Effects of Microstructure and Texture on the Formability Character of the Coatings in Three Industrial Galvannealed Steels

Anirban CHAKRABORTY and Ranjit Kumar RAY

Research and Development Division, Tata Steel, Jamshedpur, Jharkhand-831007, India.
E-mail: ani_chakra@yahoo.com, rkray@iitk.ac.in

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The microstructural and textural aspects of the substrates and the coatings on three industrially galvannealed interstitial free, interstitial free high strength and low carbon high strength quality grade steels have been carefully evaluated to determine their effects on the powdering resistance behavior of the coatings. A high amount of delta phase and a non-basal (0113)/{uvw} texture in the coating along with low Fe content have been found beneficial in this respect.

KEY WORDS: galvannealed coating; delta and interfacial layer; substrate and coating texture; powdering behavior.

1. Introduction

Among all zinc based steel coatings used in the automotive industry, galvannealed coating has received most attention because of its excellent spot weldability along with superior corrosion resistance and better paintability.1,2) In the galvannealing process the steel is first immersed in an aluminum containing zinc bath and then given a post coating heat treatment. This heat treatment causes the zinc in the coating to inter-diffuse with the substrate iron to form several Fe–Zn intermetallic phases which are stacked on the steel substrate.3) The embrittlement of industrial galvannealed coatings mainly depends on their iron content (approximately 10 wt%) and distribution of the different Fe–Zn intermetallic phases.

Most of the work to correlate the microstructure of galvannealed coatings to their formability has been carried out using galvanizing and galvannealing simulators.4–25) The present work on the other hand, has been undertaken to characterize in detail the microstructures and textures of the substrates and the coated layers of industrially produced galvannealed steels. At the same time an attempt has been made to evaluate the mechanical behavior of the coatings over an interstitial free (IF), an interstitial free high strength (IFHS) and a low carbon high strength quality (HSQ) grade steels. It is expected that this study will reveal how the actual operating conditions in the galvannealing industry control the changes in the microstructures and textures of the substrates and coatings that will ultimately get reflected on the coating properties.

2. Experimental Procedure

The chemical compositions of the steels are shown in Table 1. The galvannealing operation was carried out in the continuous galvanizing and galvannealing line in Tata Steel, Jamshedpur, India. The bath temperature was maintained at 460°C and the dissolved aluminum content of the bath was kept at a constant level of 0.134 wt%. The important industrial parameters for the galvannealing process are given in Table 2. The residence time of the steel strip in the heating zone of the galvannealing furnace was around 12 s for IF, around 20 s for IFHS and around 21 s for HSQ grade steels.

For characterization purpose all the samples for analysis were carefully cut from the sheet and precleaned by acetone followed by ethanol. Grazing incidence X-ray diffraction (GIXRD) study of the top of the galvannealed coatings, was carried out using a Panalytical X’pert PRO XRD machine. In order to minimize the depth of penetration of the X-ray

Table 1. Substrate steel composition (wt%).

| Sample No. | C  | Mn  | Al  | Ti  | Nb | Si  | S  | P  | N (ppm) |
|------------|----|-----|-----|-----|----|-----|----|----|---------|
| IF         | 0.0022 | 0.13 | 0.035 | 0.015 | -   | 0.012 | 0.010 | 0.009 | 28      |
| IFHS       | 0.0040 | 0.35 | 0.030 | 0.030 | -   | 0.008 | 0.010 | 0.070 | 40      |
| HSQ        | 0.0900 | 0.85 | 0.042 | 0.027 | 0.05 | 0.020 | 0.004 | 0.017 | 54      |

Table 2. Galvannealing processing parameters.

| Sample No. | Steel Sheet Thickness (mm) | Line Speed (meter/min.) | Galvannealing Power (kW) | Galvannealing Strip Temperature (°C) | Skin Pass Elongation (%) |
|------------|---------------------------|-------------------------|--------------------------|-------------------------------------|--------------------------|
| IF         | 0.7                       | 107                     | 786                      | 480                                 | 0.50                     |
| IFHS       | 1.0                       | 62                      | 1148                     | 515                                 | 0.79                     |
| HSQ        | 1.6                       | 58                      | 1296                     | 530                                 | 1.57                     |
beam within the sample, the X-ray incidence angle was kept at 1° with respect to the coating surface. The scan rate of the XRD measurements was maintained at 3°/min. The measured intensity vs. 2θ plots were indexed by matching the different peaks with the standard data obtained from International Centre for Diffraction Data (ICDD), 1998 edition.

