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Analysis of the Surface Coating on 22mnb5 Steel in Hot Stamping Process

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ABSTRACT :*The demand for high-strength galvanized steels for the production of automotive components by hot stamping has grown significantly. However, the processing of materials presents some difficulties due to the interaction between the coating and the substrate. In order to present an alternative to overcome these difficulties, in this work, 22MnB5 steel sheets with galvannealed-GA coating were stamped under conditions different from those used industrially. The samples have been heating at austenitization temperature of 1100ºC and two different lubrication conditions were used in the hot stamping process with coated and uncoated samples. The results of the influence of lubrication on the stamping conditions and quality of the stamped parts were observed using microstructural imagens and chemical evolution. The effect of friction and variations in the characteristics of the process were also analyzed.*

KEYWORDS *Hot stamping; High-strength steel; 22MnB5; Galvannealed-GA coating.*

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I. INTRODUCTION

Hot stamping of high-strength steels has been the solution in the automotive industry to increase the energy efficiency of automobiles and, consequently, to reduce emissions of polluting gases into the atmosphere. This is possible due to the excellent relationship between strength and weight of these class of steels, which allow the thickness of the vehicle components to be reduced, while the requirements regarding impact absorption are improved. In this context, the application of boron low carbon steels has become attractive due to the specific characteristics of these materials when hot stamped. The boron steels are the only class of steels capable of forming a totally martensitic microstructure after hot stamping when a chilled tool is used, the 22MnB5 is the most used by the automobilist industry [1,2].

22MnB5 steel sheets are usually coated with an Al–Si layer in order to avoid scale formation in the furnace, thus removing the need for an inert atmosphere during heating [3,4]. In recent years, to obtain additional cathodic protection, this material has also been produced with galvanized coatings, galvannealed-GA and galvanized-GI, allowing applications in stamped parts exposed to high moisture content [5]. Galvannealed coatings offer several advantages compared to the galvanized coating, such as better weldability [6], paintability [7], and in some cases, better corrosion resistance [8].

However, the hot stamping of the 22MnB5-GA has some limitations such a high probability to the occurrence and evolution of macro and micro-crack propagation mechanisms during the hot forming.

The propagation of macro cracks is related to the penetration of liquid zinc within the limits of austenitic grains during heating, called liquid melting embrittlement (LME) [9, 10]. LME begins during heating, wherein the blank is subjected to a high temperature of about 900°C while the pure zinc melt temperature is

419.5 °C. During heating and hot stamping, a portion of the liquid zinc contacts the substrate diffusing through the austenite grain boundaries acting as cracking nuclei and, thus, leading to brittle intergranular fracture[11].
It can be avoided by using the appropriate heat treatment. Heating for austenitizing the material must assure an iron content > 70% in the coating. Thus, the initial zinc layer is transformed solid solution enriched by zinc, α-Fe (Zn), and there is no risk to occurs LME [13].

The occurrence of micro-cracks is associated with high frictional forces between the tool and the blank [10,14,15]. These defects originate in the coating during hot stamping and reach the interface between the substrate and the coating and propagate inside the blank. The micro-cracks most often do not exceed 10-12µm. But sometimes, on prototype line with a bad contact between the tools and the sheet these cracks can reach a length of 20-50 um [12].

The failure mechanisms, macro and micro-cracks, originate in different areas within the steel. The macro-crack area is situated in the external side of the radius due to the high tensile strength while the micro-crack area is particularly situated in the wall due to a bad friction coefficient. Cracks are never observed on the top of the parts [12].

In the direct hot stamping process, the steel blank is heated in a furnace for a few minutes (3-10 min) to a temperature range of 880-930°C in order to get a steel fully austenitic [12]. Considering the importance of heat treatment and lubrication in the development of cracking mechanisms that occur during the hot stamping of 22MnB-GA steel, this work aims to analyze the material when using a processing route different from those typically used in industry. Herein, blanks of 22MnB5 and 22MnB5-GA were heated at 1100°C for 7 minutes and hot stamped under two different lubrication conditions. The influence of the protective layer and the different lubricants on the microstructural evolution, on the hardness and on the surface quality of the materials were analyzed. In samples coated with a protective layer, the chemical and microstructural evolution of the coating and the effect of process conditions on the cracking mechanisms were investigated.

II. MATERIALS AND METHODS

Cylindrical blanks with 110mm in diameter and thickness of 1.30mm were heated in an electric furnace (chamber type) at 1100ºC for 7 minutes. After heating, the blanks were transferred to a double-acting hydraulic press (DanPress®) and stamped in an axial geometry. Tools (die, punch, and holder) were kept at room temperature. The punch velocity was 19.5 mm/s. No pressure was applied to the holder because the purpose of this study was not to analyze the flange area. The Fig. 1 shown schematically the hot stamping process.

