

Influence of Delta Phase Morphology in Galvannealed Coated Steels on Formability

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Abstract. It is well known that coating microstructure can affect the frictional behavior and the formability of galvannealed steels. Several studies are available in literature describing the influence of different coating phases, such as, gamma, delta and zeta phases, on press formability. In the present study, the authors have investigated the effect of the surface morphology, specifically of the delta phase of galvannealed coating on press formability. Formability tests including conditions of (a) complete metal lockdown and (b) significant metal movement in the dies were conducted. It was found that cubic delta coatings seem to perform better (reduced splitting) in forming operations which are accompanied by significant sliding in the blankholder area than rod delta coatings. This paper presents the results of the formability evaluation for samples with different delta phase morphology and correlation with traditionally used measures for evaluation of surface behavior such as the frictional behavior and surface roughness.

1. Introduction

Zinc coated sheet steels are widely used in the automotive industry for applications in the body structure, underbody and chassis components because of effectiveness in corrosion protection and cost competitiveness. Typically, coated sheet steels are available as hot dipped galvanized, electro-galvanized or galvannealed products. The use of the type of coated sheet steels in automotive OEMs primarily results from cost considerations and compatibility of existing manufacturing systems (stamping, welding, painting) with the coating which can differ across automakers. The galvannealing (GA) process consists of dipping the incoming cold rolled sheet strip in a molten Zn pot followed by an annealing process. In GA coatings, liquid Zn reacts with Fe in the strip to form various intermetallic compounds in the coating. The three primary phases, zeta, delta and gamma phases contain about 5.1-6.1 wt.%, 7.0-11.5 wt.% and 16.0-27.8 wt.% Fe, respectively [1]. Figure 1 shows the Fe-Zn binary phase diagram [2] indicating the different intermetallic phases that can form during the GA process. Also shown in Figure 1 are metallographs (planar view and cross-sectional view) of a typical GA coated sheet steel. Zeta phase is a soft phase and occurs at the outermost surface of the coating. Gamma phase is an Fe-rich brittle phase that grows at the steel/coating interface. Delta phase forms between the gamma and zeta phases. With increase in GA cycle temperature or time, the iron content in the coating increases and the gamma and delta phases grow as the zeta phase is consumed. For similar coating thickness, presence of zeta phase indicates lower galvannealing (or under-alloying) than the coating without the zeta phase. The impact of different phases in the GA coating on stamping performance has been reported [3-6]. Low annealing temperature or time, can result in excessive zeta phase, which adheres to the stamping dies, resulting in high friction conditions leading to sheet splitting during stamping. On the



other hand, if the GA temperature or time is very high, the zeta phase decreases but the brittle gamma phase grows thicker, which can cause powdering/flaking of the coating causing build up in the forming dies and could lead to galling, and adhesive wear on the dies which consequently lead to splitting failures because of high friction conditions and increased die maintenance costs. Hence, a moderate GA temperature and time are critical to optimize the amount of coating phases for better forming performance.