Crystallographic textures of the coating surfaces were determined using a PANalytical X’pert PRO XRD machine with a texture goniometer. The (233), (054), (330), (241) and (249) pole figures were determined from which orientation distribution functions (ODFs) were calculated by the method of Bunge using Labotex software.

For cross-sectional optical microscopy samples were carefully polished and then color etched with a mixture of 4% picric acid in ethanol and 2% nitric acid in distilled water solution, along with few drops of benzalkonium chloride reagent. The differently colored Fe–Zn intermetallic phases were studied using a Leitz Labor Lux 12MES Image Analyzer.

In cross-sectional scanning electron microscopic (SEM) study there was a distinct possibility of the edges of the coating falling off the substrate or getting damaged during polishing. To prevent this, a 200 μm thin copper strip was used as the supporting material. Then the whole assembly was polished using 0.1 μm fine diamond paste. Point by point EDS analyses for Fe and Zn were carried out from the substrate side towards the top surface of the coating. SEM study was carried out using a FEI Quanta-200 SEM operated at 20 kV.

The quantitative depth profiling (QDP) was carried out using a LECO GDS-850A glow discharge optical emission spectroscope (GDOES) at different locations of the top surface of the coating.

The percentage thicknesses of the different Fe–Zn intermetallic phases were determined by superimposing the compositional ranges for the different phases on the above EDS as well as QDP-GDOES profiles.

Anodic dissolution study of the coated layers on the three steels was carried out using an EIS-300, Gamry Instrument, DC 105, USA. The electrolyte contained 250 mg/L NaCl and 50 mg/L ZnSO₄. The pH of the electrolyte was kept at 4. During the above study a current density of 0.5 mA/cm² was maintained.

The Fe contents of the coatings were determined by ASTM standard gravimetric method (A90/A 90M-01). The edges of the test pieces were covered using lacquer so that during cleaning by petroleum ether, the weights of the samples after the chemical exposure were measured. The Fe contents of the solutions were determined using an inductive coupled plasma spectroscope (ICPS), Spectro Analytical Instrument, GmbH version 2.0e/8/8/88, Germany. The amounts of Fe so determined were the actual Fe contents in the coatings.

The Fe contents of the coatings were also determined from the EDS and QDP-GDOES profiles. The details of the calculations are reported in the Appendix.

Cross-sectional TEM study was carried out using a JEOL 2000FX transmission electron microscope with an operating voltage of 160 kV. For this purpose small pieces sample were mounted in a special resin inside a 3 mm diameter Cu tube. These were then sliced and polished, followed by dimpled and ion milled.

For studying the texture of the substrate steels the galvannealed coatings were removed by exposing the coated steels to a 54.34 mass% dilute HCl solution in distilled water followed by mild polishing. After that electro-polishing was carried out in a mixture of 75.20 mass% acetic acid and 24.80 mass% perchloric acid solution with platinum electrode at 20 V. The electro polishing was carried out for a period of approximately 50 s when a mirror polished surface was obtained. The substrate steel texture was then determined using an OIM camera attached to a FEI Quantax-200 SEM operated at 20 kV. Using a step size of 1.5 μm a number of different areas were selected for texture measurement. The data was then analyzed by the TSL-OIM software to construct the ODF (Bunge notation) of the orientation distribution function (ODF).

The formability of the galvannealed coatings was determined by the double Olsen test method. The weights of the samples were measured before the testing. After that a hardened steel ball was punched on to the top surface of the coating to produce a hemispherical cup. The sample surface was then reversed and the same steel ball was again punched on to the top of the hemispherical cup. After thorough cleaning by petroleum ether, the weights of the samples were measured again, and the weight losses were calculated.

