Characteristics of Highly Formable 590-980MPa Grade Hot-dip Galvannealed Steel Sheets for Automobiles

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A series of 590-980MPa grade hot-dip galvannealed steel sheets has been developed in order to improve the formability of automotive body frame parts, such as lower pillars. These are either DP or TRIP-aided steel sheets, designed 1) to have homogeneous microstructures, 2) to inhibit the precipitation of carbide, 3) to maintain ferrite as much as possible, 4) to harden the ferrite to prevent degradation of local deformability, and in TRIP-aided steel sheet, additionally, 5) to obtain a large amount of retained austenite. The above microstructural controls are mainly accomplished by the addition of silicon, which can be adopted through a special surface preparation technology. The developed steel sheets have not only excellent formability, but also meet practical performance requirements, including good spot weldability and high coating.

Introduction

In recent years, high-strength steel sheets are more and more being used for automotive structural members to make auto bodies strong enough to meet increasingly stringent collision safety standards and light enough to meet the emission reduction requirements for environmental protection[1]. Among these sheets, galvannealed (hereinafter referred to as "GA") steel sheets are applied to parts that require corrosion resistance. In particular, high-strength GA steel sheets with excellent workability, are proactively adopted for lower parts of pillars and other structural members. With the recent increase in the number of parts employing high-strength steel sheets, the demand for further improved workability is growing[2), 3)].

In response to these needs, Kobe Steel has developed a high tensile-strength GA steel, in the strength grade of 590 - 980MPa, which has an elongation 1.3 times higher than that of conventional materials[4)]. This paper describes the concept of its microstructure control and major characteristics.

1. Concept of microstructure control

The developed materials include a dual-phase (DP) steel sheet, consisting of ferrite and martensite, and a transformation-induced plasticity (TRIP) aided steel sheet, consisting of ferrite, bainite and retained austenite. Both kinds of steel sheets ensure high ductility under the design concepts of ① homogenized microstructure, ② inhibited carbide precipitation, ③ the maximum amount of ductile ferrite, and ④ ferrite with its own strength increased by solid solution strengthening to prevent the deterioration of local deformability. In addition, ⑤ the TRIP-aided steel sheet is designed with its microstructure controlled so as to secure a large amount of retained austenite.

As a means for achieving the above objectives, the DP steel sheets adopt the technology developed by Kobe Steel for 590 - 980MPa grade GA steel sheets[5)-12)] and have compositions that largely suppress the bainite transformation during the cooling after annealing (②, ③). Furthermore, both the DP steel sheet and TRIP-aided steel sheet developed this time contain silicon (Si), an additive element playing an important role in stabilizing the ferrite and significant solid solution strengthening (③, ④). For some time, Si has been known to be effective in improving workability[13)]; however, its application to GA steel sheet was difficult because the element tends to deteriorate coating quality. To resolve this issue, Kobe Steel developed a special surface modification which enabled GA steel sheet to contain above 1.0% of Si, as in the case of cold-rolled steel sheet, leading to this development.

The addition of Si can significantly increase elongation. On the other hand, Si addition facilitates the precipitation of ferrite in the microstructure during cooling, which decreases the yield ratio, leading to a significant reduction of yield strength for a given tensile strength. Thus, when producing a steel sheet containing Si, the microstructure is controlled while focusing on the recovery and recrystallization behaviors of the cold-rolled structure, in which the cold rolling reduction is optimized for each composition and for sheet thickness by adjusting the yield strength so as not to cause the deterioration of elongation during annealing. This control method offers a technique that is effective in obtaining a homogeneous composite structure regardless of sheet thickness (①). TRIP-aided steel sheets, on the other hand, adopt a microstructure control which maximizes the amount of retained austenite. Typically, a TRIP-aided steel sheet is austempered to increase carbon concentration in untransformed austenite. When producing a GA steel sheet, the steel sheet is exposed to an elevated temperature in galvannealing treatment, which induces a phenomenon, unique to GA steel sheet, involving a structural change in which the austenite decomposes (precipitating carbide). The newly developed steel sheet contains retained austenite, whose amount is maximized by an optimized austempering (⑤). This new austempering includes galvannealing, unlike conventional austempering which simply condenses carbon.