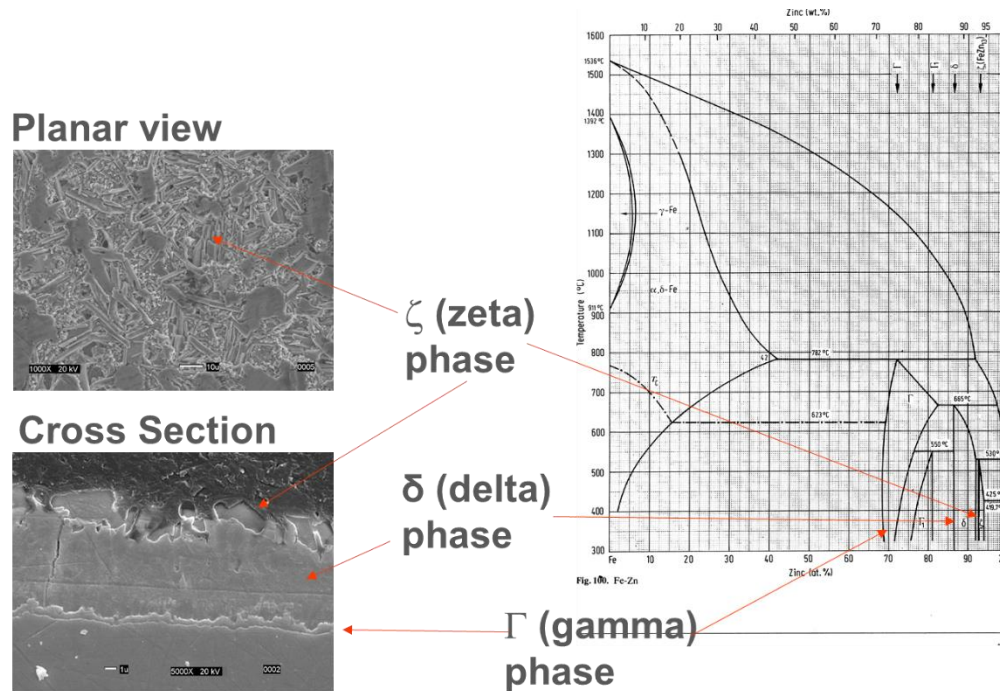


Figure 1. Fe-Zn phase diagram [2] accompanied by microscopic images showing the different phases present on the surface in a typical galvanized coated sheet steel.

Although the impact of the different phases of the GA coating microstructure has been studied, to-date there has been no reported study on the impact of morphology of the delta phase on stamping behavior. As previously mentioned, the type of intermetallic phase can be controlled by the GA cycle to result in minimum zeta phase but further optimization of the GA cycle is also possible to maximize forming performance. This study explores further refinement of the GA cycle to produce optimized coatings in terms of the phase distribution on the surface in addition to different morphologies of the delta phase. Formability was evaluated under conditions of material clamp-down using lock-beads and metal movement through the blankholder plates. The measures of formability are also correlated with typical measures of surface tribological behavior such as the friction coefficient, surface roughness and peak count.

2. Experimental procedure

2.1 Materials

To produce the above-mentioned phase controlled coatings, different thermal profiles were tested on a typical Ti-stabilized Interstitial Free (IF) steel. Figure 2 shows a schematic of the typical GA cycle. The incoming cold rolled sheet strip is dipped through a Zn bath following which the strip proceeds to the induction furnace followed by a soak furnace. The primary control parameters for the galvannealing process are the strip temperatures monitored at the exit of the induction furnace, T_{GA} and the exit from the soak furnace, T_{SE} . The details of the galvannealing process conditions are confidential. It suffices to mention that different characteristics of the GA coated surface resulted from varying these two control parameters for a fixed line speed.

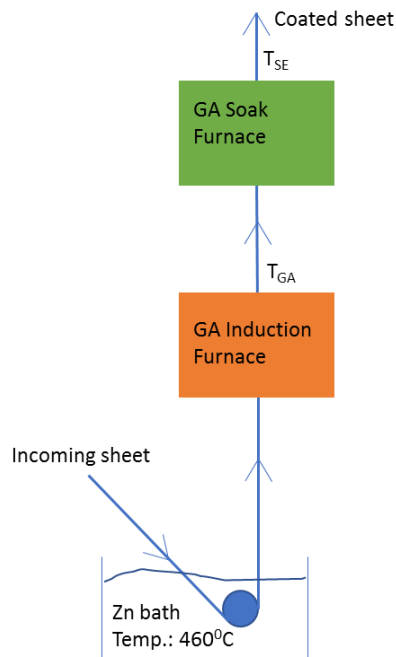


Figure 2. Schematic showing the galvannealing process conditions for the trial.

2.2 Formability Tests

Two types of formability tests were conducted on the above coated steels; (a) Square cup draw test and (b) Limiting dome height (LDH) test. The Square cup draw test [8] has been used in the past to determine formability under conditions of simultaneous stretching across the punch radius and draw-in of the metal from between the binder plates. In this test, formability is significantly influenced by friction at the sheet/punch and sheet/binder interface due to the metal flow under the binder. Figure 3(a) shows the press equipment used to form the samples and figures 3(b) and 3(c) show the formed sample and the necked region respectively. Details of the experimental procedure are given below:

- Forming Height and Speed: 38.1mm at 20 strokes/min
- Die cushion pressure (for blankholding force): 1.03 MPa
- # of replicates: 10
- Lubrication: None
- Measure of formability: % Number of safe samples (samples with no cracks or visible necking)



(a)



(b)



(c)

Figure 3. (a) Photograph of the experimental press with the square cup die-set (b) formed square cup sample (c) failure location and mode in the sample.

