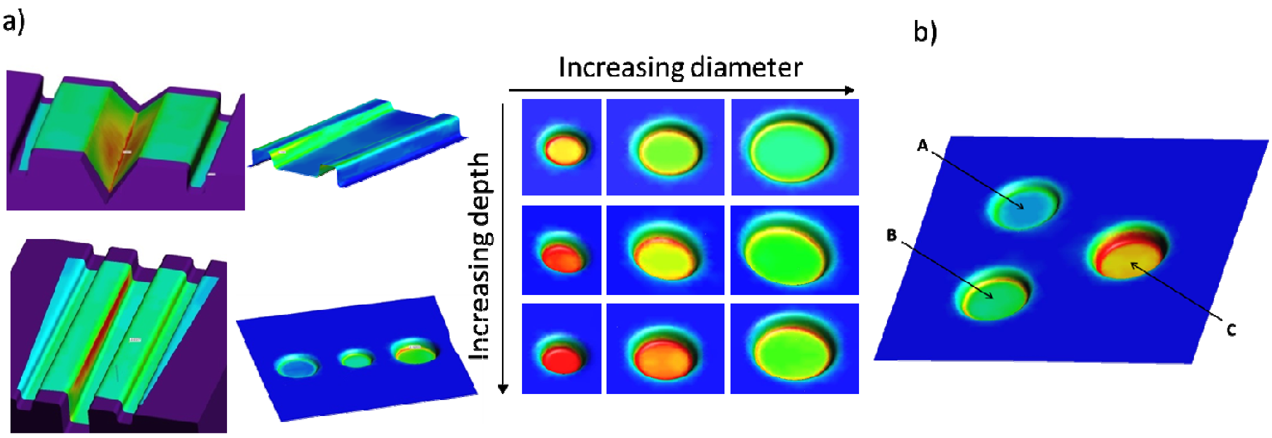

Figure 1: Linear V and U-punches and circular punches of intermediary (a) and circular punches of final (b) press tools after simulation and construction on Autoform R3.1 and Catia V5

Advanced models were based on blanks with several circular cups whose geometry would provide various values in the target thinning range, in particular between 10% and 20%. Simulations were carried out with different diameters, depths and radii, as shown in Fig. 1.a). The location and distribution of the maximal thinning and the overall geometries were evaluated for the selection of the optimal model. Finally, the cups were positioned for obtaining sufficient space for post-treatments.

The final geometry of the designed specimens is presented in Fig. 1.b) and consists of a 200 x 200 mm² blank containing three cups with an identical diameter of 35 mm and different depths. The depths of cups A, B and C are 4.25, 5.6 and 8 mm respectively and have been defined for achieving maximal thinnings of 10, 15 and 20% on the punch corner of each cup on the basis of simulations carried out on Autoform plus R3.1 WIN 64 with the solver Afthermo.solver_R3.1_HOT for hot forming. The heat transfer coefficient (HTC) was defined in dependency of the contact pressure applied by the press tools and a friction coefficient of 0.35 was used. The modeling of the forming behaviour of 22MnB5 was based on temperature-dependent flow curves. The temperature of the press tools was set to 20°C and the transfer time of the blank from the furnace to the press unit was set to 7 sec. and included heat transfer by emission and convection. The closing time was set to 10 sec. for sufficient cooling of the specimens. Flat areas located around the cups were dedicated to the investigation of the materials properties in terms of corrosion protection, paintability, weldability and the study of the process window of the products during hot stamping.

Hot Stamping of Coated Products

Experimental Setup and Process Parameters. The startup of the designed press tools was carried out on the most established base material for PHS components in the automotive industry, namely the 22MnB5 steel grade, coated either with an Al/Si or a GI layer. For the achievement of a homogeneous austenitization of the steel substrate, i.e. by heating above the Ac3-temperature, heat treatment was carried out at temperatures of at least 860°C. The dwell time was controled after reaching the latter temperature. The evolution of the temperature during hot stamping is presented in Fig. 2. Al/Si and GI pre-coated specimens with an initial thickness of 1.5 mm and a size of 200 x 200 mm² were used. A strong dependence of the heat treatment on the performance of current coated products in terms of corrosion protection has been reported in [2] and [8], in particular for GI parts, due to diffusion of iron into the protective layer.

