Hot-Dip Galvanized (GI) Steel Sheets for Automotive Use

YOSHIDA Hiromi[*1]   HOSHINO Katsuya[*2]   OGIHARA Yuki[*3]

Abstract:

JFE Steel has developed high strength hot-dip galvanized (GI) steel sheets for automotive structural parts and lubrication treated GI steel sheets, "GI JAZ^{TM}" (JFE Advanced Zinc for GI), which provide excellent press formability to GI steel sheets. Microstructure of the high strength GI steel sheet was controlled to satisfy industrial standards. In a 980 MPa grade of tensile strength, both low- and high-yield strength types show excellent bendability and anti-delayed-fracture performance, which are important especially above 980 MPa. GI JAZ provides excellent press formability with reducing friction coefficient between tools and GI steel sheets due to the surface modified layer formed on GI with JFE Steel's original lubrication treatment.

1. Introduction

Hot-dip galvanized steel sheets (GI) and electrogalvanized steel sheets (EG) are used for automotive body parts by auto makers in Europe and the United States, while galvannealed steel sheets (GA) are used mainly by Japanese auto makers. These Zn coated steel sheets exhibit high corrosion resistance. Until now, auto makers in Europe and the US have used EG steel sheets in outer panels, taking advantage of their outstanding surface appearance quality, but are increasingly substituting GI steel sheets, which offer lower production costs[1]. JFE Steel Corporation has developed GI steel sheets with excellent surface appearance quality that can be used in outer panels to meet this demand[2].

In addition, use of high strength steel sheets in structural parts is also expanding for the purposes of improving crashworthiness and reducing auto body weight. Moreover, tireless efforts to improve the press formability are also demanded in outer panel parts, in which high priority is attached to automobile structural design and a sophisticated design sense. This report describes JFE Steel's high strength GI steel sheets from tensile strength (TS) 340 to 980 MPa grade and the high lubricity GI steel sheet "GI JAZ™" (JFE Advanced Zinc for GI) with excellent formability.

2. High Strength GI Steel Sheets

2.1 Standards and Material Design of High Strength GI Steel Sheets

Standards for steel sheets used by European and US auto makers contain detailed provisions for yield strength (YS). A comparison of TS and YS in the German Industrial Standards (DIN: Deutsche Industrie Normen) and standards of The Japan Iron and Steel Federation (JFS) is shown in **Fig. 1**. In comparison with the JFS standard, the range of tensile strength is narrower in the DIN standard for steel sheets of TS lower than 590 MPa. DIN standard names with the suffix "LA" are defined as steel sheets with the addition of one or more of any of the elements niobium (Nb), titanium (Ti) and vanadium (V), and those with the suffix "X" are defined as Dual Phase (DP) microstructure consisting of ferrite and martensite, which possibly contain bainite. In order to obtain TS and YS within the range of the standards, the phase ratio of ferrite, martensite and bainite must be controlled in a narrow

† Originally published in *JFE GIHO* No. 41 (Feb. 2018), p. 28−33

*1 Senior Researcher Manager,
Sheet Products Research Dept.,
Steel Res. Lab.,
JFE Steel

*2 Senior Researcher Manager,
Coated Products Research Dept.,
Steel Res. Lab.,
JFE Steel

*3 Senior Researcher Assistant Manager,
Forming Technology Research Dept.,
Steel Res. Lab.,
JFE Steel

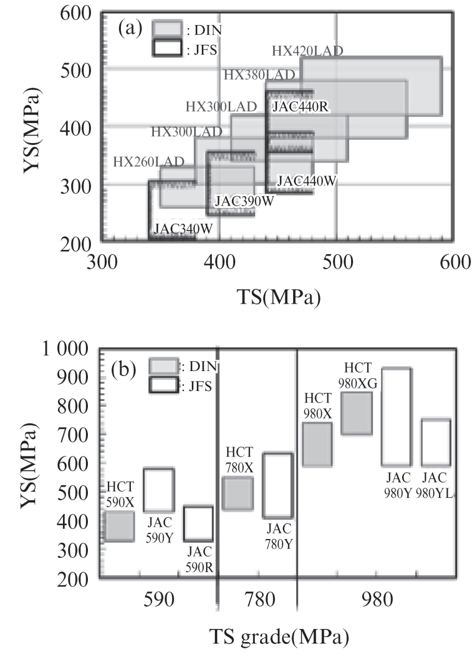

Fig. 1 Range of TS and YS of the high strength steel sheets comparing DIN to JFS
(a) Under 590 MPa grade (b) Over 590 MPa grade

