1. Introduction

Galvannealing has become one of the most important processes to assure higher corrosion resistance in steels. These materials exhibit better adhesion and response to organic coatings, as well as better weldability and higher formability, than other zinc coated products. Of these characteristics, corrosion resistance and weldability depend on the iron content within the coating, whereas formability depends on the structure of the coating, and it is sensitive to the presence of intermetallic phases. A drawback of galvannealed strips is their tendency for powdering and flaking during press-forming. Powdering has been attributed to the occurrence of hard and brittle intermetallics, mainly $\Gamma$, within the coating, whereas flaking is thought to be due to the presence of an excessive amount of phase at the surface.

Some authors have found that resistance to powdering decreases with increasing coating weight, galvannealing temperatures, iron content within the coating and the reduction of Al content in the bath. It has also been suggested that powdering resistance deteriorates as the thickness of the $\Gamma$ phase (Fe$_x$Zn$_{2-x}$) increases; presence of $\zeta$ phase (FeZn$_{13}$), together with $\Gamma$, deteriorates the coating in operations in which friction plays an important roll, whereas, in frictionless conditions, $\zeta$ phase would be beneficial due to relaxation of surface stresses, improving resistance to powdering. The development of high Fe content $\delta_1$ phase has been associated with the increment of the tendency for powdering.

Resistance welding is commonly used to join galvannealed sheets in automotive industry. This process relies on a combination of pressure and heat to produce a joint between different pieces. The heat for welding is generated by the resistance to flow of electrical current through the parts being joined. This heat may be expressed by

$$H = I^2Rt$$

where $H$ is the heat, $I$ the current, $R$ the resistance and $t$ the time of current flow.

It has been reported that the surface roughness of the strips do not exert a significative effect on welding parameters, as roughness disappears after a very short time has elapsed. It has also been claimed that the current required to obtain an acceptable joint increases with the increment of coating weight.

The aim of this work is to present the parameters that were found to affect the behavior of galvannealed strips made from interstitial free steels. A series of tests were conducted to evaluate the resistance to powdering and weldability on samples cut from various strips produced in an industrial plant.

2. Experimental Procedure

The present study was conducted on samples from four different Ti stabilized interstitial free steels strips of 1.15 mm thickness (Table 1). The material had a 68% cold rolled reduction, and was degreased, annealed in a

### Table 1. Chemical composition (wt%) of the interstitial free steels.

|    | C   | Mn  | P   | S   | Si  | Nb  | Al  | Ti  | B  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|----|
| A  | 0.020| 0.110| 0.006| 0.008| 0.005| 0.007| 0.034| 0.042| 0.002|
| B  | 0.002| 0.110| 0.006| 0.008| 0.005| 0.007| 0.034| 0.042| 0.002|
| C  | 0.002| 0.140| 0.010| 0.007| 0.006| 0.007| 0.033| 0.035| 0.003|
| D  | 0.002| 0.120| 0.007| 0.005| 0.006| 0.006| 0.036| 0.037| 0.0 |
uous furnace set to 800°C, immersed in a molten zinc bath held at 460°C and galvannealed in an induction furnace set to the power range shown in Table 2. The amount of aluminum in the molten bath and the resulting coating weight\(^{20}\) are shown in Table 2. The strips were temper rolled after their galvannealing. The roughness in the coating was measured (Table 2).

Selected samples from various strips were subjected to their analysis by optical and scanning electron microscopy, observations in the later equipment were made with the secondary and backscattered electron detectors, variation of the iron content profile within the coating was obtained by the analysis of punctual X-ray spectra produced by the electron beam. Small rectangular samples (90 by 30 mm) were cut from the galvannealed strips to study the powdering of the coating by deforming them in a press to which a V-bend device was installed. These trials were carried out with the V dies machined to 60 and 90°, the specimens were placed on an anvil, deformed to the angle machined into the dies and straightened after testing. The samples before and after testing were cleaned in a mixture of acetone and alcohol. An adhesive tape was applied to the deformed samples to remove the powder formed on the surface. The weight loss \((w_l)\) was normalized by dividing it by the surface area of the strip \((A_s)\) to obtain the powder lost \((P_w)\) by the coating\(^{3}\):\(^{3}\)

\[
P_w = \frac{w_l}{A_s} \quad \text{(2)}
\]

where \(w_l\) loss is obtained by subtracting the weight after testing \((w_o)\) from the original one \((w_i)\).

Other strips were cut from different coils to obtain the experimental samples to be spot welded in a two-electrode machine following the procedure described elsewhere.\(^{21}\) The force applied to hold in position the samples was kept constant at 3,530 N, the weld cycle was also kept constant. The force applied to hold in position the samples was kept constant at 3,530 N, the weld cycle was also kept constant. Two sets of specimens were made, those of the first one were cut to measure the weld nugget diameter and the indentation that the electrodes left on the strips. Samples from the second set were tested in tension in a servohydraulic testing machine at a constant crosshead speed following industrial standards.\(^{21,22}\) An extra set of specimens were prepared from uncoated strips (the coating was dissolved with a 10% HCl solution in water) of the material identified as C, see Table 1.

