Effect of Coating Thickness on Formability of Hot-dip Galvanized Low Carbon Steel Sheet

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In this study, formability of hot-dip galvanized low carbon steel sheets has been evaluated. The effect of coating thickness on formability has been analyzed by using galvanized sheets with five different coating weights and a comparison has been made with an uncoated sheet. The crystallographic orientation of the coatings was determined using X-ray diffraction and texture parameters were calculated. Mechanical properties of samples were determined by uniaxial tensile tests and formability of the sheets was evaluated using forming limit diagrams (FLD). From the experimental results, it was concluded that by increasing the coating thickness, the texture parameter of basal planes component was decreased. Such variations caused the yield strength of the coated sheet to increase, but ductility was reduced. The overall evaluation of the results indicated that the formability of galvanized steel with thinner coating thickness is better than uncoated and other samples with thicker coatings.

KEY WORDS: hot-dip galvanized low carbon steel; crystallographic texture; sheet metal formability; forming limit diagram.

1. Introduction

Hot-dip galvanized steel sheets have been widely used in building and automotive industries owing to their excellent corrosion resistance. Since galvanized steel sheets typically undergo heavy forming operations, the formability of the coating is an important property. The formability of galvanized steels is reduced to some extent by the brittle iron-zinc alloy layer that is produced by the reaction of molten zinc and the steel base during hot-dip galvanizing. The thickness of the alloy layer depends on the temperature–time cycle of the coating process, but it is also affected by the percentage of other metals, especially lead and aluminum, in the molten-zinc bath. It is believed that the decrease in formability is usually in direct proportion to the thickness of the iron–zinc alloy layer.1,2)

Generally, the evaluation of sheet formability is carried out using the results of tensile and stamping techniques. Using tensile tests, two important parameters of the sheet material, i.e. work hardening exponent (n) and anisotropy coefficient (r), can be determined; these parameters are criteria for the sheet resistance against necking and thinning during plastic deformation, respectively. The stamping technique is the principal manufacturing method for automobile panels.3,4) Keeler5) and Goodwin6) introduced the concept of forming limit diagram (FLD), which is useful to find out the limiting strains under such forming conditions, in 1960s. Since then it has been widely used for studying the formability of sheet metals. Hecker7) developed simplified techniques for evaluating FLD and, even in the recent years, many works are carried out on FLD.3,5)

Texture is an important factor which affects the coating properties and depends strongly on external factors such as cooling rate gradient, surface condition of steel substrate during the coating solidification process and bath chemical composition.8–12) Concerning the coating corrosion resistance, this depends in particular on the zinc layer chemical composition and also affected by the crystallographic orientation.10,11,13) It should be noted that in hot-dip galvanized coatings, it is the texture of η layer which is considered as the coating texture because this layer consists of about 99 wt% of zinc and only about 1 wt% of iron and has an important role in determining the corrosion resistance of the coating.10) It has been reported that coating thickness may influence on the texture of the coatings,11,13) formability and mechanical properties,3,7) coefficient of friction1,2) and corrosion resistance16) of coated sheets. But, these effects have not been adequately clarified and there is not sufficient literature on this subject, particularly quantitative data.

In this paper, the effect of coating thickness on texture, formability and mechanical properties of hot-dip galvanized steel sheets is presented. For this purpose, X-ray diffraction and uniaxial tensile tests were carried out and forming limit diagrams were constructed for galvanized specimens. Variations of formability are discussed in terms of thickness of the zinc coating and the crystallographic texture of the surface.