3. Experimental Results

The GIXRD patterns of the three galvannealed coated samples from IF, IFHS and HSQ steels are shown typically in Fig. 1. The different peaks have been identified as mainly from the delta (δ) phase after comparing the results with the standard ICDD of these phases as shown in Table 3. All
the GIXRD patterns appear rather similar. The analyses of the peaks indicate the presence of mainly the delta (δ) phase.

| Table No. | Phase | 20 (°) | h k l | d (Å) | Intensity (%) |
|----------|-------|--------|------|-------|--------------|
| 45-1186  | δ     | 35.581 | 2 3 3 | 2.521 | 6            |
|          |       | 36.099 | 2 3 5 | 2.486 | 7            |
|          |       | 36.803 | 0 4 1 | 2.444 | 4            |
|          |       | 37.455 | 1 4 3 | 2.399 | 6            |
|          |       | 38.385 | 1 4 6 | 2.343 | 4            |
|          |       | 41.165 | 0 5 4 | 2.191 | 45           |
|          |       | 41.621 | 1 1 25 | 2.168 | 45           |
|          |       | 42.275 | 3 3 0 | 2.136 | 100          |
|          |       | 43.208 | 2 4 1 | 2.092 | 100          |
|          |       | 43.691 | 0 5 10 | 2.070 | 19           |
|          |       | 44.367 | 0 5 11 | 2.040 | 7            |
|          |       | 45.568 | 2 4 9 | 1.989 | 10           |
|          |       | 48.318 | 5 1 10 | 1.882 | 6            |
|          |       | 48.759 | 4 2 14 | 1.866 | 8            |

| 34-1314  | ζ     | 32.329 | - 2 2 1 | 2.769 | 10           |
|          |       | 35.079 | - 4 0 1 | 2.558 | 2            |
|          |       | 35.758 | 2 2 1 | 2.511 | 11           |
|          |       | 36.804 | - 2 0 2 | 2.442 | 27           |
|          |       | 40.110 | 1 3 1 | 2.248 | 14           |
|          |       | 40.486 | 1 1 2 | 2.228 | 8            |
|          |       | 41.259 | 4 2 0 | 2.188 | 88           |
|          |       | 41.537 | 1 3 1 | 2.174 | 100          |
|          |       | 41.819 | 3 1 2 | 2.160 | 50           |
|          |       | 42.583 | - 4 2 1 | 2.123 | 88           |
|          |       | 42.795 | 2 0 2 | 2.113 | 40           |
|          |       | 43.398 | 2 2 1 | 2.085 | 49           |
|          |       | 44.019 | 5 1 0 | 2.057 | 71           |
|          |       | 45.680 | 3 3 1 | 1.986 | 15           |
|          |       | 47.874 | 4 2 1 | 1.90 | 44           |

The color etched cross-sectional optical micrographs of the galvannealed coatings on above grades of steel are shown in Figs. 2(a)–2(c). The dark brown regions in the micrographs represent the interfacial layer containing the gamma (Γ) and gamma 1 (Γ₁) Fe–Zn intermetallic phases and the δ phase is colored greenish yellow. From the above micrographs it is found that the thickness of the interfacial layer increases from IF to IFHS to HSQ.

The compositional analyses of the galvannealed coatings were carried out from the substrate side to the top surface of the coatings using EDS. In the EDS plots zero point was decided at the point where the amount of Fe present is more than 50%. This will ensure that a part of the substrate is also taken in to account, making us confident that the entire coating layer has been covered. The composition profiles of Fe and Zn concentration in the coatings are plotted in Figs. 3(a)–3(c). The different Fe–Zn phase fields have been marked by strictly following the standard Fe–Zn binary phase diagram shown in Fig. 4 and the compositional ranges of different Fe–Zn intermetallic phases are reported in Table 4. The thickness of each phase field has also been measured and these have been summarized in Table 5.

Quantitative depth profiling (QDP) plots of the galvannealed coating on IF, IFHS and HSQ grade steels, carried out using GDOES, are shown in Figs. 5(a)–5(c). The percentage thicknesses of the different Fe–Zn intermetallic phases were also determined by superimposing the compositional ranges for the phases on the above profiles and the summary of these results is reported in Table 5.

Very often anodic dissolution technique is used to identify the various phases present in galvannealed coatings. The relevant plot for the three steels using this technique is shown in Fig. 6.

The Fe content of the coatings is one of the parameters

![Fig. 2. Color etched cross-sectional optical micrographs of galvannealed coating over sample No. (a) IF, (b) IFHS and (c) HSQ.](image)

![Fig. 3. EDS profiles of galvannealed coating of sample No. (a) IF, (b) IFHS and (c) HSQ.](image)
which control the formability of the galvannealed coating. The coating Fe content was determined by wet chemical method and also from the EDS as well as from the QDP-GDOES profiles. Table 6 compares the coating Fe content obtained by the three different methods.