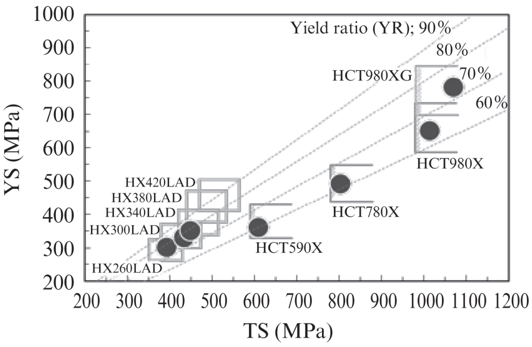

Fig. 2 Representative values of the mechanical properties of the cold-rolled GI steel sheets being produced by JFE Steel

range.

For example, in steel sheets in which carbides of Nb, Ti and V are dispersed in the ferrite phase, a high yield ratio YR (YR=YS / TS) can be obtained[3–5], while YR decreases in steel sheets in which martensite is dispersed in the ferrite[5–7], such as DP steel.

The representative properties of GI steel sheets developed by JFE Steel are shown in **Fig. 2**. Products conforming to HX260LAD, HX300LAD and HX340LAD with high YR have been developed in the TS < 590 MPa grade, products conforming to HCT590X, HCT780X and HCT980X have been developed as DP steel sheets with low YR in the TS grade of 590 MPa or higher, and high YR HCT980XG has been developed in the TS 980 MPa grade.

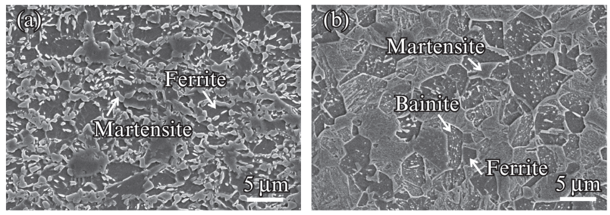

Photo 1 Targets of microstructure of 980 MPa grade GI steel sheets
(a) Low-YS type (b) High-YS type

2.2 980 MPa Grade GI Steel Sheets

2.2.1 Microstructure

As GI steel sheets in the TS 980 MPa grade, JFE Steel has developed steel sheets conforming to HCT980X (low YS type) and HCT980XG (high YS type) in the DIN standard by control of the steel microstructure. YS and elongation (El) satisfied the standards and excellent bendability and delayed fracture resistance were realized by the adjustment of the hardness of the hard phase and the crystal grain size in addition to the phase ratio.

Photo 1 shows the targets of the microstructures for manufacturing the low YS type and high YS type of 980 MPa grade GI steel sheets. The low YS type shown in (a) has a DP microstructure consisting of ferrite and martensite. In the high YS type shown in (b), high YS was successfully obtained, while El in the range of the standards, by a microstructure comprising mainly martensite and bainite, while reducing ferrite which decreases yield strength.

2.2.2 Candidate parts for application and crashworthiness

Because the expected parts for the application of TS 980 MPa grade GI steel sheets are the side sill outer, rear side member and front side member, floor cross member, etc., crashworthiness is critical.