2. Experimental Procedure

2.1. Materials

The materials used were commercial hot-dip galvanized
steel sheets and the specimens were sampled from the coils produced in a continuous galvanizing line. The substrate was a commercial low carbon Al-killed steel (St14) with the composition shown by weight percent in Table 1, which corresponds to St14 of German grade. Since manufacturing parameters of base metal can influence the formability of galvanized steel sheet, samples were selected such that finishing temperature of hot rolling, coiling temperature, reduction percent of cold rolling and annealing cycles were almost identical for all samples. The temperature of zinc bath and entrance temperature of sheet to galvanizing were almost identical for all samples. The texture parameters were determined. The texture parameters were calculated by using Eq. (1):17)

\[ X = \frac{X_0 + 2X_{45} + X_{90}}{4} \] .............(2)

where \( X \) is any tensile property at the angles of 0, 45 and 90° to the rolling direction. Plastic strain ratio \((r)\) is the commonly used parameter for estimating anisotropy of sheet materials. The \( r \)-values of galvanized sheets were evaluated using test specimens made according to ASTM E17 specifications.19) The width, thickness and gage length were measured and averaged at 7, 9, 11, 13 and 15% elongations by three extensometers in width, thickness and longitudinal direction during tensile testing. Subsequently, the plastic strain ratio \((r)\) was calculated using Eq. (3):

\[ r = \frac{\varepsilon_w - \varepsilon_l}{\varepsilon_i} = \frac{\ln \left( \frac{w_l}{w_0} \right)}{\ln \left( \frac{l_i w_0}{l_f w_f} \right)} \] .............(3)

where \( w_0, l_0 \): initial width and length, \( w_f, l_f \): final width and length, \( \varepsilon_i \): true thickness strain, \( \varepsilon_l \): true width strain, \( \varepsilon_w \): true length strain. The average of five values of \( r \) at different elongations was reported as \( r \)-value.

The \( r \)-value was evaluated in three directions with the tensile axis being parallel (0°), diagonal (45°) and perpendicular (90°) to the rolling direction of the sheet by repeating the above procedure. The normal anisotropy \((r_n)\) and

\[ I_{hkil}^0 \] is intensity of \( hkl \) reflection from random sample (zinc powder) and \( n \) is the number of reflecting planes (9 in this study). Here, each reflection from a zinc coating of random texture would have a value equal to 1, while a preference of grains with a particular plane parallel to the sheet surface would have a value greater than one. Similarly, an orientation “less than random” would have a value less than one. This technique represents orientations percent only from those reflections used in the calculation.17) It should be noted that in this study, summation of low angle pyramidal planes (1014, 1013 and 1012) are named low angles, high angle pyramidal planes (1121, 1012 and 2011) are named high angles, and prismatic planes (1010 and 1120) are named prisms.

### Table 1. Chemical composition (wt%) of St14 steel.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.027</td>
<td>0.064</td>
<td>0.222</td>
<td>0.007</td>
<td>0.004</td>
<td>0.058</td>
<td>30ppm</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

### Table 2. Coating weight of samples.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Coating weight ((\text{g/m}^2))</th>
<th>Lead content ((\text{wt%}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>180</td>
<td>0.072</td>
</tr>
<tr>
<td>W2</td>
<td>227</td>
<td>0.063</td>
</tr>
<tr>
<td>W3</td>
<td>276</td>
<td>0.053</td>
</tr>
<tr>
<td>W4</td>
<td>297</td>
<td>0.051</td>
</tr>
<tr>
<td>W5</td>
<td>398</td>
<td>0.053</td>
</tr>
</tbody>
</table>
planar anisotropy ($\Delta r$) were calculated by using Eqs. (4) and (5)\[20\],

$$r_m = (r_0 + 2r_{45} + r_{90})/4 \quad (4)$$

$$\Delta r = (r_0 - 2r_{45} + r_{90})/2 \quad (5)$$

where the subscription indicates the orientation of the specimen axis with respect to the rolling direction.

2.5. Forming Limit Diagrams (FLDs)

Forming limit diagrams were evaluated following the Hecker’s simplified technique.\[7\] In this method, the experimental procedure mainly involves three stages; grid marking the sheet samples, punch stretching the grid marked samples to failure or onset of localized necking and measurement of strains.

Grid patterns were printed on the galvanized and uncoated steel samples by electrochemical etching method. In this experiment, the diameter of the grid circles is 2.54 mm. Forming up to fracture was carried out on a single action hydraulic press of 20-ton capacity (Amsler BUP 200 machine). A 60 mm diameter hemispherical punch was used in this research.