Fig. 1 shows typical microstructures of the newly developed steel sheets: (a) DP steel sheet of 980MPa grade and (b) TRIP-aided steel sheet of 780MPa grade. Both the steel sheets contain large amounts of ferrite with no carbide precipitate observed. Furthermore, the DP steel sheet has a homogeneous and fine composite structure, while the TRIP-aided steel sheet is predominantly massive retained austenite with needle-like retained austenite (indicated by the arrows in the figure) between the laths of bainitic ferrite. **Fig. 2** shows the grain boundary distribution inside the 980MPa grade DP steel sheet obtained by a crystal orientation analysis based on an electron backscattering pattern (EBSP) measurement. In the grain boundary distribution diagram (Fig. 2 (b)), the black solid lines represent large angle grain boundaries with crystal misorientation of 15 degrees or larger, while the gray solid lines represent small angle grain boundaries with crystal misorientation smaller than 15 degrees. The figure indicates that the ferrite structure contains many small angle grain boundaries, which are remainders of a cold-rolled structure that has been annealed and is subgrained. The newly developed materials make use of such subgrain structures to adjust strength characteristics so as to achieve the high elongation described later. **Fig. 3** shows cross-sectional SEM micrographs of the newly developed 590MPa grade and 980MPa grade DP steel sheets, both having the quality of exhibiting homogeneous coating layers with favorable powdering resistance.

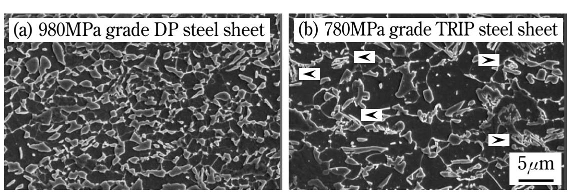

Fig. 1 SEM images of microstructure in developed steel sheets ((a)980MPa grade DP and (b)780MPa grade TRIP)

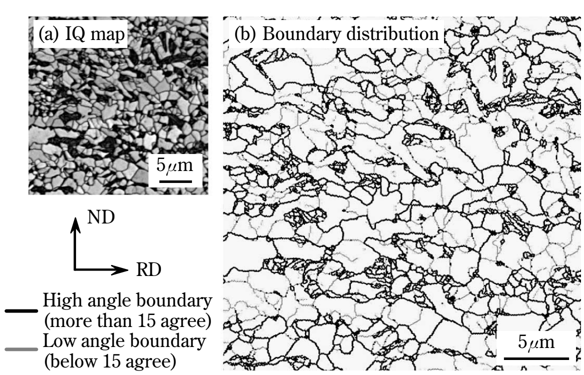

Fig. 2 Image Quality map (a) and Crystal orientation image map with boundary distribution (b) in developed 980MPa grade DP steel sheet

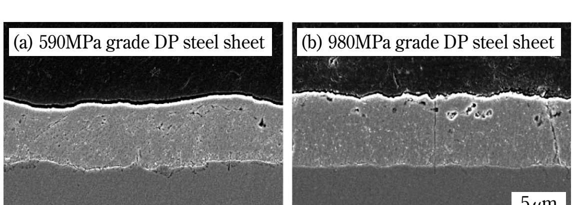

Fig. 3 SEM images of coating layer in developed steel sheets ((a)590MPa grade, (b)980MPa grade DP steel)

2. Main characteristics of newly developed materials

2.1 Formability

Table 1 summarizes the typical tensile properties of the newly developed materials (thickness 1.6mm). Also included in this table are the typical values of 590 - 980MPa grade cold-rolled steel sheets, in which the reference values of the 980MPa grade cold-rolled steel sheet are represented by those of a conventional Kobe Steel DP steel sheet that was developed for higher elongation[14]. All the newly developed materials exhibit elongations equivalent to those of the reference cold-rolled steel sheet in the same strength grade. **Fig. 4** compares the tensile strengths (*TSs*) and elongations (*ELs*) of the newly developed sheets of 980MPa grade DP steel and 780MPa grade TRIP-aided steel with those of the conventional materials. As the result of the composition design and microstructure control described previously, both of the newly developed sheets realize elongations up to 1.3 times greater than that of Kobe Steel's conventional materials. A

Table 1 Tensile properties of developed GA (Galvannealed) steel sheets and reference CR (Cold-Rolled) steel sheets

Steel	TS grade	Category	*YP* (MPa)	*TS* (MPa)	*EL* (%)
Galvannealed (GA) steel (Developed)	590MPa	Dual Phase	387	613	34
	780MPa	Dual Phase	481	828	23
		TRIP	478	823	29
	980MPa	Dual Phase	619	1,037	18
Cold-rolled (CR) steel	590MPa	Dual Phase	388	633	33
	780MPa	Dual Phase	509	838	22
	980MPa	Dual Phase	635	1,032	18

・Specimen thickness : 1.6mm
・Tensile test : JIS Z2241 (JIS Z2201 ＃5 specimen in Transverse direction)