In contrast to the square cup test where there is significant draw-in between the binder plates, in the LDH test the material is locked out beyond the drawbead resulting in almost no draw-in from the binder area. In this test, formability is mainly influenced by friction at the sheet/punch interface. Figure 4 shows the equipment and a typical sample with failure occurring under localized necking conditions.



Figure 4. Photograph of the press equipment used for conducting LDH tests and a formed sample.

The bulleted list below shows the experimental details of the LDH test.

- Sample width: 133mm (simulative of plane strain conditions)
- Speed: Quasi-static
- # of replicates: 3
- Fully locked out specimen (no draw-in)
- Lubrication: none
- Measure of formability: Forming height at maximum punch load (instance of localized necking)

The square draw test is more simulative of production stamping under exaggerated draw-in conditions where the part design and hence the draw depth is fixed. During production stamping, formability is often evaluated as % of failed parts (or rejection rate). In contrast, the LDH test is a traditional test to evaluate formability under plane strain conditions. In addition to formability tests, the steels were analyzed for coating roughness to correlate roughness with formability. Roughness was tested in longitudinal & transverse orientations on the top & bottom sides and the reported values are the average of three replicates of both orientations and both sides. The friction coefficient was determined using the Pin-on-Disk (POD) test [9]. Two tests per each sample were conducted and their values averaged.

3. Results

Optimum GA coatings produced using the different trial conditions yielded coatings with primarily delta phase, and controlled gamma phase thickness. However, the shape of the delta phase particles varied depending on the processing conditions, as shown in Figure 5. The planar view of the delta phase was cubic using a higher GA temperature cycle (Processing condition 3) and rod-like using the moderate GA temperature cycle (Processing condition 2) which will be referred to as cubic delta and rod delta, respectively. One of the processing conditions (Processing condition 1) was used to intentionally generate zeta phase at the surface. Extended heating in the GA soak section allows additional iron diffusion from the steel in to the coating and converts the zeta phase to rod-like delta phase. When the coating is galvanized at higher temperatures, cubic shaped delta crystals were formed [7].

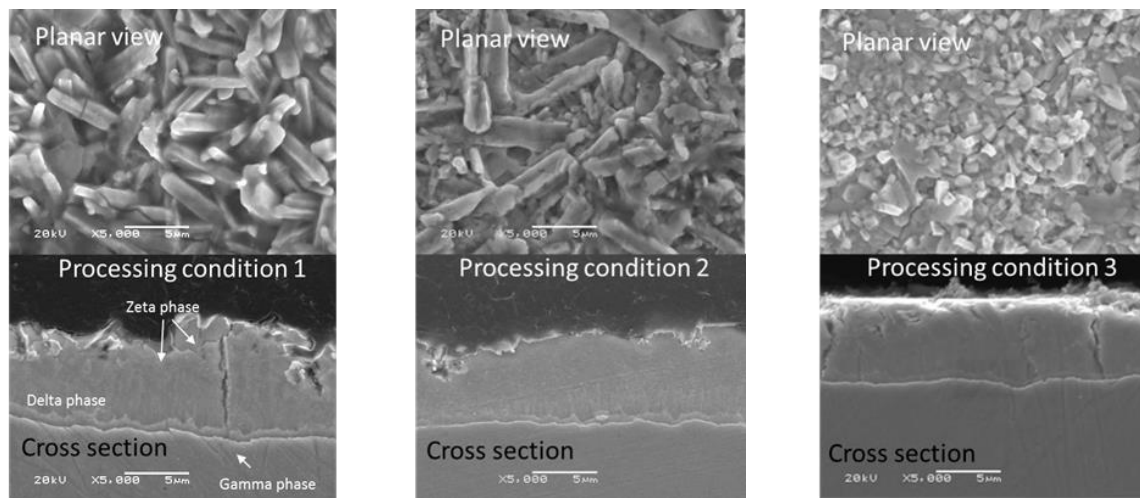


Figure 5. Surface coating microstructures using a Scanning Electron Microscope (SEM) showing the top view and the cross-section resulting from three galvannealing trials conducted by changing T_{GA} and T_{SE} shown in Figure 2.