The sheet samples were subjected to different strain states, namely tension–tension, plane strain, and tension–compression varying the width of the samples between 25 and 115 mm by biaxial stretching test (Erichsen test). For each blank width, three to four specimens were tested to get the maximum number of data points. All Erichsen tests were carried out under dry condition (without lubrication) except those specimens tested for strain ration near unity.

The circles on the sheet samples became ellipses during forming operation. The major and minor diameters of the ellipses were measured using Miller ruler. Using this data, the major strain ($e_r$) and the minor strain ($e_\theta$) were calculated, lying in safe, necked and fractured regions. FLD was drawn by plotting the major strain versus the minor strain and by drawing a curve which separates the safe region from the unsafe region.

3. Results and Discussion

3.1. Coating Layers

The relation between the mean value of coating thickness and the coating weight is plotted in Fig. 1. It is evident from Fig. 1 that mean coating thickness increased with coating weight.

Figure 2 shows a typical cross section of zinc coated specimen W5; four distinct coating layers of hot-dip galvanized steel can be identified in this micrograph. EDS analyses of coating layers confirmed that coating consisted of four layers; $\Gamma$ (70.1 wt% Zn, 29.9 wt% Fe), $\delta$ (93.2 wt% Zn, 6.8 wt% Fe), $\zeta$ (96.5 wt% Zn, 3.5 wt% Fe) and $\eta$ (99.1 wt% Zn, 0.9 wt% Fe). To some extent, it was expected that with concentrations above 0.1 wt% aluminium in the zinc bath, (~0.2 wt% in this study), Fe$_2$Al$_5$ layer is formed and suppressed the formation of $\delta$ and $\eta$ phases.\[21,22\] However, microscopic investigations confirmed that four layers have been formed and EDS analysis detected no aluminium within the layers. This is probably because for Fe$_2$Al$_5$ layer to form, in addition to the required value of aluminium concentration in the bath,\[21,23\] lower temperature of bath\[24\] and rather high difference between coil entrance and bath temperatures\[25\] must be maintained. The low temperature of bath can slow down the reaction rate of zinc–iron and provides a chance for reaction of aluminium and iron.\[13\] The high temperature difference between coil and galvanizing bath can effectively increase Al–Fe reaction rate.\[23,24\] In this work, the temperature of zinc bath was high (~460°C) and variation between bath and coil entrance temperatures (~460°C) was small (~6°C), thus, formation of Fe$_2$Al$_5$ was suppressed.\[26\]

3.2. Crystallographic Texture of the Sheets

Figure 3 shows the influence of coating weight on the texture parameter of three specimens. The results of Fig. 3 were reconstructed as texture parameter vs. coating thickness in Fig. 4. The texture parameter of basal plane for coating thickness of 18 µm is ~9× Random and by increasing the coating thickness to 40 µm decreased to ~6× Random. Also, by increasing the coating thickness, other components of texture including prisms, high angles and low angles are strengthened.

The microstructural observations indicated that although the production parameters of these samples were the same, the thickness of $\eta$ layer increased with coating weight as a result of the decrease in the galvanizing line speed. This can influence the intensity of basal texture to weaken.

These effects would probably be ascribed to the surface and strain energies. Since texture is determined by a competition between surface and strain energies; at small thicknesses, the coating shows an orientation corresponding to that with lowest surface energy and highest strain en-

![](image-url)
ergy.\textsuperscript{14,15,27}) In other words, when the coating is thin, the strain energy of the coating structure is very low and negligible. Conversely, the surface energy is high and important because surface energy does not vary with the coating thickness\textsuperscript{14,15}); therefore, the texture of the coating consists of planes which have the lowest surface energy and highest strain energy to compensate the shortage of strain energy and make a balance between surface and strain energies.\textsuperscript{14,15,27}

3.3. Mechanical Properties of the Steels

The effect of coating weight in the range of 180–400 g/m\textsuperscript{2} (equivalent to 18–40 \(\mu\)m thickness on each side of the sheet) on tensile properties and anisotropy parameters (\(r\)) of uncoated and all five coated sheets are shown in Fig. 5. These data, obtained from standard uniaxial tensile test, indicate that coating caused an increase of more than 10% in yield strength (YS) and about 15% tensile strength (TS) as compared with the uncoated steel sheet of similar thickness. Reduction of total elongation with increasing coating thickness is observed, too, but it is less significant (Fig. 5(b)). While reduction of elongation is due to the cracking of the brittle phase at the interface, it seems that zinc coating has increased the apparent yield strength and reduced the apparent strain hardening ability of the steel sheet.