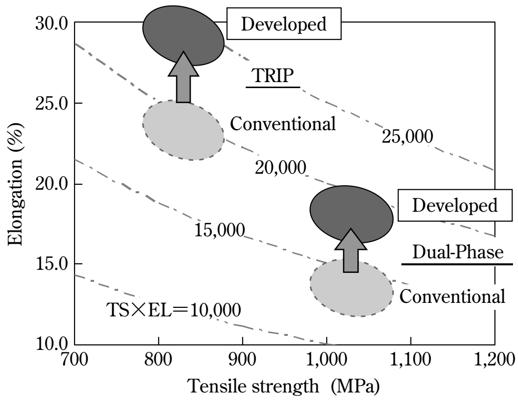

Fig. 4 Relationship between tensile strength and elongation in developed 980MPa grade DP and 780MPa grade TRIP steel sheets

stretch forming test confirmed that the TRIP-aided steel sheet exhibits extremely high strain dispersibility with less likelihood of local thickness reduction and achieves a limit-forming height comparable with that of a conventional 590MPa grade DP steel sheet which is one grade lower in terms of strength.

Table 2 shows the typical values of the hole expansion ratio (λ value), an index for stretch-flangeability, and the minimum bending radii in a 90 degree V-bending test. The minimum bending radius was determined from the smallest bending radius that causes no crack in a tested material bent by a 90 degree punch with a tip radius (*R*) of 0 - 5.0mm. The direction of bending was vertical to the direction of rolling. Also included in the table are the typical values for conventional 590 - 980MPa grade GA steel sheets. The newly developed materials have λ values that are all equivalent to those of the conventional materials in the same strength grade, with suppressed deterioration of local deformability, and as a result have superior balances of *EL* and λ compared with conventional materials. In general, bendability is known to correlate with stretch-flangeability as well as with local ductility [15), 16)]. Thus the minimum bending radius is regarded to correlate favorably with λ. The newly developed material, however, exhibits an excellent bendability despite its λ comparable to that of the conventional materials. This indicates that the bendability is not necessarily determined by λ. In other words, there may be effects other than the generally-known one of the addition of Si decreasing the difference in hardness between ferrite and martensite, improving the local deformability. However, the detailed mechanism has not been clarified yet, and a study is being conducted to elucidate the details. **Fig. 5** shows the forming limits for (a) the newly developed material of 590MPa grade and (b) 980MPa grade DP steel sheet (both having a thickness of 1.2mm). The scribed circle diameter is 0.25inch, and the dashed lines represent the forming limits for the conventional materials in the same strength grade for comparison. It has been shown that both of the newly developed materials have forming limits higher than those for conventional materials in a plane strain state, which is the most stringent forming condition. The high forming limit is attributable to the previously described composition design and microstructure control, both having an effect of improving elongation.

Table 2 Hole expansion ratio and Minimum bending radius of developed and conventional steel sheets

Steel	TS grade	Category	Thickness (mm)	λ-value (%)	Minimum bending radius 〈Transverse direction〉
Developed steel	590MPa	Dual Phase	1.6	74	0.0
	780MPa	Dual Phase	1.6	27	0.0
		TRIP	1.4	29	0.0
	980MPa	Dual Phase	1.6	27	0.0
Conventional steel	590MPa	Dual Phase	1.6	68	0.0
	780MPa	Dual Phase	1.6	31	0.5
	980MPa	Dual Phase	1.6	25	2.0

・Stretch flanging (Hole expanding) test :
Hole expansion ratio : λ-value obtained by method of JFST1001
・Bending test : V-block method (90 degree angle) according to JIS Z2248 (JIS Z2203 #3 specimen in transverse direction)

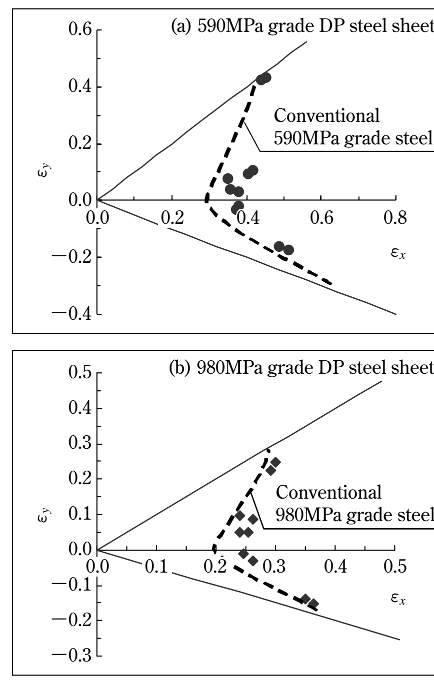

Fig. 5 Forming limit diagrams of developed steel sheets ((a)590MPa, (b)980MPa grade DP)