Therefore, the effect of the YS of the steel sheets on crashworthiness was investigated. Using steel sheets of TS 590 MPa grade and TS 980 MPa grade, hat-shaped members (length: 500 mm, longitudinal direction is perpendicular to the rolling direction of the steel sheet) having the cross-sectional geometry shown in **Fig. 3**(a) were fabricated, and a bending crash test with 3-point support (3-point bending test) was performed using a punch with a radius of 100 mm, as shown in Fig. 3(b), with a stroke speed of 0.1 m/s. The average force (F_{ave20})[8] in the initial period of deformation (from 0 mm to 20 mm), which is an index of crashworthiness, is shown in Fig. 3(c). The load increased as YS became higher, showing that high YS material is advantageous for crashworthiness.

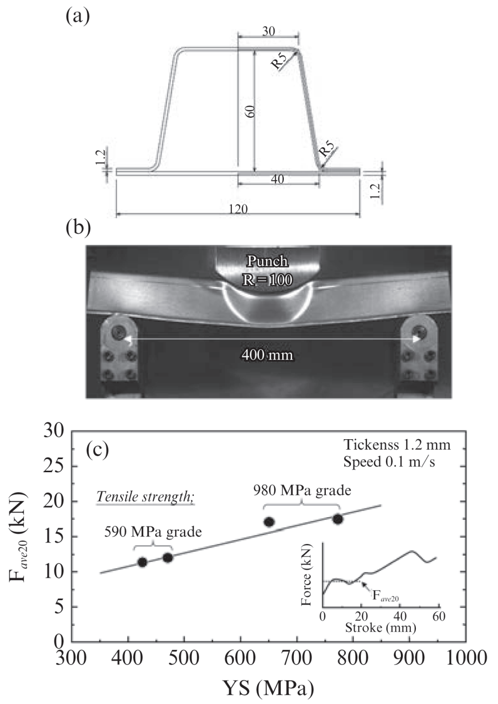

Fig. 3 Effect of yield strength on average force in 3-point bending tests
(a) Dimensions of cross-section of the test specimen
(b) Appearance of 3-point bending fixture
(c) Relationship between average force and yield strength in 3-point bending tests

Table 1 Mechanical properties of 980 MPa grade GI steel sheets

Steel type	Thickness (mm)	Tensile properties				Bendability
		Direction	YS (MPa)	TS (MPa)	El (%)	*R*/*t*
Low-YS	1.2	L	665	1 029	14	1.7
High-YS	1.2	L	785	1 090	12	2.1

Table 2 Results of delayed fracture test of 980 MPa grade GI steel sheets

Steel type	Thickness (mm)	Applied load (N)	Result (After 96 h)
Low-YS	1.2	8 880	No crack
High-YS	1.2	10 200	No crack

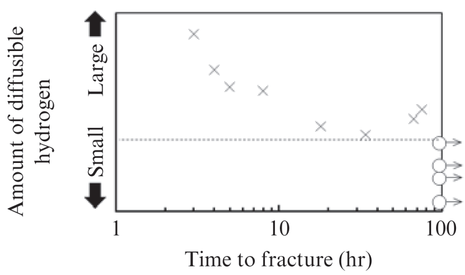

Fig. 4 Effect of amount of diffusible hydrogen in steel sheet on delayed fracture time of 980 MPa grade GI steel sheets

2.2.3 Tensile properties and bendability

High bendability is necessary in forming the parts in which use of 980 MPa grade steel sheets is assumed, as mentioned in section 2.2.2. In bending forming, necking occurs in the surface layer in the area around the apex of bending. Bendability is improved by enhancing both the uniform deformation characteristics before necking and the local deformation characteristics after necking.

Table 1 shows an example of the results of a tensile test and bending test of TS 980 MPa grade GI steel sheets. The tensile test was conducted under a cross-head speed of 10 mm/min using a JIS No. 13A test piece (gauge length: 80 mm, width of parallel part: 20 mm). YS was obtained as 0.2% proof stress. For bendability, a 90° V-bending test was performed in accordance with ASTM E 290-14, and bendability was evaluated by the ratio *R*/*t* of the limit bending radius (*R*), defined as the minimum bending radius without cracking, and the sheet thickness (*t*). The sheet thickness of the sample material was 1.2 mm, and the test was performed so that the ridgeline of bending was parallel to the rolling direction of the steel sheet, using a 35 × 100 mm test piece in which the edges were treated by grinding. The bending radius at the limit where cracking did not occur was 2.0 mm with the low YS type and 2.5 mm with the high YS type, and the *R*/*t* of both steel sheets was 2.5 or less.