Increasing the yield strength with coating thickness should be attributed to an increase in the thickness of the intermetallics phases. The hardness of intermetallics phases (e.g. \(\Gamma\) layer \(\sim 320\) HV\textsubscript{0.025}) is higher than that of the base metal \(\sim 100\) HV\textsubscript{0.025}, consequently, when coating thickness is increased, the strength of the coated sheet increased, too. However, Fe–Zn intermetallic phases are considered brittle and, as a result, the formability of sample in uniaxial tension test would be reduced. The \(\delta\) and \(\Gamma\) phases are the two brittle constituents in Fe–Zn coatings, while the \(\zeta\) phase is relatively ductile.\textsuperscript{13} Cracks are usually initiated within a brittle intermetallic layer, from where they can propagate to the surface. Thus, it could be concluded that the decrease in formability is in direct relation to the thickness of the brittle iron–zinc alloy layers.

It is also observed that (Fig. 5(e)) by increasing the coating thickness, the value of \(r_m\) decreased. Generally, a metal with high \(r_m\) value has high drawability because it possesses good resistance to thinning in the thickness direction during deep drawing.\textsuperscript{28} It is expected that by increasing the coating weight, the value of planar anisotropy decreased for specimens from W1 to W5 and become closer to zero and, consequently, earring property is improved. Since for these specimens, the process parameters such as substrate composition, sheet thickness and lead content of zinc bath were approximately similar, it is concluded that changing the coating thickness has changed the ductility of the specimens.

3.4. FLDs of the Steels

Formability limit diagrams of the investigated galvanized and uncoated steels are presented in Fig. 6. On the FLDs, the regions corresponding to negative minor strain (tension–compression region) and positive minor strain (tension–tension region) are not symmetrical. Thus, in tension–compression region, the slope of the forming limit curve is higher and the safe zone is wider than those of tension–tension region. The lowest limit strain of a FLD, which corresponds to 0% minor strain, is known as plain strain (FLD\textsubscript{p}). Since failure appearing in cold-formed parts
under pressed condition often occurs in this state, $FLD_0$ value represents the most critical strain state on the FLD. High value of $FLD_0$ means better formability.\(^{29}\) In addition, the dome height at the point of initiation fracture of samples was measured. This height is referred to as “Erichsen cup depth (ED)”.\(^{29}\)

Figure 7(a) shows $FLD_0$ value that obtained from Fig. 6 and Fig. 7(b) shows variations of ED vs. coating thickness.

Fig. 5. Effect of coating weight on the a) yield strength, b) tensile strength c) elongation, d) $n$ value, e) $r_m$ value, f) $\Delta r$ value.

Fig. 6. Effect of coating weight on FLD of galvanized steel sheets.

Fig. 7. Effect of coating weight on a) $FLD_0$ and b) ED.
It can be seen that FLD₀ and ED values of uncoated steel is lower than W1 and W2 specimens of galvanized sheets. It could be due to reducing friction during punch stretching as the zinc-coating acts as a solid lubricant during forming process. This is because, the coatings compared to steel are often softer and consequently their shear strength is lower. However, FLD₀ and ED values of coated steel decreased by increasing the coating weight. It was mentioned above, the thickness of intermetallic phases increased with increasing the coating thickness. The brittle nature of these phases and their role in initiation and propagation of crack could have resulted in reducing formability of these sheets.

