Press formability of newly developed high lubricity hot-dip galvanized steel sheets

S Furuya¹, K Hoshino¹, Y Ogihara², Y Yamasaki¹ and S Taira²

¹ Steel Research Laboratory, JFE Steel Corporation, 1, Kokan-cho, Fukuyama, Hiroshima 721-8510, Japan
² Steel Research Laboratory, JFE Steel Corporation, 1, Kawasaki-cho, Chuo-ku, Chiba 260-0835, Japan
s-furuya@jfe-steel.co.jp

Abstract. Surface modification technology was applied to hot-dip galvanized steel sheets (HDG) in order to improve their press formability. The frictional behavior and press formability of surface modified HDG were investigated in comparison with those of conventional HDG, conventional electrogalvanized steel sheets (EG) and pre-phosphate treated EG (EG pre-phos). Specimens of these coated mild steel sheets with various mechanical properties were used as test materials. The friction coefficient was measured by a flat sliding test, and press formability was evaluated by a deep drawing test and a stretch forming test. As a result, surface modified HDG showed a lower friction coefficient and higher press formability than conventional HDG and conventional EG. The friction coefficient and press formability of surface modified HDG were similar to those of EG pre-phos. In deep drawing, the inflow of material from the flange area to the cracking area becomes easier due to the lower friction coefficient of surface modified HDG, which leads to improvement of deep drawability. In stretch forming, the outflows of material from the sheet/punch contact area to the cracking area become easier due to the lower friction coefficient of surface modified HDG, leading to improvement of stretch formability. These results indicate that surface modified HDG is a promising material for automotive use.

1. Introduction
Hot-dip galvanized steel sheets (HDG) are popular automotive materials because they easily satisfy both high corrosion resistance and low manufacturing cost. However, it is well known that the friction coefficient of HDG is higher than that of cold-rolled steel sheets [1], and this higher friction coefficient causes cracking and wrinkles in the press forming process.

Galvannealed steel sheets (GA) and electrogalvanized steel sheets (EG) also have higher friction coefficients than cold-rolled steel sheets [1]. Therefore, various kinds of lubrication treatment have been developed for GA and EG to improve their press formability and have been widely used practically. For example, Ni-base inorganic film [2] and other organic and inorganic coatings [3-6] for GA were developed and its frictional behavior and press formability were reported. Regarding the lubrication treatment of EG, pre-phosphate (pre-phos) treatment is used widely around the world [7, 8]. In contrast, few researches on lubrication treatment of HDG has been reported, although the surface texture and frictional behavior of HDG has been investigated [9, 10]. The application of these treatment having thick film to HDG could cause the deterioration of other characteristics such as electrode life in resistant spot welding, because usually HDG has much shorter electrode life than that of GA and EG [11, 12]. In order to satisfy both high lubricity and other characteristics such as weldability, new lubrication system having...
a thinner film is necessary for HDG. Hoshino et al have reported that naturally segregated Al-based oxide on HDG surface reduced the friction coefficient of HDG due to adhering Al-based oxide on tool surface [13-15]. Presumably, control of the adhering material by lubrication treatment on HDG can achieve the high lubricity with thin film because the oxide accumulate on the tool surface as the sliding length increase. To refer to this mechanism, recently we have developed the new lubrication treatment system, called surface modification [16]. This technology is the method of modifying several tens of nano-meters surface of HDG, and its frictional behavior and other characteristics such as weldability have been reported.

In this study, frictional behavior and press formability of this newly developed surface modified HDG were investigated in comparison with those of conventional HDG, conventional EG and EG pre-phos. In addition, the mechanism of the effect of the surface modification treatment on deep drawability and stretch formability was discussed.