Table 1 shows a comparison of the different coatings resulting from trials conducted by varying T_{GA} and T_{SE} shown in Figure 2. The samples are distinguished according to phase at the contacting surface which was determined using X-ray diffraction and optical microscopy. As seen in Table 1, specimens with high zeta coatings also exhibited high average roughness (R_a). Compared with specimens showing rod-like morphology of the delta phase, the specimens showing cubic morphology showed somewhat lower surface roughness and peak count. The POD results given in Table 1 show a clear distinction for high zeta versus low zeta coatings. However, this test did not distinguish between rod-like delta versus cubic delta.

Table 1. Comparison of the mechanical characteristics of the coating such as surface roughness and frictional behavior as determined by the Pin-On-Disk friction test.

Sample ID	Surface Roughness		POD value (μ)	
	R_a (μin)	RPc50 (ppi)	Top	Bottom
8 (High Zeta)	42	326	0.318	0.333
10 (Rod Delta)	36	237	0.141	0.133
11 (Rod Delta)	33	247	0.135	0.144
21 (High Zeta)	44	269	0.307	0.335
14 (Moderate Zeta)	35	238	0.321	0.308
15 (Moderate Zeta)	31	198	0.169	0.192
18 (Cubic Delta)	32	209	0.14	0.131
19 (Cubic Delta)	30	176	0.133	0.127

Figures 6 and 7 show results from formability testing using the Square cup test and the LDH test respectively. As seen in the figures, coatings with delta phase at the surface had better formability than

the coating with zeta phase. From Figure 6, there seems to be an improvement in formability as measured by the % safe samples for a given draw depth with the cubic delta morphology. In samples where cubic delta formed the bulk of the contacting surface, the improvement in formability was more significant with no failures for the draw depth and the forming conditions. In contrast from Figure 7, cubic delta coatings exhibited a smaller improvement in formability when compared to coatings with rod delta. In the LDH tests, there is no metal movement between the binder plates and the frictional effects on formability are only experienced at the punch/sheet interface. As a result, the LDH formability results may be less sensitive to subtle differences in coating morphology.

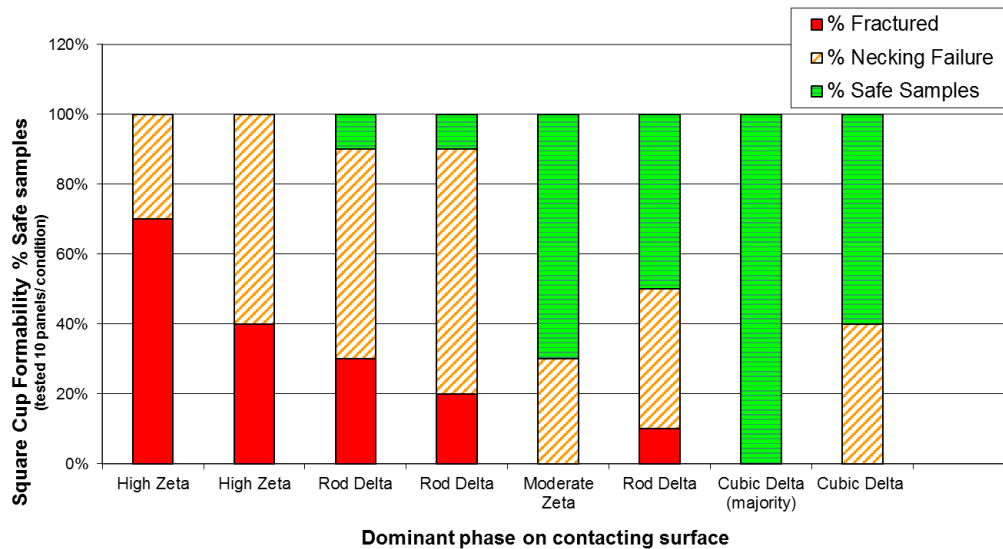


Figure 6. Influence of phases of the GA coating on the formability as determined using the square cup test.