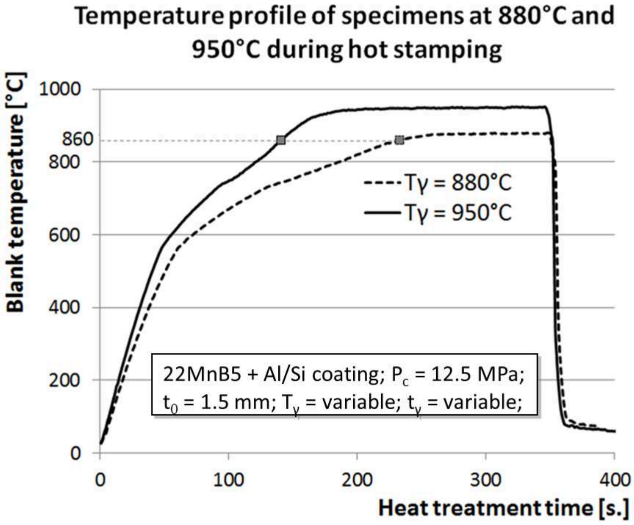

Figure 2: Temperature profile during hot stamping of Al/Si-coated specimens at 880°C and 950°C

As a result, in order to reduce the risks of corrosion on body parts, the investigation of the process window during hot stamping plays an essential role in the evaluation of their manufacturability and production costs. Evaluation of the products' performance should therefore be based on various temperatures and dwell times during hot stamping. Parameters used for the present work are presented in Table 1.

Table 1: Experimental parameters (dwell time and specimens' temperatures) of Al/Si and GI-coated products

Temperature / Dwell time	T_γ: 880°C		T_γ: 920°C	T_γ: 950°C
Austenitizing time to 860°C [sec]	220		180	140
t_1 [sec]	Al/Si: 120	GI: 45	GI: 45	Al/Si: 120
t_2 [sec]	Al/Si: 180	GI: 120	GI: 120	Al/Si: 180
t_3 [sec]	Al/Si: 240	GI: 180	GI: 180	Al/Si: 240

Hot stamping of standard coated specimens was performed at the Institute of Manufacturing Technology at the Friedrich-Alexander-Universität Erlangen-Nürnberg on a type TSP 100SO hydraulic press (Lasco, Coburg) with a force of 1,000 kN. As stated earlier on, the press unit comprised a punch and a die cooled down with an 18°C tap water flow. The heat treatment prior to hot stamping was carried out in a type ME 45/13 furnace (Rohde, Prutting) placed beside the press. Heated blanks were transferred manually to the press unit for about 7 seconds and quenched subsequently with a constant closing speed and a contact pressure of 12.5 MPa. Quenching started above 800°C, depending on the furnace temperature. The specimens were held in the press tools for 10 seconds. The temperature during heating and quenching was monitored by 1.1 mm thick K-type thermocouples connected in the middle of one blank edge. The measurement of the specimens' shape and thickness was either carried out with a cross section or with optical 3D scanning (GOM ATOS Core 300) at the Institute of Manufacturing Technology at the Friedrich-Alexander-Universität Erlangen-Nürnberg.

Forming Behaviour of Current Coated Products. Distribution of the specimens' thickness after simulation of hot stamping, measurement of specimens' thickness after hot stamping of blanks, as well as distribution of the thickness after cross-section investigations is presented in Fig. 3. The results show a similar behaviour of the coated materials in the case of cups A and B for simulated and real specimens. Indeed, the maximal thinning is located on the punch radius for both cups. However, a different behaviour of the blanks has been observed in the case of the cup C. 3D scanning and cross section investigations showed maximal thinning located in the middle of the punch depth, contrary to the punch radius in the simulation data. No significant difference in the location of the maximal thinning has been made for Al/Si and GI specimens annealed at 880°C and 950°C.