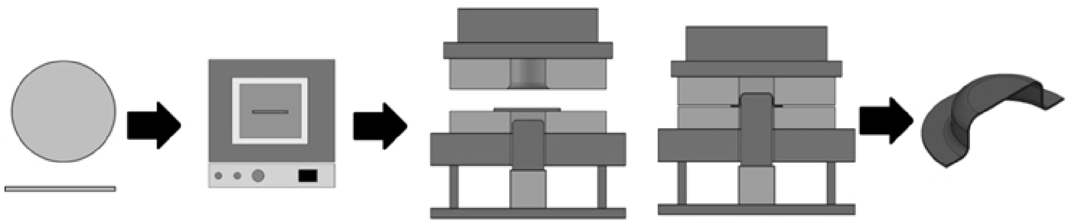


Fig.1. Hot stamping process steps (schematically).

The experimental tests were performed using steel sheets of 22MnB5 with GA coating and uncoated. The lubrication conditions and the displacement of the punch were varied, those conditions are shown in Table 1. In the first process, the lubricant Forge EASY 956 BR (BD -20), Fuchs (R), with a graphite formula, was applied on tools surfaces. After that, in the second process, just graphite powder was used as a lubricant, the blanks have been heated immersed in the lubricant. For this condition, there was no application of lubricants in the tooling.

Table 1.Lubrication conditions and punch displacement.

Sample	Material (blank)	Lubrication	Punch displacement (mm)
1	22MnB5	Graphite powder	25
2	22MnB5	FORGE EASY	25
3	22MnB5	Graphite powder	15
4	22MnB5	Without lubrication	25
5	22MnB5-GA	Graphite powder	25
6	22MnB5-GA	FORGE EASY	25
7	22MnB5-GA	Graphite powder	15
8	22MnB5-GA	Without lubrication	25

The characterization of the parts after hot stamping was performed: (i) chemical composition and observation of integrity the coating using EDS/SEM; (ii) optical microscopy and metallographic technique to observe the coating and substrate (Nital 4%); (v) Vickers microhardness tests and (vi) Measurement of the surface roughness.

III. RESULTS AND DISCUSSIONS

3.1. INITIAL CHARACTERIZATION

In the initial condition, the coating of the galvanized samples has an average thickness of 10µm and a composition of 11% Fe, it was verified by EDS chemical analysis and SEM image, as shown in Fig. 2 (a).

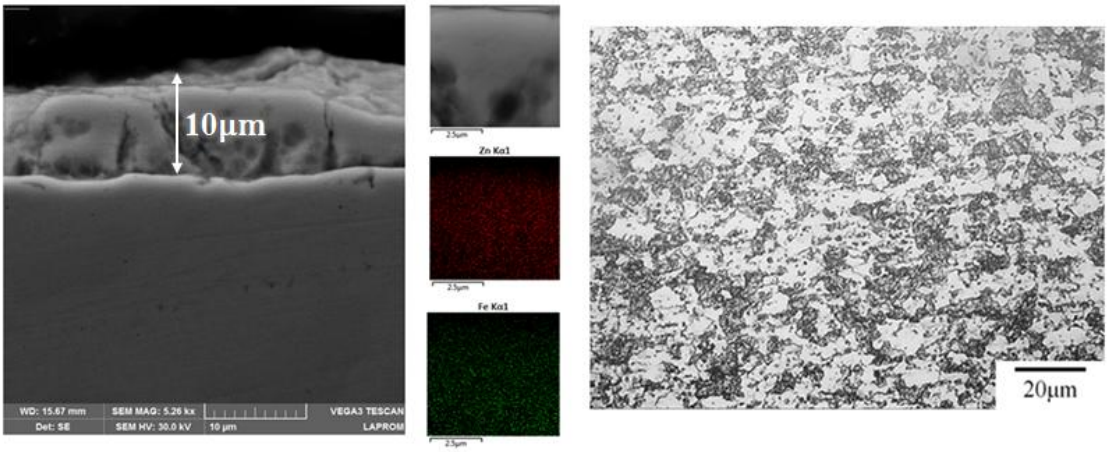


Fig.2. (a) 22MnB5-GA in the initial condition. Magnification 5200x. (b) Optical micrography. Magnification 1000x.

Table 2 shows the chemical composition of the substrate that is per the nominal range present in the literature [1]. In all samples, coated or uncoated, the substrate microstructure observed is ferrite and perlite, as shown in Fig. 2 (b).

Table 2.Chemical composition of 22MnB5 (% w.t).

C	Mn	P	S	Si	Cr	Mo	V	B
0,23	1,24	0,021	0,002	0,21	0,19	-	0,004	0,002

3.2. SUBSTRATE ANALYSIS AFTER HOT STAMPING

Fig. 3 a and b shows the final microstructure of the samples with coating and Fig. 3 c and d without a zinc coating, both of them after the hot stamping process. The microstructure of all samples after processing is a mix of bainite and martensite. However, the morphology of the constituents of the microstructure in coated samples is different from those without the presence of the surface coating.