2.2.4 Delayed fracture resistance

The delayed fracture resistance of the punched edge was evaluated by a constant load test in accordance with SEP1970. The thickness of the sample materials was 1.2 mm. Holes having a diameter of 20 mm were punched with a clearance of 12.5% in the center of test pieces with dimensions of 30 × 100 mm, and whether cracking occurred or not was evaluated when the sample was held for 96 h with an applied load of 8 880 N or 10 200 N on the punched edge. These loads were equivalent to the upper limit of YS in the DIN standard (low YS type = 740 MPa, high YS type = 850 MPa, respectively). **Table 2** shows the test conditions and results. With both the low YS type and high YS type samples, cracking did not occur from the punched edge, even when loaded with stress equivalent to the upper limit of YS in the DIN standard. The relationship between the time to occurrence of cracking at the punched edge and the diffusible hydrogen content in the steel in this test is shown in **Fig. 4**. When the diffusible hydrogen content was large, cracking showed a tendency to occur in a short time. Thus, reducing the diffusible hydrogen content in the steel is effective for securing delayed fracture resistance.

As described above, HCT980X (low YS type) and HCT980XG (high YS type) with excellent bendability and delayed fracture resistance, in addition to mechanical properties satisfying the DIN standard, were developed by optimum control of the microstructure.

3. High Lubricity GI Steel Sheet “GI JAZ™”

3.1 Development Concept and Sliding Property

The friction coefficient of Zn-coated steel sheets is higher than that of cold-rolled steel sheets owing to the high adhesion between zinc and the tool, and the formable range is narrow. This can easily lead to crack and wrinkle defects in mass-production stamping processes. To improve the press formability of GA and EG steel sheets, high lubricity GA steel sheets[9–13] and high lubricity EG steel sheets[14] were developed by using a lubrication treatment that secures a stable low friction coefficient. These materials are already widely used. Although a similar technique for improving the press formability of GI steel sheets is also conceivable, virtually no development of lubrication treatment techniques for GI had been carried out[15,16].

JFE Steel developed an original lubrication treatment[9–11, 17–20] for GA steel sheets by nanometer-scale surface modification based on a completely different concept from the use of a solid lubricant film, which had been the conventional lubrication treatment until now. The high lubricity GA steel sheet “GA JAZ™” (JFE Advanced Zinc for GA), on which this lubrication treatment is applied, realizes a stable low friction coefficient by applying a mechanism that suppresses adhesion between the Zn coating layer and tools due to adsorbates, oxides and the like[9–11]. These principles can also be applied to GI steel sheets.

Therefore, as shown in the schematic diagram in **Fig. 5**(a), GI JAZ was manufactured by applying this lubrication treatment to a GI steel sheet with a mild steel substrate, and the friction coefficient was measured with a flat sliding test. As comparison materials, the friction coefficients of a conventional GI steel sheet, the generally widely-used GA JAZ and a high lubricity EG steel sheet “EG Pre-Phos” were also measured in the same manner. The test pieces were ultrasonically cleaned in alcohol and then coated with a commercial anti-rust oil as a lubricating oil. The viscosity of the anti-rust oil was 60 mm^2/s at 40°C, and its density was 0.91 g/cm^3. The sliding test was performed using an SKD bead with a contact surface of 10 × 50 mm under conditions of a sliding distance of 100 mm, sliding speed of 200 mm/min and contact pressure of 7.8 MPa. The average value of the friction coefficient (μ: $\mu = F/N$) was calculated from the normal load (N) and the drawing force (F). The results are shown in Fig. 5(b). In comparison with the conventional GI steel sheet, the friction coefficient of GI JAZ was low, showing that the developed material was effective for reducing the friction coefficient. As the friction coefficient of GI JAZ was similar to those of GA JAZ and EG Pre-Phos, both of which have an extensive record of use as automotive steel sheets, press formability on the same order as those materials can also be expected with GI JAZ.