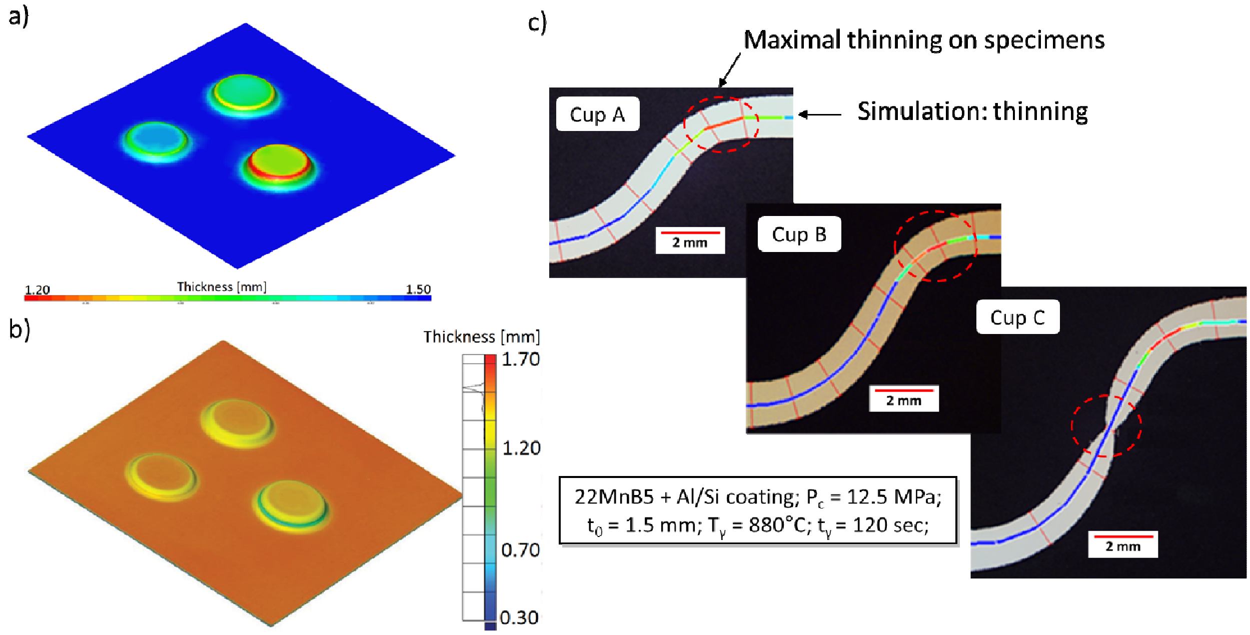

Figure 3: Simulation of hot stamping (a), 3D scanning of a hot stamped specimen (b) and cross sections of cups A, B and C on hot stamped samples and from the simulation data (c)

Behaviour of Aluminized Specimens. Cross sections of direct hot stamped aluminized specimens revealed strong cracking and rupture of the coating on areas subject to tensile stresses, as shown in Fig. 4.