In coated samples, the cooling of austenite formed martensite and lower bainite. In mixed microstructures of bainite-martensite the lower bainite has an acicular morphology [16]. It is formed at lower temperatures than the upper bainite. In the samples appears with the martensite in uncoated regions. In addition, the 22MnB5-GA samples showed a refined microstructure when compared to samples of 22MnB5. It is possible to assume that coating changed the thermal evolution of the hot stamping process, modifying the heating and cooling rates causing the reduction of the initial austenitic grain size and reducing the temperature of transformation of austenite into bainite.

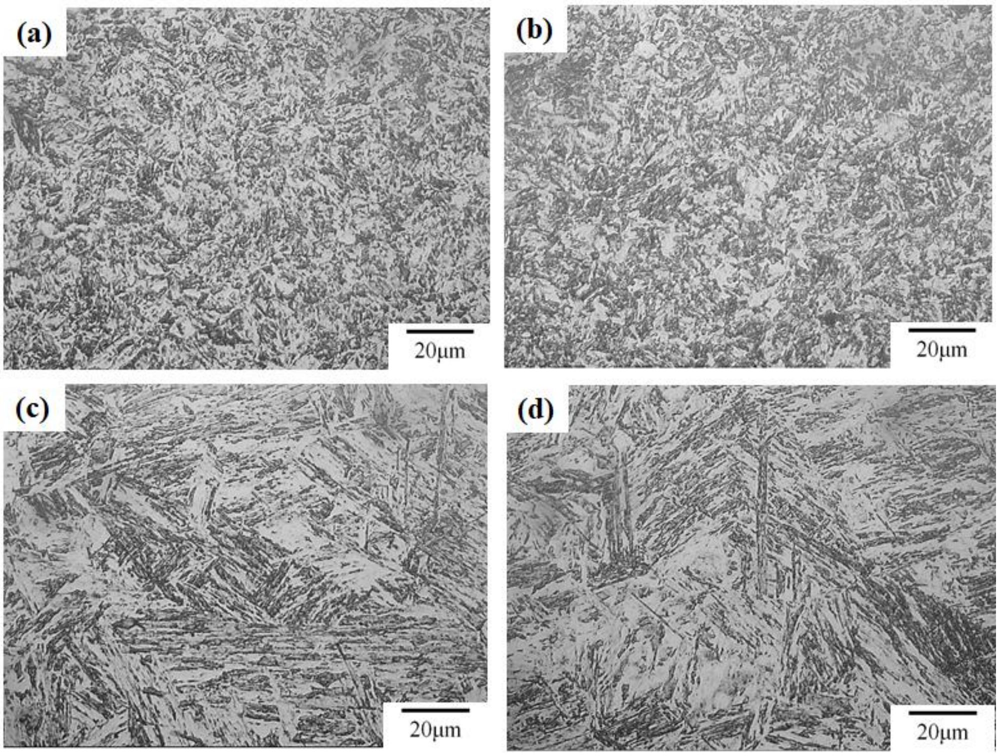


Fig.3. Optical micrograph of samples after hot stamping. Magnification1000x.

The morphological variation in the microstructure did not affect the hardness of the samples as shown in Fig. 4. The hardness values confirm the formation of mixed microstructures of bainite-martensite after hot stamping.

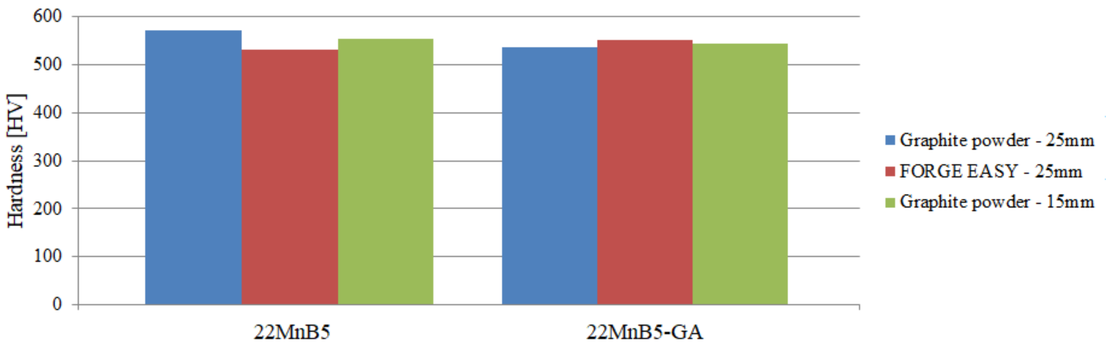


Fig.4. Hardness of the samples after hot stamping.

3.3. COATING ANALYSIS

In the samples of 22MnB5-GA stamped using the FORGE EASY lubricant on the tools occurred the complete removal of the coating. In Fig. 5 it is possible to observe that there is no protective layer only a superficial oxide.