These results are in controversy with the investigations of Gupata et al. They worked on formability of galvanized interstitial-free (IF) steel sheets with various coating thickness in the range 120–220 g/m² and reported that by increasing the coating thickness, the coefficient of friction decreased, and in result, the FLD₀ and ED values increased. These differences could be due to discrepancy in intermetallic layers that formed on their samples. They have identified three intermetallic layers (δ phase, Γ and Γ₁ phases) at the interface in all their samples; an obvious difference with the four distinct layers of the present investigation.

3.5. Prediction of Formability

Several theoretical approximations have been suggested to identify the correlation between FLDs and mechanical properties. However, the relationships between the experimentally constructed FLDs and basic mechanical properties of galvanized steel sheets are scarce.

According to the experimental results, the effects of me-
mechanical properties (YS, TS, E, n, r and ED) and texture parameter of basal planes on the FLDs of uncoated and galvanized steel sheets are analyzed on the basis of their effect on the FLD. The variations of the FLDs with the results of these properties are plotted in Fig. 8. It is evident from Figs. 8(a) and 8(b) that, FLDs decrease with increasing yield and tensile strengths. Figures 8(c)–8(e) depict the increase of FLDs with increasing elongation, n, r and ED. Figure 8(f) shows the variations of FLDs with n-r value. It is interesting to note that n-r value is a measure of stretchability; as n-r value rises, this parameter is increased. The variation of FLDs with texture parameter of basal planes is evident from Fig. 8(g).

The linear relationship between FLDs and the mechanical properties and texture parameter of basal planes (Fig. 8) for uncoated and galvanized steel sheets are empirically quantified in Table 3 with the coefficient of determination ($R^2$) values, where the proposed equations become more reliable if $R^2$ approaches to 1. The graphs showing the effect of YS (Fig. 8(a)), TS (Fig. 8(b)) and E (Fig. 8(c)) with respect to FLDs seem reasonable, although their empirical equations have rather low reliability due to their low $R^2$ values (0.14–0.25). The relationships between FLDs and n (Fig. 8(d)) and r (Fig. 8(e)) exhibit moderate $R^2$ value (0.54 and 0.41, respectively). However, the reliability of correlation between FLDs and $r \times n$ ($R^2=0.91$, Fig. 8(f)) is better than that for either n or r. The best correlation is found for ED (Fig. 8(g)) with $R^2$ value of 0.97. Reliability of the equation between FLDs and TP is rather high (0.78) for the present. Accordingly, it appears that for the parameters studied in this research, $r \times n$, ED and TP could be considered relevant properties to account for the formability of deep drawing quality of galvanized steel sheets. It is emphasized that the method of specimen selection was so that all other variables were nearly constant and the formability tests were carried out under identical friction conditions. Therefore, these results are reproducible and can be used as technical data for those galvanized low carbon steel sheets produced under similar technology. For other cases, however, these results may be considered as a guideline for comparison purposes.

4. Conclusions

(1) As the coating thickness increases, the texture parameter of basal planes decreases and, the texture parameter of high angle pyramidal, low angle pyramidal and prismatic planes increases.

(2) Based on the elemental analyses of the interface layers between zinc coating and the substrate in the galvanized sheets, it is expected that η, ζ, δ and Γ phases exist at the interface in all coated samples. The brittle nature of last two phases and their role in initiation and propagation of cracks would reduce formability of these sheets.

(3) By increasing the coating thickness, the FLDs have decreased marginally. The FLDs and Erichsen cup depth (ED) of 180 g/m² are higher when compared to uncoated and other sheets with higher coating thickness.

(4) Since the plain strain intercept (FLDp) is the most critical strain limit on the FLD, the relationship between FLD and mechanical properties and texture parameter of basal planes are quantified on the basis of “FLDp-property” graphs. Amongst the measured properties in the present research, most reliable correlations were obtained for Erichsen cup depth (ED), $r \times n$ value and texture parameter of basal planes in the forms of; $F_{LDp}=0.026ED-0.23$, $F_{LDp}=1.066r \times n+0.091$ and $F_{LDp}=0.031TP+0.051$, respectively.

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REFERENCES

6) G. M. Goodwin: Metall. Italiana, 60 (1968), 764.
(1993), 55.