Figures 7 and 8 show typical cross-sectional TEM micrographs of the galvannealed coatings over IF and HSQ grade steel samples. The TEM micrograph of the IFHS sample is rather similar to that of the IF and hence has not been included. Selected areas diffraction patterns (SADP) were recorded from different regions across the circled area in Fig. 7 and also from the magnified portion of the circled area in Fig. 8. The SADPs were indexed and the phases were identified after comparing with the standard ICDD charts. From the cross-sectional TEM study it is clear that in all the three steels the $\delta$ phase is present at the top part of the coatings, below which the $\Gamma$ and $\Gamma_1$ phases form. The $\delta$ phase is more prevalent in the coating of the IF steel (and also in the IFHS steel), but less so in case of the HSQ steel.

Figure 9(a)–9(c) represent the $\Phi_2=45^\circ$ ODF sections for...
the IF, IFHS and HSQ grade steel substrates steels. The grain boundary character distribution (GBCD) plots of the steel substrate are shown in Figs. 10(a)–10(c).

The color coded maps of {111}, {113}, {313}, {001} and {101} crystal planes of the substrate steels are shown in Figs. 11(a)–11(c). The densities of the these planes parallel to the rolling planes were measured from the ODFs as well as from the color coded maps of crystal planes of the substrate steel and these are displayed in Figs. 12(a), and 12(b).

The $\Phi_2$ sections of the complete ODF of the galvannealed coatings on IF, IFHS and HSQ grade steels appear rather similar visually. A typical plot for the IF steel is shown in Fig. 13. However, some subtle differences between the $\Phi_2$ section plots for the three steels can be brought clearly in Figs. 14(a)–14(c), where the $\Phi_2=0^\circ$ sections of the above ODFs have been shown on a magnified scale. Although the texture components of the coatings in all three cases are of the type $\{01.3\}(uv.w)$, a careful examination of the $\Phi_2=0^\circ$ ODF sections in all the three cases clearly indicates that for the sample IF there exists almost a complete fiber of the type $\{01.3\}(uv.w)$, the fiber character changes into a set of discrete orientations in sample HSQ. The continuity of this fiber in the IFHS steel is intermediate between these two.

The weight losses measured before and after the double olsen test in case of the three steels are reported in Table 7.

4. Discussion

Cross-sectional SEM-EDS results [Figs. 3(a)–3(c)] clearly indicate that in the samples IF and IFHS the top part of the coatings is made up of the pure $\delta$ phase, although its thickness decreases from IF to IFHS. In the HSQ sample no pure $\delta$ phase has been found, however, the $(G_1)$ phase field has been quite extensive. Compared to the IF and the IFHS, the HSQ steel exhibits a much wider $G$ phase range. The major difference between the EDS and QDP-GDOES results [Figs. 3(a)–3(c) and 5(a)–5(c)] is that the latter technique could detect the $\zeta$ phase also which eluded the EDS technique (Table 5). The percentage thickness of the $\delta$ layer measured by GDOES is much less than the

| Method        | % Fe Content of the Coating |
|---------------|----------------------------|
| Wet Chemical  | 10.35  11.10  14.61        |
| EDS Profile   | 11.06  11.95  15.21        |
| GDQES Profile | 12.48  12.98  14.13        |

Table 6. Fe Content of the galvannealed coating obtained by different methods.
amount measured by the EDS method for IF and IFHS samples. On the other hand, by this technique pure δ phase was identified for HSQ sample. The major reason for the discrepancy in the values obtained by the two methods lies in the fact that by using the GDOES technique monatomic layers can be analyzed separately by sputtering, which is not feasible in SEM-EDS. In the EDS method the relatively large interaction volume of the electron beam with the sample causes error in the measured values. Therefore, the QDP-GDOES results are more accurate and reliable than the SEM-EDS results.