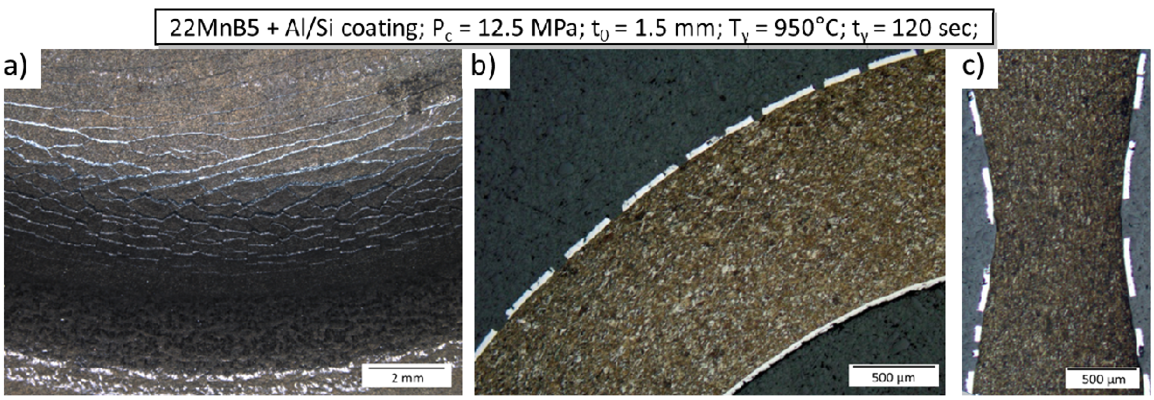

Figure 4: Rupture of the Al/Si coating during direct hot stamping: surface topography (a), cross section of the punch radius (b) and cross section of the punch center of the cup C (c)

Zhong-Xiang et al. [7] investigated the formation of cracks generated during hot stamping of Al/Si-coated PHS and identified three types of cracks. The first crack mechanism occurs during austenitization prior to hot stamping due to a difference in the thermal expansion coefficients of the intermetallic compounds and the substrate steel. The micro-cracks formed can act as nucleation sites for macro-cracks in areas undergoing tensile deformation during forming. Finally, interfacial cracks can form on the coating/substrate interface if the substrate steel yield strength is higher than the adhesion strength and if the stress concentration reaches the adhesion strength. All three types of cracks have been observed in the present study. Moreover, it should be noted that no crack propagated into the steel substrate.

Behaviour of Galvanized Specimens. As stated earlier on, GI coating induces strong cracking in the steel substrate during direct hot stamping due to the presence of a liquid phase in the coating during forming at high temperature. An example of the surface topography of cup A, B and C is presented in Fig. 5 and shows the clear presence of cracks.

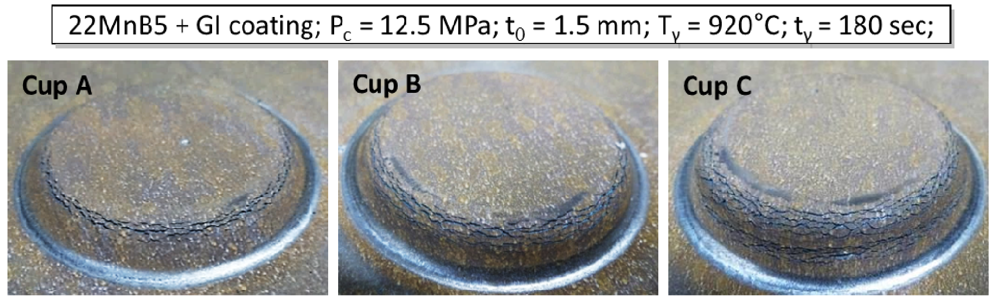

Figure 5: Surface topography of the cups of a galvanized specimen after direct hot stamping

Cross sections carried out on hot stamped GI specimens are shown in Fig. 6. These investigations confirm the visual observation of the sample, and illustrate the cracking induced by LME in the steel substrate in areas subject to tensile stress. The SEM image shown in Fig. 6 (right) reveals the presence of a zinc-rich phase in the steel substrate, responsible for the decohesion of the substrate grain boundaries. It should be noted that no cracks formed on areas undergoing compression stresses.