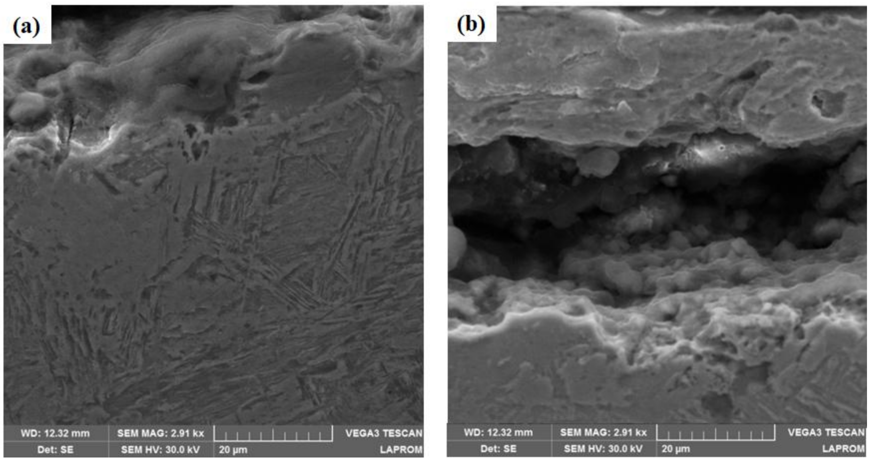


Fig.5. 22MnB5-GA samples after the hot stamping process.

Radlmayr et al. [17], Fan [18] and Lee et al. [11] demonstrated that heating in non-inert atmospheres generates the formation of superficial layers of oxides that inhibit the evaporation of zinc. Despite the use of a non-inert atmosphere, the high heating temperature, higher than those found in the literature, evaporated the coating.The coating was removed during stamping by the powdering of the zinc coating. During heating, the elevated temperature occurs the diffusion of iron into the zinc layer and the increase in the iron in the surface layer causes an increase in the weight loss of the coating and increases the tendency to powdering during plastic deformation [8]. Powdering is the formation of particles due to breaks between the coating and the steel resulting in the formation of powders during stamping operations [19].

Chemical analysis obtained by EDS (Fig.6) confirmed the removal of the zinc layer and the formation of oxide in the surface of samples. The oxide layer is composed of iron and manganese oxides. The manganese initially located on the steel substrate diffuses through the zinc layer during heating and form the oxide layer.

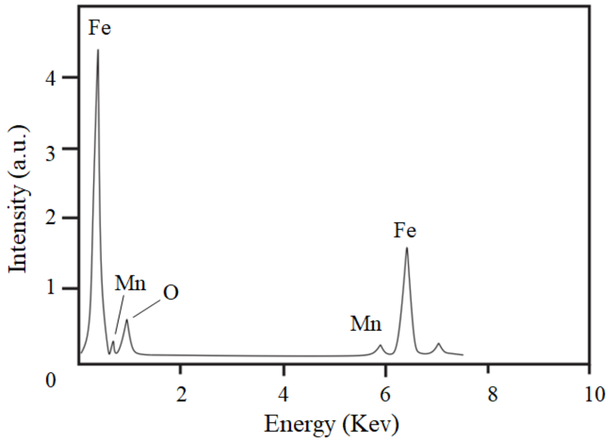


Fig.6. EDS analysis of the sample surface.

The superficial zinc coating of the samples heated immersed in graphite powder remain adhered to samples after the heating and stamping and occurs an increase in the thickness of the coating. During the heating, the coating layer has thicknesses in the range of 19 to 27 μm, increasing the average from 10 to 25μm, as shown in Fig. 7. This significant increase in thickness is due to the intense diffusional interaction that occurs at high temperatures and changes the chemical composition of the protective layer.

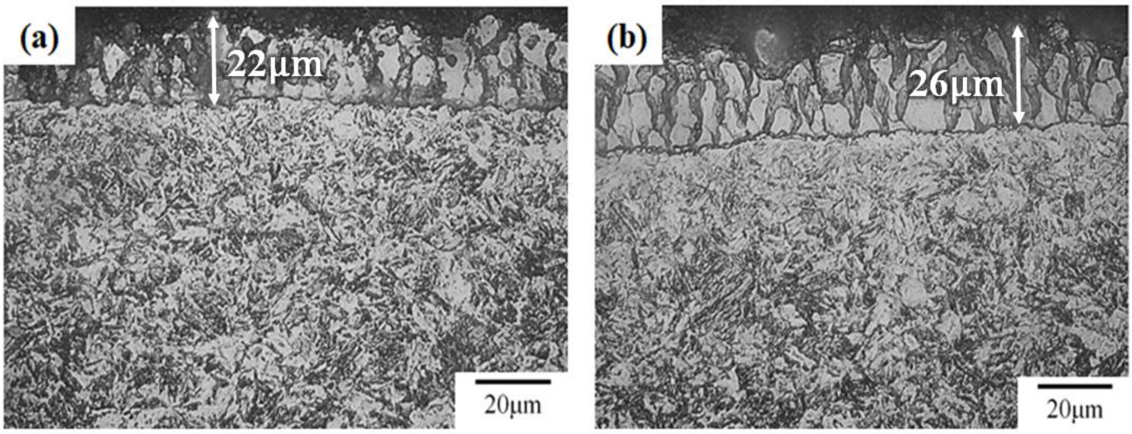


Fig.7. 22MnB5-GA samples after the hot stamping process.