2. Experimental procedure

2.1. Materials
Surface modified HDG, conventional HDG, EG pre-phos and conventional EG of mild steel sheets with similar sheet thicknesses and similar Zn coating weights were prepared as test materials. Materials with various mechanical properties, in particular elongation and the mean r-value, were prepared. The properties of the test materials are listed in table 1.

| No. | Coating type       | Sheet thickness (mm) | Zn coating weight (g/m2) | Yield strength (MPa) | Tensile strength (MPa) | Total elongation (%) | Mean r-value |
|-----|--------------------|----------------------|--------------------------|----------------------|------------------------|----------------------|--------------|
| 1   | Surface modified HDG | 0.76                 | 62                       | 226                  | 344                    | 39.7                 | 1.73         |
| 2   | Surface modified HDG | 0.76                 | 61                       | 148                  | 290                    | 53.1                 | 2.08         |
| 3   | Surface modified HDG | 0.76                 | 71                       | 160                  | 296                    | 51.8                 | 1.72         |
| 4   | Surface modified HDG | 0.76                 | 70                       | 154                  | 299                    | 51.2                 | 2.07         |
| 5   | Surface modified HDG | 0.76                 | 75                       | 147                  | 279                    | 55.5                 | 2.15         |
| 6   | Conventional HDG    | 0.75                 | 64                       | 142                  | 279                    | 55.2                 | 2.24         |
| 7   | Conventional HDG    | 0.75                 | 63                       | 148                  | 290                    | 53.3                 | 2.07         |
| 8   | EG pre-phos         | 0.75                 | 62                       | 149                  | 287                    | 52.7                 | 2.25         |
| 9   | EG pre-phos         | 0.75                 | 58                       | 155                  | 290                    | 52.5                 | 2.15         |
| 10  | Conventional EG     | 0.75                 | 64                       | 158                  | 284                    | 52.6                 | 2.27         |
| 11  | Conventional EG     | 0.75                 | 63                       | 158                  | 293                    | 51.4                 | 2.15         |

2.2. Flat sliding test
The friction coefficient was measured by a flat sliding test. A schematic diagram of the tool and the test conditions are shown in table 2. The test conditions were chosen as the obtained friction coefficient has a good correlation with press formability [13, 17, 18]. Test specimens were drawn while receiving a constant normal load by the tool, and the friction coefficient was calculated by the ratio of the measured drawing force to the normal load. Before the sliding test, the tools were polished with #2000 polishing paper along the direction orthogonal to the sliding direction, and the test specimens were degreased with alcohol, and after degreasing, 2 g/m² of lubrication oil was applied. The lubrication oil was a commercial product whose density and viscosity are 0.91 g/cm³ at 15 °C and 21 mm²/s at 40 °C, respectively.
2.3. Deep drawing test
The limiting drawing ratio (LDR) was obtained by a deep drawing test. A cylindrical punch with a 50 mm diameter and a 5 mm shoulder radius and a die with a 53 mm diameter and a 5 mm shoulder radius were used. Disk-shaped specimens with different diameters between 90 mm and 120 mm were used in this test. The blank holding force was varied from 4.9 kN to 88.2 kN. The drawing tests were carried out 3 times at each diameter of specimen and the maximum diameter of each specimen which could be formed without cracking, necking or wrinkles all 3 times was determined. LDR was calculated by the ratio of the determined maximum diameter to the punch diameter. Before the deep drawing test, the specimens were degreased and lubricated in the same way as in the flat sliding test.

2.4. Stretch forming test
The formable height just before crack initiation in a stretch forming test was measured. A cylindrical punch with a 100 mm diameter and a 10 mm shoulder radius and a die with a 153 mm diameter and a 10 mm shoulder radius were used in this test. The die had a lock bead, and the blank holding force was fixed at 980 kN in order to prevent material inflow from the flange. Specimens with a size of 200 mm square were used in this test, and were degreased and lubricated before the test in the same way as in the flat sliding test. The formable height was determined by the recorded punch strokes and punch force during the tests because the effect of rigidity was quite small and negligible.

2.5. Surface observation
Tools after the flat sliding test were observed by a scanning electron microscope (SEM) with the acceleration voltage of 1 kV. Before the observation, tools were degreased with alcohol. The center of the tool surface was observed.