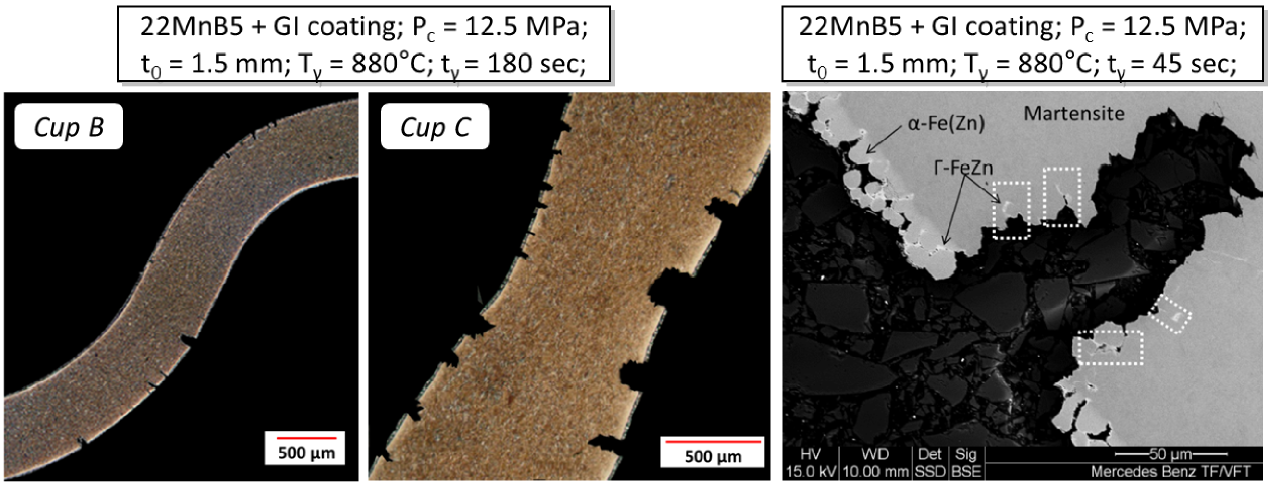

Figure 6: Presence of cracks in the substrate of GI-coated specimens after direct hot stamping for cups B and C (left); SEM micrograph of a crack: diffusion of Γ-FeZn phase in the steel substrate (dashed areas) (right)

Anticorrosive Performance of Coated Press-Hardened Steel Parts

Corrosion of Press-Hardened Parts. PHS components imply more challenges than cold formed parts in terms of corrosion protection due to the heat treatment prior to press-hardening. Indeed, diffusion of iron from the substrate into the coating is generated and leads to the reduction of corrosion resistance of the products. GI coating is especially affected by this phenomenon. As reported in [8] and presented in Fig. 7 (left), good anticorrosive performance of the GI coating is mostly provided by the zinc-rich Γ_1-ZnFe phase acting as a sacrifical anode for the base material due to its electrochemical potential much lower than that of steel. This phenomenon is called cathodic corrosion protection.

Fig. 7 (right) illustrates the phenomenon of diffusion occurring in GI coatings during heat treatment. Annealing for 180 sec at 880°C prior to hot stamping increases the amount of iron in the protective coating and reduces the thickness of the zinc-rich superficial layer. The Al/Si coating presents a rather low dependence of the heat treatment on the anticorrosive performance. More information regarding corrosion mechanisms, performance of current products and industrial protection measures is presented in [9].