### Table 2. Processing variables and roughness of the samples studied.

| Batch | Heating power (kW) | Al in bath (%) | Coating weight (g/m²) | \(R_u\) (µm) |
|-------|-------------------|----------------|-----------------------|-------------|
|       | Minimum | Maximum |                |             |             | RD | TD |
| A     | 500     | 700     | 0.13            | 143          | 2.06        | 1.91         |
| B     | 380     | 500     | 0.13            | 119          | 1.98        | 1.84         |
| C     | 200     | 300     | 0.13            | 110          | 1.59        | 1.85         |
| D     | 240     | 260     | 0.14            | 110          | 1.43        | 1.39         |

RD: Rolling direction
TD: 90° to RD

Figure 1. Cross-section of the coated interstitial free steel samples, SEM images produced by backscattered electrons.
studied by means of a reversible V-bend test. Figure 5 shows the variation of $P_L$ as a function of either the thickness of $\Gamma$ phase or that of the total coating, and, as can be seen, the losses increased directly with the increment in thickness, independently of the geometry of the V-dies, although it is worth mentioning that the material is more sensitive to the test with 60° dies, as result of the higher bending deformation.

Different geometrical parameters were recorded after welding the strips. The size of the imprint diameter left by the electrodes was measured directly after welding, whereas the amount of penetration and the diameter of the welded nugget were measured after the samples were prepared for their metallographic inspection. Variation of the diameter of the imprint left by the electrodes in samples from material A can be seen in Fig. 6. It is possible to draw a single relationship for the size of the imprint, with respect to the
welding current, left by either electrode up to a current below than 12.2 kA. Once this value is surpassed the dependence of the diameter with the current keeps being linear, but now two different lines, one for each electrode, should be traced, and this may be due to the expulsion of the material.

Variation in the size of the welded nugget as a function of the current is shown in Fig. 7 for the different samples, data for the uncoated material is also added for comparison. All the samples exhibit a similar behavior, which is that of bigger nuggets with higher currents, but it can be observed that, for a given current applied, the size of the nuggets in the uncoated steel is around 20% bigger than those in galvannealed strips, a feature that has been attributed to the higher electrical resistance of the uncoated steel.14,15,17,18

Penetration of the electrodes follow a similar pattern, Fig. 8, i.e., more penetration with higher current, but data for all the different samples fall within the same scatter band, although the points corresponding to the uncoated material exhibit higher penetration, as this parameter reflects the changes in the temperature dependent mechanical properties of the steel.

Expulsion of the zinc coating was observed to occur when welding the samples. Figure 9 shows a secondary electrons image of a sample from material A welded with a current of 10.72 kA, the numbers within the image indicate the positions at which punctual X-ray analysis were made.

Table 5. Punctual analysis (wt%) carried out on the sample shown in Fig. 9.

| Position | Fe     | Zn     | Al  |
|----------|--------|--------|-----|
| 1        | 89.65  | 9.54   | 0.80|
| 2        | 88.93  | 10.17  | 0.89|
| 3        | 92.13  | 7.52   | 0.35|
| 4        | 94.77  | 3.06   | 0.17|
| 5        | 97.73  | 2.27   | -   |
| 60 µm from point 4 | 99.59 | 0.41 | - |
| 120 µm from point 4 | 100.00 | -    | -  |

Figure 10 shows the variation of the maximum load recorded during tensile testing of coated and welded samples as a function of the welding current. The data shown two different types of failure, that marked as interfacial consisted in separation of the strips due to the formation of either small or brittle nuggets, whereas in those marked as pull out, deformation and tearing of steel took place. Data points marked as expulsion correspond to those specimens in which part of the base steel was expelled during welding, and should not be confused with the phenomenon shown in Fig. 9. All the specimens identified as expulsion failed in the pull out mode during tensile testing. It is clear from Fig. 10 that, in the samples under study, the steel is not welded until a current of around 10.5 kA is surpassed, whereas expulsion will not take place below 12.5 kA.

The reduction in strength of welded joints when base material is expelled has been noticed before.26 Although the data shown in Fig. 10 fall within a broad scatter band,
the results of strips with the lighter coatings (C and D) exhibit the tendency to resist higher loads. Previous research\cite{14,15,18,19,27} have established a link between the current required to weld galvannealed steels and the nugget size, or the correlation between the mechanical resistance of welded joints and the size of the nugget,\cite{26} results that agree with the ones found in the present work. Figure 11 correlates the changes in maximum tensile load with nugget size, and, as it can be seen, the load increases with the nugget, up to the point where expulsion of base material starts to occur.

The occurrence of cracks originated at the electrode-steel interface was found in samples welded with high currents, Fig. 12. Figure 13 shows the variation of hardness measurements made on two different specimens from material D welded with 12.32 and 13.96 kA, the latter one corresponds to Fig. 12. Hardness was evaluated at three positions, center of nugget and at 1 and 1.9 mm from one of the edges; the thickness reported in Fig. 13 corresponds to that of the two joined strips. It is worth noticing that the hardness reported at mid-thickness and in the region in contact with the top electrode is the same in both samples, but that corresponding to the zone in contact with the bottom one is higher in the specimen shown in Fig. 12, and is close to the martensite expected for the low carbon content of the steel.\cite{28} It is worth reminding that both electrodes are cooled with water, the difference between them is that as soon as the welding cycle is accomplished the top electrode is raised, and the welded piece remains on top of the bottom electrode, chilling the bottom surface of the piece.

Cracks such as the one shown in Fig. 12 did not exert any influence on the type of failure of the specimens tested in tension as they were not in any position that will allow them to propagate, but they may be able to do if the specimens were tested in reversing bending fatigue, that was not contemplated in this work, and may cause the failure of a welded joint during actual operation.

4. Conclusions

It was found in the samples under study that the iron profile within the coating was affected by the settings of the galvannealing furnace, although no significative differences in the average iron content were found.

\textbf{Acknowledgements}

The authors thank the support and facilities provided by CONACYT and SIREYES, México, as well as the material and industrial facilities provided by Galvak, S.A. de C.V. M.P.G. and R.C. recognize the support provided by PAICYT-UANL.
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