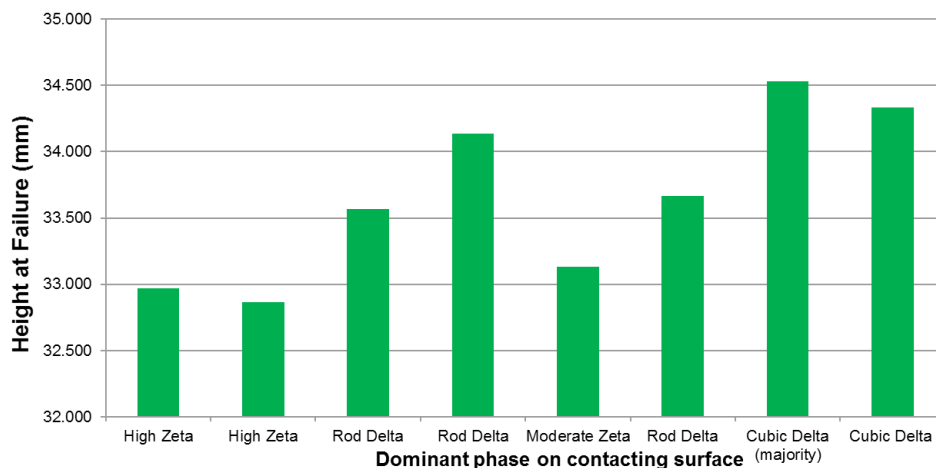


Figure 7. Influence of phases of the GA coating on the formability as determined using the LDH test.

Formability results were correlated with POD friction measurements and coating roughness data as shown in Figure 8. The correlation between formability and surface characteristics such as Peak count and R_a were consistent, where improved formability as measured by both tests was observed with reducing peak count and R_a . However, the trend of formability vs. friction coefficient was clear only for the LDH test, where the failure height decreased with increased friction coefficient. For the square cup tests, the trend was not as clear. Because the formability in the square cup test is strongly dependent on metal movement over a significant area of the blank, non-uniformity in surface microstructure might

be manifested more in the Square cup test than in the POD friction test which uses a much smaller sample size.