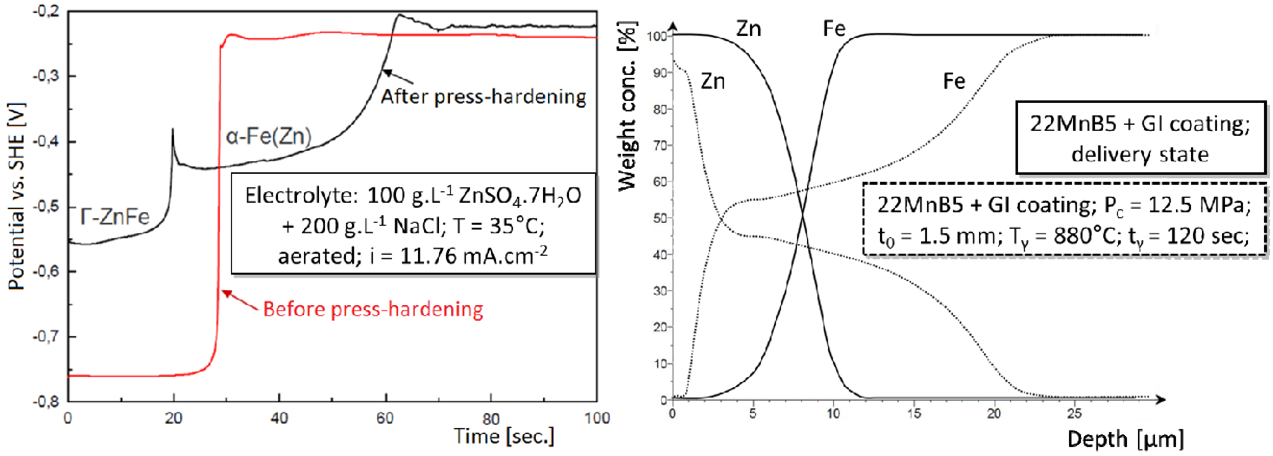

Figure 7: Galvanostatic dissolution of a GI coating before and after press-hardening (left) [8]; Glow Discharge Optical Emission Spectroscopy (GD-OES) of a galvanized steel specimen before (solid line) and after (dotted line) direct hot stamping (right)

Assessment Criteria and Anticorrosion Performance of Current Coated Products. Performance of protective coatings for PHS parts is generally assessed by investigating the protection against cosmetic, perforating and cut-edge corrosion after carrying out cyclic corrosion tests such as VDA 621-415, VDA 233-102 or internal tests developed by car manufacturers. Cosmetic corrosion is observed when superficial defects cause a delamination of the protective layers and a degradation of the optical quality of the products. This mechanism is generally evaluated by applying a linear scribe down to the substrate on painted panels. Corrosion of steel substrate, called perforating corrosion, can also occur on a scribe and reduce the functional properties of the components. The scribe delamination and the scribe depth are measured after exposure to corrosion [6]. As PHS body parts are generally cut after being coated, they contain areas called cut-edges which are not protected by an Al/Si or a GI layer. The delamination of the protective coatings and the appearance of red rust are evaluated after a cyclic corrosion test. The galvanized coating has been reported to provide better performance in cut-edges and cosmetic corrosion protection than the Al/Si-coated product [6]. The study of perforating corrosion in the event of crevice corrosion can be carried out by fixing glass flanges on non-painted areas, as reported by Allély et al. [10].

Cathodic protection can be assessed by galvanostatic dissolution of the protective coating, as presented in Fig. 7 (left). The GI coating provides a sufficient protective effect due to its lower electrochemical potential compared to bare steel, but suffers from a strong dependence of the heat treatment parameters [8]. Although aluminized coatings do not offer cathodic corrosion protection, good corrosion protection has been reported due to the formation of stable oxides with a low solubility rate and acting as a barrier to the diffusion of oxygen towards the steel surface, i.e. hindering corrosion mechanisms [11].

Summary and Outlook

Specific press tools have been designed and started up for this work and permitted to study the behaviour of current coated products under extreme conditions, i.e. with a wide range of thinning of the specimens, radial tensile stresses and small punch radii. Aluminized specimens presented a rupture and peeling of the layer in areas with tensile stress. No cracks were observed in the steel substrate. On the contrary, a strong cracking called LME occurred for GI specimens, caused by the presence of a zinc-rich liquid phase during forming at high temperature, penetrating in the grain boundaries of the substrate and reducing the strain capacity of the Zn-coated material [4]. The achievement of good formability of galvanized parts at high temperature would reduce the complexity of the manufacturing process chain, the production costs, along with the obtaining of products with cathodic corrosion protection. Future works will be dedicated to the investigation of alternative zinc-alloys coatings for direct hot stamping with the mentioned specimens' geometries. The alloying of zinc with adequate elements can increase the melting temperature of the coating and reduce or suppress the presence of liquid phases in the coating during hot forming. Due to a strong influence of the hot stamping parameters such as the temperature and the dwell time, a characterization of the materials, forming capacities and anticorrosive performance will be carried out in order to evaluate the overall performance and the manufacturability of the coated products.

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