According to analyzes by EDS (Fig. 8), the chemical compositions of the coatings have iron contents above 80%. The time in the oven allows the iron to be distributed evenly over the entire thickness of the coating, resulting in the formation of a solid solution of ferrite supersaturated with zinc α-Fe (Zn).

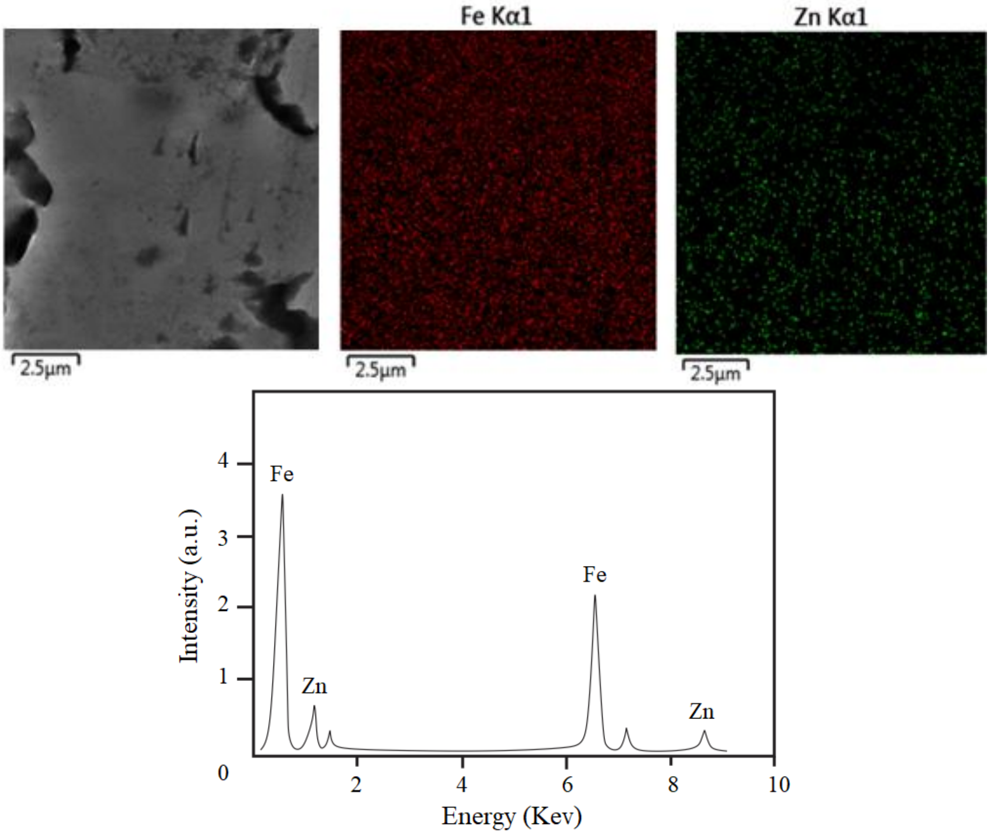


Fig.8. EDS analysis of the sample surface.

3.4. FRICTION EFFECT

Lubricants are employed in stamping operations in order to (a) improve the material flow into the die cavity, (b) reduce wear and galling in the die and (c) obtain good surface finish of the part. [20]. In the hot stamping of materials with zinc coatings the lubrication must generate frictional conditions capable of inhibiting the spread of microcracks. Poor friction conditions on the zinc coating surface generate high-stress levels, mainly shear stress at the interface between coating and substrate, this mechanism leads to the formation of microcracks [12].

The performance of a lubricant depends on parameters such as the sheet material and surface finish, tool material/coating and surface finish, forming velocity, interface pressure, and interface temperature [20]. Therefore, the lubricant can generate different friction conditions that depend on the presence of surface coating on the plate and the type of coating. Thus, friction is a critical aspect in hot stamping of GA coated steel and analysis of lubricant performance is essential.

The force required to carry out the process can be used to assess the performance of a lubricant [20]. Therefore, during the tests, the force and displacement values were measured. Fig. 9 shows the evolution of the stamping force with the advance of the punch displacement for the different conditions studied.