3. Experimental results
3.1. Friction coefficient
Figure 1 shows the measured results of the friction coefficients. The bar charts show the average value of each coating type, and the error bars show the maximum and minimum values. The friction coefficient of surface modified HDG was smaller than that of conventional HDG and similar to that of EG pre-phos. After the flat sliding tests, trace of contact was observed on the surface of test specimens and the surface of specimens were worn by the tool. Therefore, the lubrication regime under this test condition was confirmed to be the boundary lubrication regime.
3.2. Deep drawability

Figure 2 shows the relationship between the LDR obtained by the deep drawing test and the mean r-values of each steel sheet. With each coating type, LDR tends to increase with increases of the mean r-value. The tendency of increasing LDR with increase of mean r-value corresponds to past reports [19, 20]. When compared at the same mean r-value, the LDR of surface modified HDG was larger than that of conventional HDG and was similar to that of EG pre-phos. The LDR of conventional EG was the smallest of the four coating types used in this study.

3.3. Stretch formability

Figure 3 shows the relationship between the formable heights in the stretch forming test and the total elongations of each steel sheet. With each coating type, the formable height tends to increase with increases of total elongation. The tendency of increasing formable height with increase of total elongation corresponds to past reports [20]. When compared at the same total elongation, the formable height of surface modified HDG was higher than that of conventional HDG and was similar to that of EG pre-phos. The formable height of conventional EG was the lowest of the four coating types used in this study.
4. Discussion

4.1. Friction coefficient
In order to clarify the cause of lower friction coefficient of surface modification HDG compared to conventional HDG, surface observation of tools after flat sliding test was conducted. The result is shown in figure 4. An in-lens secondary electron detector was used in this observation to obtain contrast depends on the difference of the substances [21]. Before sliding, polishing trace orthogonally to the sliding direction was observed as shown in figure 4(a). After sliding of conventional HDG, dark contrast areas corresponding to the polishing trace were observed as shown in figure 4(b). The dark contrast areas also observed after sliding of surface modified HDG as shown in figure 4(c), but the area was much larger than that of conventional HDG. The dark contrast areas show adhered materials on the tool after sliding. These adhered materials are suggested to have the effect of reducing adhesion force between metallic Zn of HDG and the tool, and reducing the tool roughness [13-15]. Much more adhered materials accumulate on the tool surface after sliding of surface modified HDG compared to conventional HDG, resulting in lower friction coefficient of surface modified HDG than that of conventional HDG and similar to that of EG pre-phos, as shown in figure 1.

4.2. Deep drawability
Surface modified HDG displays a larger LDR than that of conventional HDG due to its lower friction coefficient in comparison with conventional HDG. In order to clarify the effect of the friction coefficient on deep drawability, the maximum forming loads in the deep drawing test of Steels 5, 6, 9 and 11 were measured at the blank holding force of 98 kN. The test materials were selected to have similar
mechanical properties. Figure 5 shows the relationship between the maximum forming loads and the drawing ratios of each steel sheet. The maximum forming load tends to increase with increases of the drawing ratio. At the same drawing ratio, the maximum forming load of surface modified HDG was lower than those of conventional HDG and conventional EG and similar to that of EG pre-phos.

In deep drawing, deformation resistance, which is measured as a forming load, is equal to the resistance of material inflow from the flange area \( R_{if} \) when cracking does not occur. \( R_{if} \) is represented by the sum of bending-unbending resistance \( R_{be} \), shrink flanging resistance \( R_{sh} \) and frictional resistance \( R_{fr} \) [22]. In this study, the test materials were assumed to have similar values of \( R_{be} \) and \( R_{sh} \) because the mechanical properties of the selected materials were similar. Therefore, the difference of a forming load indicates the difference of frictional resistance. When the friction coefficient was low, material inflow prevents overconcentration of strains to the cracking area, the specimen is formed uniformly, and as a result, LDR increases [13, 18].