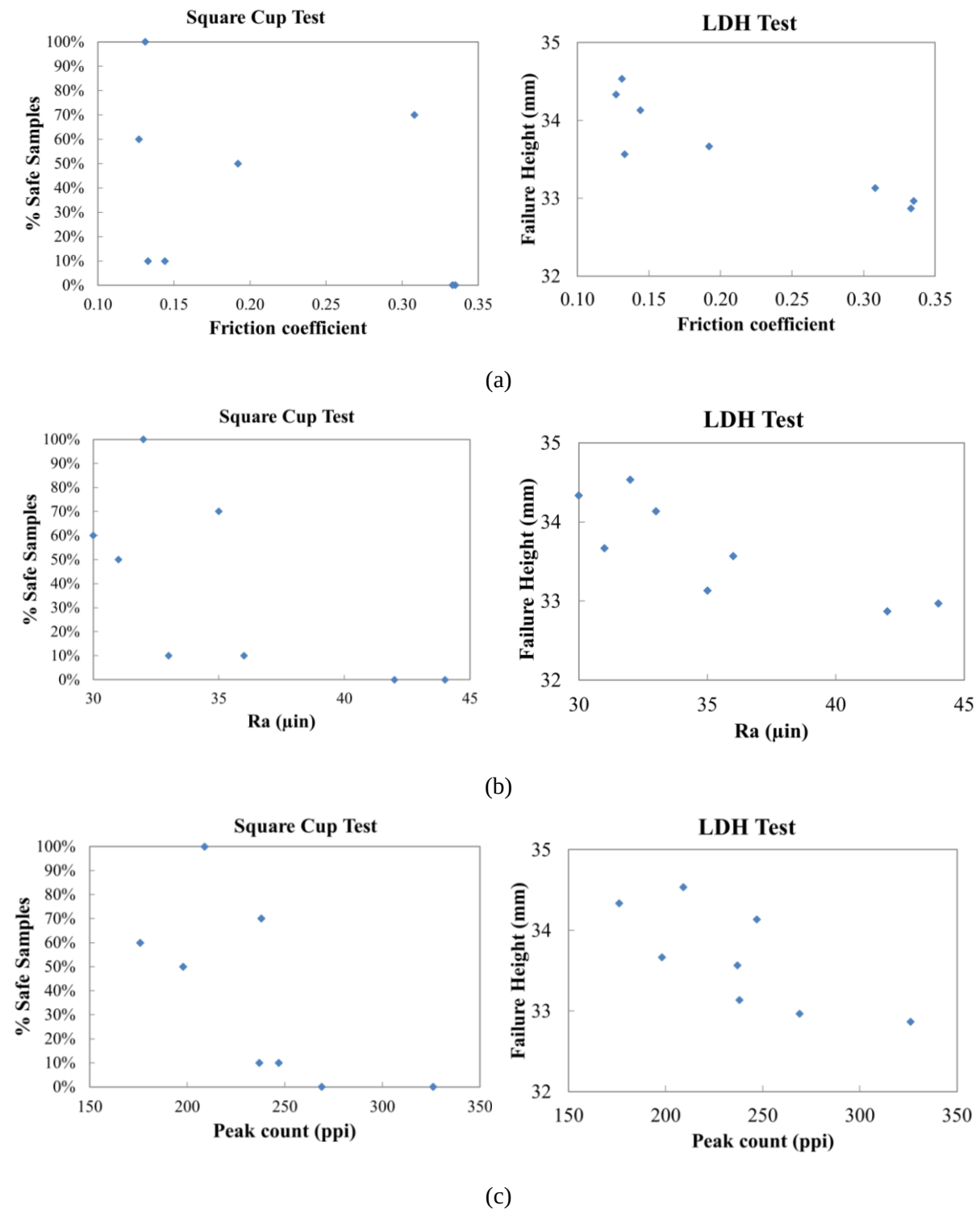


Figure 8. Correlation between formability results determined using the square cup test and the LDH test and different measures of surface characteristics such as (a) Friction coefficient (b) R_a and (c) Peak Count

4. Discussion

The GA process parameters, T_{GA} and T_{SE} can be effectively used to produce coated surface microstructures such that the zeta phase and the brittle gamma phase can be minimized [7]. In addition to minimizing the zeta phase, it is also feasible to produce a surface morphology to maximize the forming performance as evaluated by occurrence of splits under conditions of severe sliding. In both extremes of formability evaluation, coatings with cubic delta morphology performed better than the rod delta morphology. This investigation also highlights the difficulty with using a given measure of frictional behavior such as the friction coefficient obtained in the POD test with formability. For conditions with significant metal movement, the coating exhibiting cubic delta morphology provided better performance. This was also observed for the LDH test but the improvement was found to be somewhat less dramatic. This could also be caused by the differences in the measure of formability (% safe samples for the square cup test vs. height at failure for the LDH test). Interestingly, the POD test could not differentiate between rod delta and cubic delta morphologies. It is strongly recommended that simulative formability tests with varying degrees of stretching and drawing be conducted in addition to friction tests to get a more complete picture of formability improvement with engineered surfaces.

5. Conclusions

Multiple trials were conducted at a production coating facility in ArcelorMittal to study and optimize the galvanized coating microstructure by altering the thermal profiles. Different coating cross-section and surface microstructures were obtained during the trials. This study focused on the influence of delta phase surface morphology, rod-like versus cubic shape, on formability. Results from this investigation are summarized below.

- Pin-on-disk friction test distinguished high zeta coatings from low zeta coatings. No difference in the POD value was observed between rod delta and cubic delta coatings.
- Formability tests showed that cubic delta coatings have better formability than rod delta coatings.
- Cubic delta coatings seem to be more critical in forming operations with high metal movement than rod delta coatings.
- Coatings with lower roughness and peak count exhibited better formability.

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