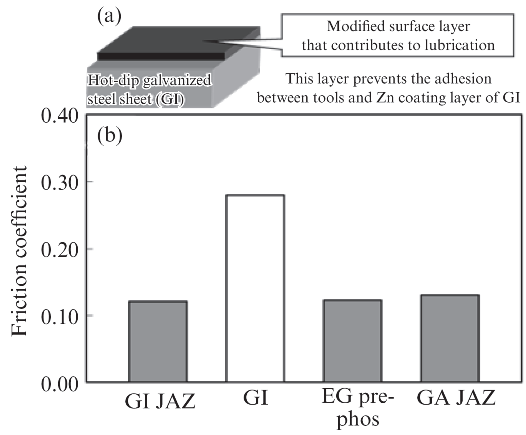

Fig. 5 Schematic image of the lubrication treated GI steel sheet “GI JAZ™” and its friction coefficient (a) Schematic image (b) Friction coefficients

3.2 Press Formability

3.2.1 Press formability with small–scale model test

In press forming of automotive panel parts, the deep drawability and stretch formability of the steel sheet are critical properties. They were evaluated using GI JAZ steel sheets in which the substrate materials were mild steel sheets with a thickness of 0.75 mm and the Lankford values (hereinafter, *r*-value) and total elongation (hereinafter, elongation) were different. For comparison, a conventional GI steel sheet, GA JAZ and EG Pre-Phos with the same sheet thickness were evaluated in the same manner.

For the evaluation of deep drawability, a cylindrical deep drawing test was carried out using a punch with a diameter of 50 mm and shoulder radius of 5 mm and a die with an inner diameter of 53 mm and a shoulder radius of 5 mm (in both cases, SKD material), and the limiting drawing ratio (LDR) was used as an index of deep drawability. Machined circular blanks of various diameters were ultrasonically cleaned in alcohol and

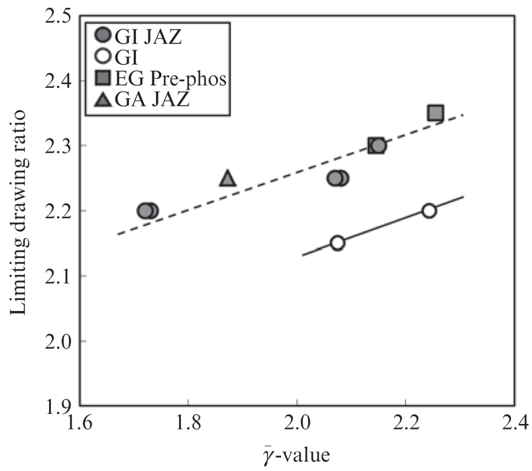

Fig. 6 Relationship between the limiting drawing ratio obtained with the deep drawing tests and the $\bar{r}$-value of the steel sheets

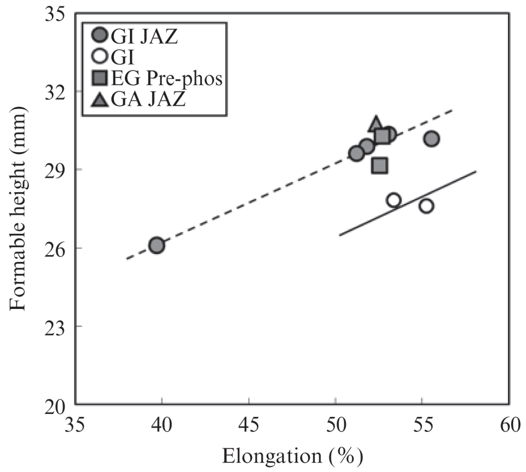

Fig. 7 Relationship between the formable height obtained with the truncated conical stretch forming tests and the elongation of the steel sheets

then coated with the same anti-rust oil as mentioned above. Forming was performed under various blank holder forces (BHF), and LDR (LDR = D_{max} / d_p) was obtained from the maximum blank diameter (D_{max}) with which forming was possible without cracks or wrinkles and the punch diameter (d_p).