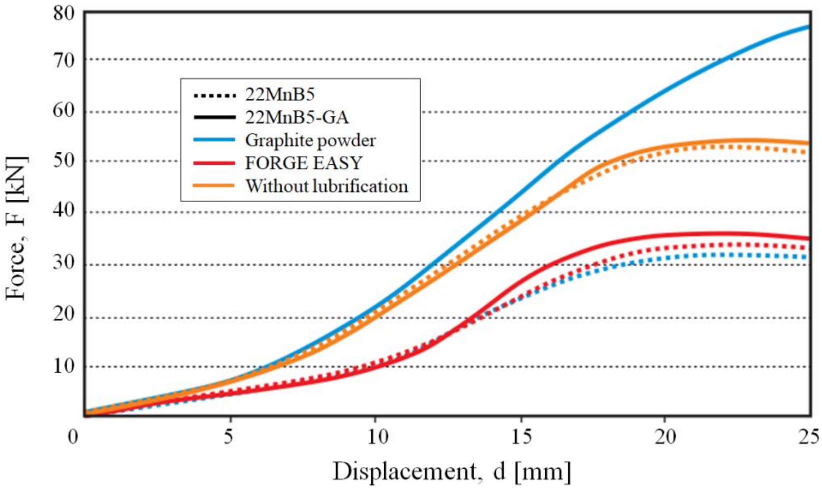
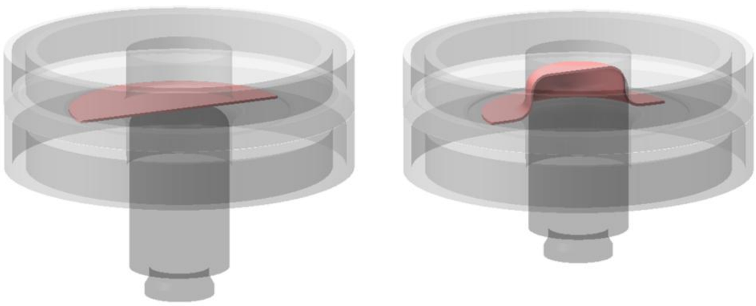


Fig.9. Evolution of the stamping force with the advance of the punch in the hot stamping process for different materials and lubricants.

The apparent friction coefficient of each lubricant as a function of stroke could be estimated through inverse FE analysis by matching the ironing load stroke curve from experiment to results of the FEM simulation. The entire test sequence was simulated using the software Simufact.Forming 15.0®. The analysis of the numerical model, shown in Fig. 10, was performed in 2D, with the part discretized into 0.3mm square elements.



(a) (b)

Fig.10. Numerical model of the hot stamping process: (a) First step (start of the process); (b) Last step (process concluded).

Figure 11 shows the numerical results of the force as a function of the course of the punch for different friction coefficients.

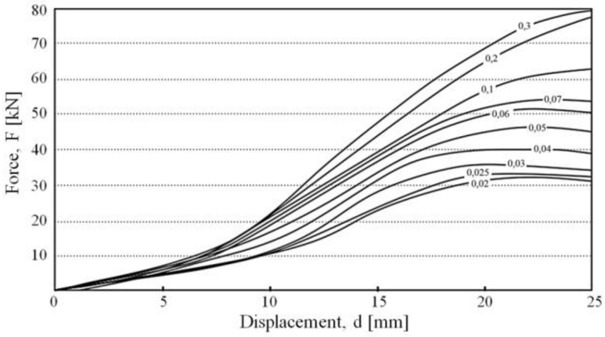


Fig.11. Numerical results of the evolution of the stamping force versus the displacement of the punch for different values of friction coefficient.

The Coulomb's friction law was used, as the interface pressure is relatively smaller than the shear strength of the sheet material. Superimposing the curves obtained experimentally (Fig.9) on the calibration curves obtained from numerical simulation (Fig.11), the friction coefficient values were estimated for the different conditions analyzed and listed in table 3.

Table 3. Friction coefficient values, μ, estimated by inverse analysis for the different conditions studied.

Material	Lubrificant	Friction coefficient (μ)
22MnB5	Graphite powder (Lub.1)	0.02
22MnB5	FORGE EASY (Lub.2)	0.025
22MnB5	Without lubrication	0.07
22MnB5-GA	Graphite powder (Lub.1)	0.2
22MnB5-GA	FORGE EASY (Lub.2)	0.03
22MnB5-GA	Without lubrication	0.07

The samples with GA coating showed a higher friction coefficient in all studies lubrication conditions. When FORGE EASY lubricant was used and in the non-lubricated condition, the difference between the results was not significant. However, when lubrication was performed by immersion in graphite, the expressive difference between the results was observed. The reason for this behavior is in the heating step. As described in section 3.3, the 22MnB5-GA samples heated immerse in a graphite powder maintained the coating during heating due to the reducing atmosphere generated by the graphite. On the other hand, the samples heated in atmosphere, due to the high temperature occurs the evaporation and powdering of the coating during heating and stamping. In the processes in which the FORGE EASY lubricant was used, the coating was completely removed at initial of the stamping process and the results of the samples with and without coating are the same.

The analysis of samples heated immersed in graphite powder allows to verify that the presence of the zinc coating increased the friction coefficient from 0.02 to 0.2 and increase 40kN the force to stamping of the part. This result is according with reported in the literature [8], which confirms that Galvannealed (GA) coating cause worse friction conditions during hot stamping processes when compared to uncoated steel sheets. GA coated materials have a higher coefficient of friction than Galvanized steel sheets (GI) [4] and Al-Si coated sheets [12]. The highest friction coefficients are attributed to the microstructure of the coating made up of Fe-Zn intermetallic phases on the steel surface that provides abrasion resistance [19].