Since in the anodic dissolution study the coating gets dissolved from the top surface, layer by layer, perfect flat plateaus can be expected in the potential versus time plots for the dissolution of a particular phase. However, perfect plateaus may not be obtained in practice because of the complex mixture of the phases in the coating. Obviously, first step formed will be for the dissolution of the uppermost ζ phase followed by (ζ + δ), δ, (δ + Γ'), Γ', (Γ' + Γ) and Γ. In the plot for the IFGA sample, these specific steps have been marked; however, such distinct steps in the anodic dissolution plots could not be detected in the other two steels (Fig. 6). It may be mentioned here that the ζ phase is usually present on the top surface of the coating in the form of isolated small islands. Therefore, detection of this phase is a matter of chance. However, during anodic dissolution study the area exposed to solution is much higher
In that case even if some small amount of $\zeta$ phase is present, this signals from this phase may be effectively masked by the signals coming from the more extensive $\delta$ phase; so much so that it may not be possible to distinguish the characteristic step for $\zeta$ phase from that of the $\delta$ phase. For this reason the $\zeta$ phase was not possibly detected during the anodic dissolution study for the galvannealed coating over IFHS and HSQ grade steels. However, as mentioned earlier, the $\zeta$ has been detected in all the three steels by QDP-GDOES method. The potential of a particular phase depends on the Fe content of that phase. The overall Fe content of the galvannealed coating on HSQ is maximum as compared to the IF or IFHS. The $\delta$ phase is an intermediate phase which has a range of solubility for Fe. For the HSQ sample, the Fe content of the $\delta$ phase is higher compared to the other samples. As a result, it shows higher potential during anodic dissolution.

For determining the Fe content of the galvannealed coating, in wet chemical method the coated sample is immersed into an acidic solution for dissolving the entire galvannealed coating. In this case there is a chance of arriving at an excess Fe content value in the coating due to the possibility of dissolution of at least some of the substrate steel in the acidic solution. On the other hand, it is also possible that the entire coating may not be dissolved into the acidic solution and in that case less Fe content is obtained in the coating. By and large, the EDS analysis does not suffer from such kind of problems. However, we must remember that EDS analysis is carried out over a number of discrete points only and this could be a limitation of this technique. Again the interaction volume of the electron beam in the EDS method may be quite large and this will preclude correct chemical analysis from a particular phase. GDOES results appear to be the most accurate where the analysis is carried out in each atomic layer. The necessary calculations for determining the Fe content of the galvannealed coatings from SEM-EDS and QDP-GDOES profiles are shown in the Appendix. The above results clearly indicate that coating Fe content is minimum for the IF, maximum for the HSQ steel and IFHS lies in between (Table 6). For the reasons stated above the QDP-GDOES method appears to be the most reliable and accurate among the three analytical methods for the purpose of identifying the chemistry and phase composition of the different Fe–Zn compounds present in the coating.

From the substrate textural study [Figs. 9(a)–9(c)] it is found that a reasonably strong gamma ($\gamma$) fibers can be detected in the IF and IFHS samples. However, these fibers are not very uniform in nature and show maxima at $\{111\}$ locations. The presence of sharp $\gamma$ fibers indicate satisfactory formability of the IF and IFHS steel sub-

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### Table 7. Average weight loss during double olsen test of galvannealed coating.

| Sample No. | Average Weight Loss (mg) |
|------------|--------------------------|
| IF         | 5.90                     |
| IFHS       | 8.80                     |
| HSQ        | 14.56                    |

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Fig. 13. $\Phi_2$ Sections of the ODF of the galvannealed coating on sample No. IF.

Fig. 14. Magnified view of $\Phi_2=0^\circ$ sections of galvannealed coating on sample No. (a) IF, (b) IFHS and (c) HSQ.
The HSQ sample also shows a γ fiber together with an alpha (α) fiber as well as rotated cube component in the \( \Phi_2 = 45^\circ \) ODF section. This is indicative of the fact that the formability of this steel is poorer than that of the IF and IFHS steels. Figures 10(a)–10(c) clearly show the presence of nearly equal number fractions of low angle (\(<15^\circ\)) and high angle (\(>15^\circ\)) grain boundaries for the IF and IFHS steels, whereas in the HSQ grade steel, the fraction of high angle grain boundaries is much higher than that of the low angle boundaries. The rather high densities of the low angle boundaries in the IF and IFHS steels indicate a very sharp texture, in this case a sharp γ fiber. The less sharp γ fiber texture in the HSQ steel is reflected in the rather low number fraction of low angle boundaries in this case. All the three steels show a rather small number fraction of the Co incidence Site lattice (CSL) boundaries.