Figure 6 shows the relationship between the *r*-value and LDR of each of the steel sheets. LDR increases with increases in the *r*-value. When the LDR of GI JAZ and the conventional GI steel sheet was compared at the same *r*-value, the LDR of GI JAZ was higher. In deep drawing, the friction coefficient of the area where the flange and die shoulder part and the material are in contact influences the material flow to the vertical wall[21]. Since the friction coefficient of GI JAZ is low in comparison with that of the conventional GI steel sheet, LDR increased due to an increase in the material flow from the flange to the vertical wall. The fact that the LDR of GI JAZ is similar to that of GA JAZ and EG Pre-Phos is attributed to the similar friction coefficients of the GI JAZ to those of the GA JAZ and EG Pre-Phos. Moreover, from the shift in the *r*-value at the same LDR, the deep drawability improvement effect of GI JAZ vs. the conventional GI steel sheet can be estimated as 0.2 or more as improvement in the *r*-value.

In the evaluation of stretch formability, the formable height was obtained by performing truncated conical stretch forming tests using a flat-bottomed cylindrical punch with a diameter of 100 mm and shoulder radius of 10 mm and a die with bead with an inner diameter of 153 mm and a shoulder radius of 10 mm (in both case, SKD material). The size of the test pieces was 200 mm square. After ultrasonic cleaning in alcohol, the test pieces were coated with the above-mentioned anti-rust oil. While applying a constant BHF to prevent material flow from the flange, the forming height immediately before cracking occurred was measured as the formable height.

Figure 7 shows the relationship between the elongation of the steel sheets and the formable height in the truncated conical stretch forming tests. When the formable heights of the GI JAZ and the conventional GI steel sheet are compared at the same elongation, the formable height of the GI JAZ is higher. Moreover, the slope of the formable height of the GI JAZ vs. elongation was similar to those of the GA JAZ and EG Pre-Phos. In truncated conical stretch forming, the friction coefficient in the area where the material is in contact with the punch bottom and punch shoulder part influences the material flow to parts with a danger of cracking[21]. Since the friction coefficient of GI JAZ is lower than that of the conventional GI steel sheet, the material flowed easily to parts with a danger of cracking, and as a result, strain was uniformly dispersed and the formable height of the GI JAZ increased. The fact that the formable height of the GI JAZ is similar to those of the GA JAZ and EG Pre-Phos is due to the similarity of the friction coefficient of the GI JAZ to those of the GA JAZ and EG Pre-Phos. From the shift of the elongation at which the same formable height could be obtained, the stretch formability improvement effect of GI JAZ vs. the conventional GI steel sheet is estimated at approximately 4% or more in elongation.

3.2.2 Actual press formability using model front side fender

The results of a press formability test with a model front side fender using a 1 200 t single action mechanical press at JFE Steel are shown in **Fig. 8**. The formable range without occurrence of wrinkles or cracks was

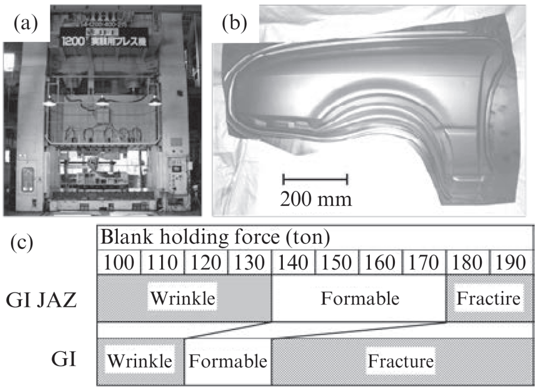

Fig. 8 Press formability in actual press forming tests with the model front side fender
(a) Appearance of the press
(b) Model front side fender
(c) Formable range of the GI JAZ™ and conventional GI steel sheet