According to GARZA [8], with the increase in phases zinc-rich on the coating surface, the friction coefficient increases. It also occurs when the iron content in the coating decreases. In the heated samples of 22MnB5-GA immersed in graphite powder the zinc layer was totally transformed into a solid solution of ferrite supersaturated with zinc α-Fe (Zn) and high iron content on the surface. This aspect has been decisive for the friction coefficient not to have more significant increase.

3.5. SURFACE INTEGRITY

The roughness of the parts was measured for the analysis of surface quality and the results are shown in Fig. 12. The surface quality was not significantly changed when coated sheets and uncoated has been compared but the uncoated material shows slightly better results in all conditions. The results shown that part surface in better condition was obtained using the uncoated samples heated immerse in graphite powder, with roughness Ra of 1.3μm. In the other hand, the worst surface condition was result of the combination of coated sheet conformed with the lubricant applied to the tools, with roughness Ra higher than 6μm.

Fig.12. Roughness values Ra and Rz after hot stamping.

The similar roughness values for the coated and uncoated samples prove the good surface quality provided by the GA coating. Moreover, it does not require any shot blasting step since a 1-3µm thick surface oxide layer allows an homogeneous phosphatizing and then a good paintability [12].

3.6. FRACTURE MECHANISMS

The fracture mechanisms can occur in the rays and in the walls of the part, the entire profile of the stamped geometries was examined in an optical microscope and scanning electron microscope (SEM) to verify the occurrence of possible defects in the coating and substrate.

The single-phase layer of α-Fe (Zn), compact and completely adhered to the substrate, has cracks as shown in Fig. 13. During high temperature deformation, cracks are easily initiated at a-Fe(Zn) grain boundaries in the surface alloy as this phase has much lower strength than the austenite phase of the matrix. [22]. However, the complete transformation of the zinc layer in the solid solution α-Fe (Zn) is beneficial, since the number of cracks was greater if the coating had different Fe-Zn phases [23]. The cracks formed in the coating during the stamping operation, even in regions with higher levels of plastic deformation, were absorbed by the layer entirely formed by α-Fe (Zn), limiting the extension of the coating and not spreading to the substrate. Thus, it is possible to assume that these defects have little impact on the elongation of hot stamped steel [4].

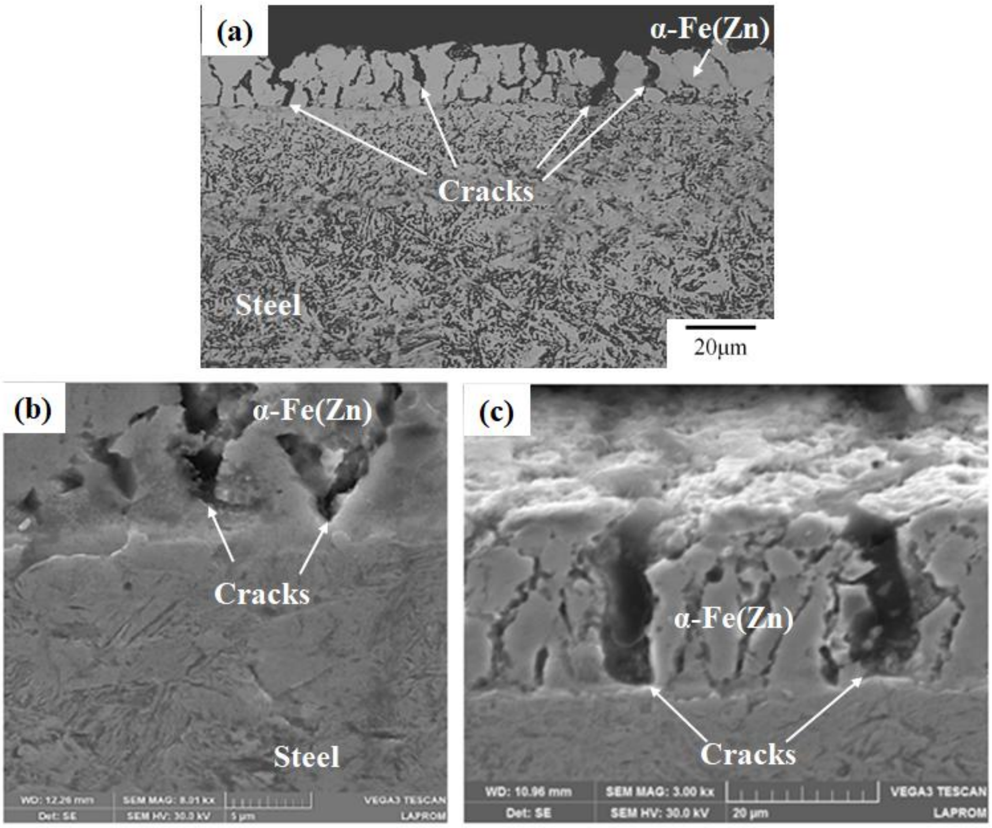


Fig.13. Optical micrograph of the 22MnB5-GA samples after hot stamping. Magnification (a) 500x, (b) 8000x and (c) 3000x.