The \{111\}, \{113\}, \{313\}, \{001\} and \{101\} planes of the substrate steel are known to control the growth rate of the \( \zeta \) phase.\(^{(29,30)} \) It has been found that higher the fraction of \{111\}–\{113\}–\{313\} planes on the surface of the steel, higher is the amount of pillar like ordered \( \zeta \) crystals formed, which have lower growth rate. On the other hand, randomly oriented \( \zeta \) crystals with higher growth rate are formed on \{001\}–\{101\} substrate planes.\(^{(29)} \) Figure 12(a) clearly indicate that in the IF and IFHS steels not much variation is observed in the relative densities of the \{111\}, \{113\} and \{313\} planes parallel to the rolling plane (RP). By contrast, as shown in Fig. 12(b) the density of the \{001\} plane parallel to the rolling plane is higher in steel IFHS compared to the IF. Therefore, it is expected that chances of formation of fast growing \( \zeta \) crystals should be higher in the IFHS than in the IF steel. This is essentially what has been observed in the present case (Table 5). It therefore appears that the crystallographic texture definitely plays a role in the formation and growth of the \( \zeta \) phase during galvannealing. Industrially speaking, the substrate texture should be controlled in such a manner that \( \zeta \) crystals with lower growth rate only can form. In that case these crystals can be easily converted into the favorable \( \delta \) phase during the short galvannealing time. In the case of the HSQ grade steel, however, the densities of the planes \{001\} and \{101\} parallel to the rolling planes are maximum among all the three steels indicating larger formation of the fast growing \( \zeta \) phase. Table 5 however, shows that the amount of the \( \zeta \) phase is minimum in the HSQ steel.

Since the thickness as well the coating Fe content of the HSQ steel is the highest among the three steels, the effect of the substrate texture independently on the formation of the intermetallic compounds in this case can not be stated with certainty. It is known that during galvannealing the first Fe–Zn reaction starts through the ferrite grain boundaries of the substrate steel. More clean the grain boundary region, faster is the Fe–Zn reaction. The grain boundary regions of the HSQ grade steel are not as clean as in IF or IFHS grade steels. Therefore to enhance the Fe–Zn reaction generally higher galvannealing power or galvannealing temperature is maintained in case of the HSQ steel (Table 2). It may be suggested here that the amount of the \( \zeta \) phase formed in this steel was possibly the highest, however, due to the higher galvannealing temperature most of it might have converted into the \( \delta \) phase. Not only that, due to the higher heat input during galvannealing some amount of \( \delta \) phase could also get converted into the deleterious \( \Gamma \) phase as shown in Table 5.

In the hexagonal \( \delta \) phase, the primary slip planes are the basal (0002) planes. If the basal planes of \( \delta \) crystals are aligned in such a way that under the applied stress a significant amount of resolved shear stress exists on these planes, then plastic flow will be facilitated.\(^{(31)} \) The \{013\} planes make an angle \(<60^\circ\) with the basal planes \{002\}. Therefore, in these galvannealed samples, the basal planes are inclined at \(<60^\circ\) with respect to the sheet planes. Shaffer et al.\(^{(32)} \) observed that in electrogalvanized materials no cracking takes place when the basal plane makes an angle between 40–70° with respect to the substrate surface. The presence of an almost continuous fiber [Fig. 14(a)] of the type \{013\}\((\eta\eta\gamma\gamma)\), as found in case of the IF sample, seems to be most beneficial in this respect. Breakdown of this fiber [Figs. 14(b), 14(c)] into discrete orientations in case of IFHS and HSQ steel may cause deterioration in the powdering resistance behavior. However, it must be remembered that the amount of the \( \Gamma \) and \( \delta \) phases in IFHS is higher than in the IF, while this amount is the highest in the HSQ steel. It is well known that the \( \Gamma \) phase deteriorates the formability of the coating. Therefore, the amount and the orientational aspects of \( \delta \) can not wholly determine the formability; instead it will be one of the contributing factors.

The weight loss is minimum for the IF sample and maximum for the HSQ as shown in Table 7. The IFHS sample shows a value which is higher than but very close to that of the IF and at the same time much less than in case of the HSQ steel. These results agree very well with the results of the textural studies on the coatings.