In this study, because the friction coefficient of surface modified HDG was lower than that of conventional HDG, as shown in figure 1, its frictional resistance \( R_{fr} \) was lower than that of conventional HDG. Therefore, the material inflow from the flange area occurred more easily, and much material was supplied to the cracking area. As a result, the LDR of surface modified HDG was larger than that of conventional HDG. The LDR of EG pre-phos showed a similar trend to that of surface modified HDG because the two types of material had similar friction coefficients. The smaller LDR of conventional EG was caused by its higher friction coefficient.

In addition, galling was observed on the surface of conventional EG after the drawing test, as shown in figure 6(a). In contrast, no galling occurred on the surface of conventional HDG, as shown in figure 6(b). Thus, in addition to the difference in the friction coefficients of conventional EG and conventional HDG, this difference in galling could cause the difference of deep drawability observed with these two coating types.

![Figure 5. Relationship between the maximum forming load and the drawing ratio in deep drawing test.](image)

![Figure 6. Appearances of (a) conventional EG and (b) conventional HDG after deep drawing test.](image)
4.3. Stretch formability

The higher formable height of surface modified HDG than that of conventional HDG is derived from its lower friction coefficient in comparison with conventional HDG. Therefore, in order to clarify the effect of the friction coefficient on stretch formability, the sheet thickness reduction ratios after the stretch forming test of Steels 5, 6, 9 and 11 at the forming height of 24 mm were measured. At this forming height, no cracks were initiated in any of the specimens. The test materials were selected to have similar mechanical properties. Figure 7(a) shows the distribution of the thickness reduction ratios, and figure 7(b) shows the measured points of a stretch formed specimen. The thickness was measured at 20 equally-spaced points from A to B along the line A-B shown in figure 7(b). The steel sheet and punch were in contact at the points from 11 to 20. In this area, the thickness reduction ratios of surface modified HDG were similar to those of EG pre-phos and higher than those of conventional HDG and conventional EG. In all specimens, the largest thickness reduction was obtained at point 10, which is expected to be the area where a crack will be generated at a higher forming height. The thickness reduction ratio of surface modified HDG in this area was similar to that of EG pre-phos and smaller than those of conventional HDG and conventional EG.

In stretch forming, the friction coefficient between the test specimen and the punch bottom affects the material outflow from the area where the test specimen and the punch bottom are in contact with the cracking area. When the friction coefficient is low, this material outflow prevents overconcentration of strains to the cracking area, the specimen is formed uniformly, and as a result, the formable height increases [13, 18].

In this study, figure 7(a) indicates that the material outflows from the sheet/punch contact area to the cracking area of surface modified HDG and EG pre-phos occurred more easily because their friction coefficients were lower than those of conventional HDG and conventional EG. As a result, the formable height of surface modified HDG was higher than those of conventional HDG and conventional EG. The formable height of EG pre-phos showed a similar trend to that of surface modified HDG because the two coating types had similar friction coefficients. The lower formable height of conventional EG was caused by its higher friction coefficient, as shown in figure 1.

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**Figure 7.** (a) Distribution of thickness reduction ratio after stretch forming and (b) measured points.
5. Conclusions
In this study, the frictional behavior and press formability of surface modified hot-dip galvanized steel sheets (HDG) were investigated, and the mechanism of press forming was discussed. The conclusions obtained from this study are shown below.

(1) Surface modified HDG shows a lower friction coefficient and better press formability compared to conventional HDG and similar friction coefficient and formability to pre-phosphate treated electrogalvanized steel sheet (EG pre-phos).

(2) Adhered materials accumulate on the tool surface during sliding of surface modified HDG, resulting in lower friction coefficient compared to conventional HDG.

(3) In deep drawing, the material inflows from the flange area to the cracking area occur more easily due to the decrease of friction resistance, which leads to better deep drawability.

(4) In stretch forming, the material outflows from the sheet/punch contact area to the cracking area occur more easily due to the decrease of friction resistance, which leads to better stretch formability.

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