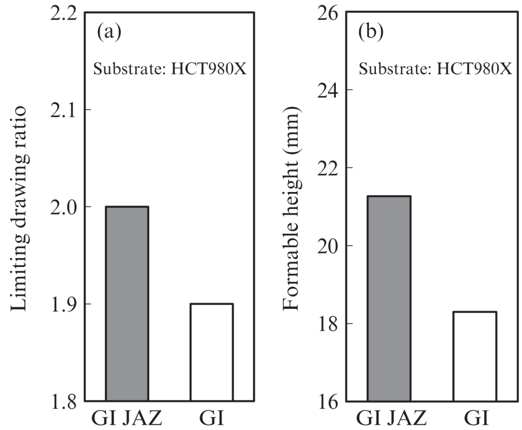

Fig. 9 Press formability of the 980 MPa grade GI JAZ™
(a) Limiting drawing ratio obtained with the deep drawing tests
(b) Formable height obtained with the truncated conical stretch forming tests

evaluated using GI JAZ and the conventional GI steel sheet with the same mechanical properties. In both steels, the substrate was mild steel with a thickness of 0.75 mm. The formable range of the GI JAZ was larger than that of the conventional GI steel sheet, demonstrating that the developed material has excellent press formability at the actual vehicle scale.

3.3 Application to High Strength GI Steel Sheets

Bending formability is an important property in forming of 980 MPa grade GI steel sheets as mentioned above. In the future, however, it is thought that shapes that include drawing or stretching will increase for integration of separated parts with the aim of reducing costs, etc. GI JAZ can be applied to all of the high strength GI steel sheets described in Chapter 2, and similar formability improvement effects can be expected. For example, the results of an evaluation of formability in case JAZ is applied to low YS type 980 MPa grade GI steel sheets (HCT980X) with a sheet thickness of 1.2 mm are shown in **Fig. 9**. As in the previous section, deep drawing formability was evaluated by using the LDR obtained in the cylindrical deep drawing test as an index, and stretch formability was evaluated by the formable height in the truncated conical stretch forming test. It was also possible to obtain a formability improvement effect similar to that of GI JAZ using a mild steel sheet as the substrate, as described above, when HCT980X was used as the substrate.

3.4 Other Properties of GI JAZ

Table 3 shows the results of an investigation of resistance spot weldability and phosphate treatability, which are critical types of performance in the automobile assembly and painting processes, in GI JAZ and the conventional GI steel sheet with a thickness of 0.75 mm with a mild steel sheet substrate. The above-mentioned properties are similar in GI JAZ and GI steel sheets, demonstrating that application of this lubrication treatment to GI steel sheets is not an impediment to practical use in auto body parts.

Table 3 Summary of the weldability and phosphate treatability of GI JAZ™

Specimens	Weld ability		Phosphate treatability	
	Electrode tip life (welds)	Available welding current ranges (kA)	Coating weight (g/m^2)	Uniformity
GI JAZ	800	0.9	2.0	Good
GI	800	0.8	1.7	Good

4. Conclusion

This report described the features of JFE Steel's high strength GI steel sheets and the press formability improvement effect of the high lubricity GI steel sheet "GI JAZ™" (JFE Advanced Zinc for GI).

Among JFE's high strength GI steel sheets, in the TS 980 MPa grade, two types of steels were developed, HCT980X (low YS type) and HCT980XG (high YS type). Mechanical properties that satisfied the target industrial standards and satisfactory bendability and delayed fracture resistance were realized while also maintaining excellent surface quality by precise control of the chemical composition of the steel sheets and the annealing temperature of the hot-dip galvanizing line.

The friction coefficient of GI JAZ is lower than that of the conventional GI steel sheet and is similar to those of the high lubricity GA steel sheet "GA JAZ™" (JFE Advanced Zinc for GA) and high lubricity EG steel sheet "EG Pre-Phos," both of which are widely used. The press formability of GI JAZ is also similar to that of GA JAZ and EG Pre-Phos. Moreover, GI JAZ can be applied to the above-mentioned high strength GI steel sheets.