There is a tendency for microcracks to appear on the part lateral surfaces due to the high frictional forces in these regions. In order to verify the influence of these forces the height of the stamped geometry was varied between 15 and 25mm. Even with the increase of forces and tensions on the lateral surfaces, the propagation of microcracks in the substrate was not verified.

The spread of microcracks is also influenced by microstructural aspects. It has been reported by Drillet [12] that the spread of microcracks to substrate is favored if layers of ferritic phases form at the coating-substrate interface. It was observed in Fig.13 (a) that the mixed microstructure of bainite-martensite is uniform until the interface substrate-coating. This microstructure combines the high resistance of martensite with the toughness of bainite being able to inhibit the propagation of cracks to the substrate.

No cracks induced by penetration of liquid metal into the substrate (LME) were observed. It can be confirmed with the analysis of the Fe-Zn binary phase diagram [12], shown in Fig. 14. Heating at 1100°C during the 7 minutes guaranteed an iron content of > 70% in the coating, preventing the liquid + solid state, highlighted in red, being reached. In this way, the coating was totally transformed into a supersaturated solid solution in zinc, α-Fe (Zn), inhibiting the contact of liquid zinc phases with the steel substrate and, consequently, suppressing the risk of LME occurrence [8, 13, 24].

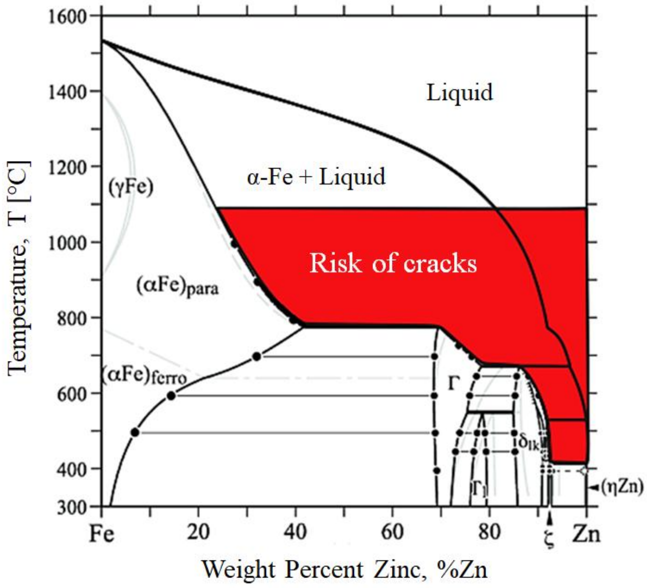


Fig.14. Binary diagram Fe-Zn [12] highlighting the region with a tendency for cracks induced by LME.

The EDS analysis of the substrate-coating interface is shown in figure 15 and confirms that there was no penetration of liquid zinc into the substrate, with the zinc content concentrated in the coating.

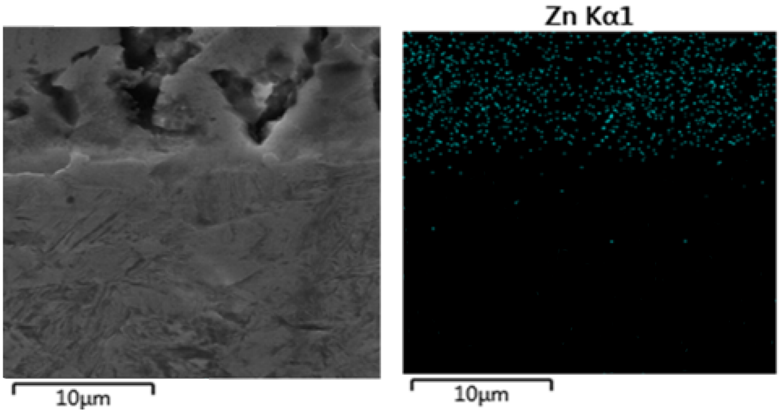


Fig.15. EDS from the interface of substrate-coating.

The hot stamping operation introduced some cracks in the Fe-Zn surface layer, microscopic analysis of the entire profile of the parts showed that the defects did not propagate to the substrate guaranteeing the integrity of the final part

IV. CONCLUSION

Despite the advantages of applying zinc coatings to high-strength steels, processing these materials requires the control of possible deterioration mechanisms that may occur due to the interaction between the coating and substrate. Thus, the analysis of the hot stamping process of 22MnB5-GA herein proposed allowed to conclude:

- It was not observed cracks in the regions of the substrate for all conditions analyzed.
- Heating at 1100°C for 7 minutes forms a microstructure completely formed by a solid solution of supersaturated zinc ferrite that inhibits the formation of cracks in the substrate.
- The heating carried out in non-inert atmosphere resulted in the complete removal of the coating due to evaporation and powdering of the zinc layer.
- The superficial layer of zinc supersaturated ferrite formed during heating significantly increases the friction coefficient in the stamping process when compared to materials initially without a protective zinc layer.

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