It is now clear that the formability behavior of the galvannealed coating is controlled by the amount of \( \Gamma \) and \( \delta \) phases together with the amount and orientational aspects of the \( \delta \) phase in the coating. The difference in the powdering resistance behavior of the three steels can be clearly explained on the above basis. The other important factor which may play a very significant role is the total Fe content of the coating. The minimum Fe content for the IF steel may contribute to its best formability while the maximum Fe content for the HSQ steel may be the cause of its worst formability. According to this criteria the formability of the IFHS steel should lie between the above two extremes. This difference in behavior between the coatings on the three experimental steels has also been corroborated by the coating microstructure and texture.

5. Conclusions

The key findings of this investigation can be summarized as follows:

(1) Among all the three galvannealed coated steels, highest amount of delta phase forms in sample IF and lowest in HSQ. The IFHS shows an intermediate value.

(2) The coating Fe content is minimum in sample IF and maximum in HSQ with the IFHS possessing an intermediate value.

(3) Similar volume fractions of the \{111\}–\{113\}–\{313\} planes at the top of the steel substrates, in case of the
IF and IFHS steels, may be one of the reasons for the presence of rather similar amounts of $\zeta$ crystals in the IF and IFHS steels. By contrast, much higher volume fraction of the {001}–{101} planes on the top of the substrate in the HSQ steel could promote the $\zeta$ crystals with higher growth rate. The observed small volume fraction of $\zeta$ crystals in the HSQ steel is most likely due to the much higher galvannealing power in that case. However, the substrate texture can not independently determine the formation of the intermetallic compounds in the three steels which vary in thickness as well as in coating Fe content.

(4) In all the three steels the {013} planes of $\delta$ phase in the coating are parallel to the substrate steel surface. Such alignment of the {013} planes of $\delta$ is beneficial for the coating formability. In the IF sample almost a complete fiber of the type {01.3} (uvw) is present, the fiber character changes into a set of discrete orientations in the IFHS and the HSQ samples. This may partly explained the difference in the formability of the coatings on the three steels, which will additionally be affected by the amounts of the $\Gamma_1$ and $\Gamma$ phases.

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Appendix. Determination of Fe Content of the Galvannealed Coating from SEM-EDS and QPD-GDOES Profiles

- Average Fe Content of Different Fe–Zn Intermetallic Phases

From the Table 4

The average Fe content of $\Gamma$ phase

$$\frac{(20.3+27.0)}{2} = 23.65 \text{ wt\%}$$

The average Fe content of $(\Gamma+\Gamma_1)$ phase

$$\frac{(20.3+18.2)}{2} = 19.25 \text{ wt\%}$$

The average Fe content of $\Gamma_1$ phase

$$\frac{(16.2+18.2)}{2} = 17.20 \text{ wt\%}$$

The average Fe content of $\Gamma_1+\delta$ phase

$$\frac{(16.2+11.3)}{2} = 13.75 \text{ wt\%}$$

The average Fe content of $\delta$ phase

$$\frac{(7.4+11.3)}{2} = 9.35 \text{ wt\%}$$

The average Fe content of $(\delta+\zeta)$ phase

$$\frac{(7.4+6.1)}{2} = 6.75 \text{ wt\%}$$

The average Fe content of $\zeta$ phase

$$\frac{(5.2+6.1)}{2} = 5.65 \text{ wt\%}$$

- Density of Pure Elements

Density of Fe: 7.86 g/cc

Density of Zn: 7.14 g/cc
• The Density of Different Fe–Zn Intermetallic Phases
For determination of density of intermetallic phases, inverse rule of mixture is applied

Density of \( G \) phase (\( \rho_G \)):
\[
100 \rho_G = \left( \frac{23.65}{7.86} \right) + \left( \frac{100-23.65}{7.14} \right) = 7.2981 \text{ g/cc}
\]

Density of \((G'+G)\) phase (\( \rho_{G+G'} \)):
\[
100 \rho_{G+G'} = \left( \frac{19.25}{7.86} \right) + \left( \frac{100-17.20}{7.14} \right) = 7.2682 \text{ g/cc}
\]

Density of \((G_1+\delta)\) phase region (\( \rho_{G_1+\delta} \)):
\[
100 \rho_{G_1+\delta} = \left( \frac{13.75}{7.86} \right) + \left( \frac{100-13.75}{7.14} \right) = 7.2311 \text{ g/cc}
\]