JFE Steel has begun commercial production of both products at its West Japan Works (Kurashiki District). We will continue to contribute to satisfying both auto weight reduction and crashworthiness, and to improvement of automobile structural design and a sophisticated design sense in automobiles by applying these products to automotive bodies.

References

1) Quantin, D.; Ronin.E. 40th. MWSP Conf. Proc. ISS. 1998.
2) Tobiyama, Y.; Abotani Y. JFE Technical Report. 2004, no. 4, p. 55–60.
3) Oouchi C.; Ookita T.; Yamamoto S. Testu-to-Hagane. 1981, vol. 67, no. 7, p 969–978.
4) Urabe T.; Hosoya Y. Journal of the JSTP. 2005, vol. 46, no. 534, p. 560–564.
5) Takechi H. Testu-to-Hagane. 1982, vol. 68, no. 9, p. 1244–1255.
6) Hashiguchi K.; Nishida M.; Kato T.; Tanaka T. Kawasaki Steel Giho. 1979, vol. 11, no. 1, p. 68–77.
7) Matsudo K.; Shimomura T.; Osawa K.; Okuyama T.; Kinoshita M.; Osaka S. NKK Giho. 1980, vol. 84, p. 14–24.
8) Sato, K.; Inazumi T.; Yoshitake A.; Liu. S-D. International Journal of Impact Engineering. 2013, vol. 54, p. 1–10.
9) Newly Developed Galvannealed Steel Sheet with Excellent Press Formability JAZ® (JFE Advanced Zinc). JFE Technical Report. 2007, no. 10, p. 35–37.
10) Yoshimi, N.; Masuoka, H.; Taira, S.; Imokawa, T.; Nagoshi, M.; Yamasaki, Y.; Sugimoto, Y.; Fujita, S. Proceedings of GALVATECH 2007, Osaka, Japan, ISIJ. 2007, p. 504–509.
11) Hoshino, K.; Taira, S.; Yoshimi, N.; Higai, K.; Yamasaki, Y.; Nagoshi, M.; Sugimoto Y. SAE Tech. Pap. Ser. 2011, Paper no. 2011-01-1056.
12) Sakurai, M.; Yamasaki, Y.; Hashimoto, S.; Inoue, S.; Hiraya, A.; Urakawa, T.; Inagaki, J. Proceedings of GALVATECH '98, Chiba, Japan, ISIJ. 1998, p. 620–625.
13) Nakajima, S.; Katagiri, T.; Kato, C. Kawasaki Steel Technical Report. 2003, no. 48, p. 23–27.
14) Aoyama, M.; Nomura, S. Nippon Parkerizing Giho. 1995, no. 8, p. 33–40.
15) Payen, G.R.; Felder, E.; Repoux, M.; Mataigne, J.M. Wear 276–277. 2012, p. 48–52.
16) Cardoso, A.P.D.; Costa, C.E.; Oliverira, F.C.; Souza, F.B.P. Proceedings of GALVATECH 2015, Toronto, Canada, AIST. 2015, p. 112–120.
17) Hoshino, K.; Higai, K.; Taira, S. JFE Technical Report. 2013, no. 18, p. 89–95.
18) Hoshino, K.; Taira, S.; Higai, K.; Shinmiya, T.; Yamasaki, Y.; Yoshimi, N. Transactions of Society of Automotive Engineers of Japan. 2014, vol. 45, no. 4, p. 751–756.
19) Hoshino, K.; Yamasaki, Y.; Nagoshi, M.; Tanimoto, W.; Taira, S.; Yoshimi, N. Journal of the JSTP. 2015, vol. 56, no. 658, p. 986–992.
20) Hoshino, K.; Yamasaki, Y.; Nagoshi, M.; Tanimoto, W.; Taira, S.; Yoshimi, N. Mater. Trans. 2017, vol. 58, no. 6, p. 873–879.
21) Usukouhan-Seikei-Gijutsu-Kenkyukai. Press Seikei Nan-i Handbook 3rd Edition. Nikkan-Kogyo-Shinbunsya, Tokyo. 2007, p. 434–436.