Density of \( \delta \) phase (\( \rho_\delta \)):
\[
100 \rho_\delta = \left( \frac{9.35}{7.86} \right) + \left( \frac{100-9.35}{7.14} \right) = 7.2017 \text{ g/cc}
\]

Density of \((\delta+\zeta)\) phase (\( \rho_{\delta+\zeta} \)):
\[
100 \rho_{\delta+\zeta} = \left( \frac{6.75}{7.86} \right) + \left( \frac{100-6.75}{7.14} \right) = 7.1844 \text{ g/cc}
\]

Density of \( \zeta \) phase (\( \rho_\zeta \)):
\[
100 \rho_\zeta = \left( \frac{5.65}{7.86} \right) + \left( \frac{100-5.65}{7.14} \right) = 7.1771 \text{ g/cc}
\]

• Determination of Fe Content of the Coating
Let length of the coating (m)=\( L \)

Width of the coating (m)=\( W \)

\( G \) layer thickness (\( \mu m \)): \( G \)

\((G'+G)\) layer thickness (\( \mu m \)): \((G+G')\)

\( G_1 \) layer thickness (\( \mu m \)): \( G_1 \)

\((G_1+\delta)\) layer thickness (\( \mu m \)): \((G_1+\delta)\)

\( \delta \) layer thickness (\( \mu m \)): \( \delta \)

\((\delta+\zeta)\) layer thickness (\( \mu m \)): \((\delta+\zeta)\)

\( \zeta \) layer thickness (\( \mu m \)): \( \zeta \)

Volume of \( G \) layer (m\(^3\))=\( G \times L \times W \times 10^{-6} \)

Volume of \((G+G')\) layer (m\(^3\))=\((G+G') \times L \times W \times 10^{-6} \)

Volume of \((G_1+\delta)\) layer (m\(^3\))=\((G_1+\delta) \times L \times W \times 10^{-6} \)

Volume of \( \delta \) layer (m\(^3\))=\( \delta \times L \times W \times 10^{-6} \)

Volume of \((\delta+\zeta)\) layer (m\(^3\))=\((\delta+\zeta) \times L \times W \times 10^{-6} \)

Volume of \( \zeta \) layer (m\(^3\))=\( \zeta \times L \times W \times 10^{-6} \)

Mass of \( G \) layer (kg)=\( G \times L \times W \times 10^{-6} \times 7298.1 \)

Mass of \((G+G')\) layer (kg)=\((G+G') \times L \times W \times 10^{-6} \times 7254.3 \)

Mass of \((G_1+\delta)\) layer (kg)=\((G_1+\delta) \times L \times W \times 10^{-6} \times 7231.1 \)

Mass of \( \delta \) layer (kg)=\( \delta \times L \times W \times 10^{-6} \times 7201.7 \)

Mass of \((\delta+\zeta)\) layer (kg)=\((\delta+\zeta) \times L \times W \times 10^{-6} \times 7184.4 \)

Mass of \( \zeta \) layer (kg)=\( \zeta \times L \times W \times 10^{-6} \times 7177.1 \)

Mass of Fe content of the coating (kg)=\( (G+G') \times L \times W \times 10^{-6} \times 7298.1 \times 0.2365 \)

Mass of Fe content of \((G_1+\delta)\) layer (kg)=\((G_1+\delta) \times L \times W \times 10^{-6} \times 7254.3 \times 0.1720 \)

Mass of Fe content of \((\delta+\zeta)\) layer (kg)=\((\delta+\zeta) \times L \times W \times 10^{-6} \times 7268.2 \times 0.1375 \)

Mass of Fe content of \( \zeta \) layer (kg)=\( \zeta \times L \times W \times 10^{-6} \times 7201.7 \times 0.0935 \)

Mass of Fe content of \((\delta+\zeta)\) layer (kg)=\((\delta+\zeta) \times L \times W \times 10^{-6} \times 7268.2 \times 0.0675 \)

Mass of Fe content of \( \zeta \) layer (kg)=\( \zeta \times L \times W \times 10^{-6} \times 7201.7 \times 0.0565 \)

Total mass of all layers (kg)=\( A+B+C+D+E+F+G \)

Total Fe content of all layers (kg)=\( H+I+J+K+L+M+N \)

\% Fe content of the coating=(P/O)\times 100=2\%

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