2.2 Spot weldability

Fig. 6 (a) and (b) respectively show the tensile shear strength (*TSS*) and cross tensile strength (*CTS*) of the 590MPa grade and 980MPa grade DP steel sheets, both newly developed, for varying welding

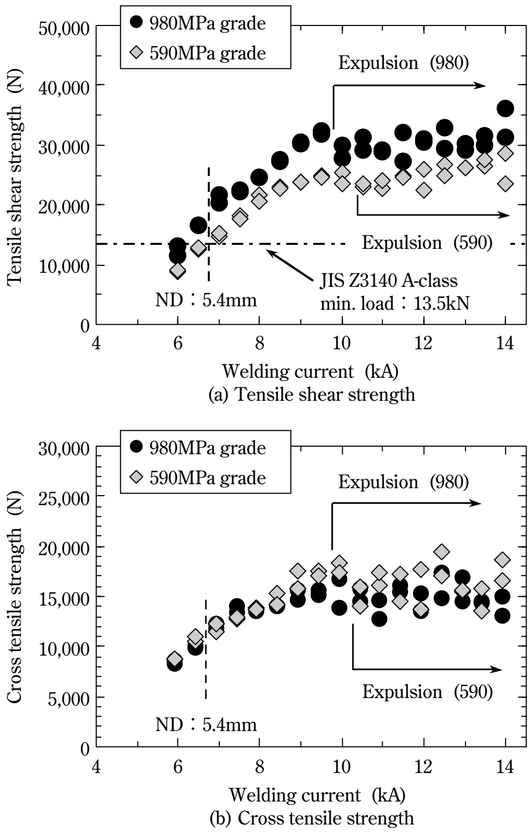

Fig. 6 Relationship between welding current and (a)tensile shear strength, (b)cross tensile strength in developed 590MPa and 980MPa grade DP steel sheets

current. Each sample sheet has a thickness of 1.6mm welded under the conditions shown in **Table 3**. Both the 590MPa grade and 980MPa grade steel sheets newly developed, have tensile shear strengths exceeding the requirement of JIS-A grade; i.e., 13.5kN, with a nugget diameter of 5.4mm. A suitable current range, not causing expulsion, is confirmed to be as large as 2.5kA or wider. On the other hand, cross tensile strength may decrease as an effect of the composition[17]. However, the newly developed materials exhibit no noticeable deterioration in strength. The newly developed materials of 590MPa grade and 980MPa grade result in a ductility ratio, the ratio between the tensile shear strength and cross tensile strength (*CTS*/*TSS*), of 0.65 or higher and 0.48 or higher, respectively, in the suitable welding current range. **Fig. 7** shows the relationship between the tensile shear strength and sheet thickness for a nugget of the newly developed 980MPa grade material that has a diameter of 5.4mm. For the thicker sheets, the electrode diameter and applied pressure were increased and the current period was extended. As a result, a favorable joint strength with a tensile shear strength greatly exceeding the load specified by JIS-A class was obtained.

Table 3 Spot welding conditions for Fig.6

Electrode tip	Dome type Cu-Cr
Tip diameter	8mm
Electrode force	4,950N
Welding time	28cycle (60Hz)
Welding current	6-14kA
Cooling water (Upper, Lower)	1.5L/min

Thickness	1.2mm	1.6mm	2.0mm
Tip diameter	6mm	8 mm	8mm
Electrode force	3,750N	4,950N	6,450N
Welding time (60Hz)	23 cycle	28 cycle	29 cycle

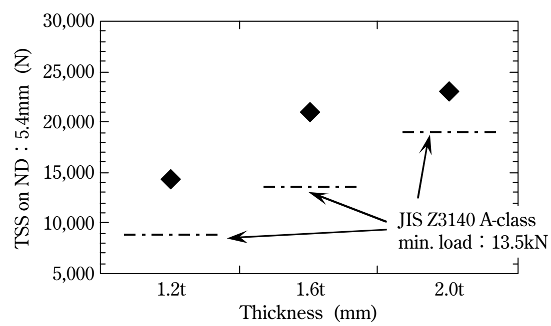

Fig. 7 Relationship between tensile shear strength and sheet thickness in developed 980MPa grade DP steel sheet

Table 4 Spot weldability in developed 590MPa and 980MPa grade DP steel sheets welded with/without gap (1mm) between sheets

TS grade (steel)	Gap between sheets	Welding current		
		ND:5.4mm	A-class TSS: 13.5kN	Expulsion
590MPa (Developed steel)	0mm	6.5kA	6.5kA	9.0kA
	1mm	6.5kA	6.5kA	9.0kA
980MPa (Developed steel)	0mm	6.0kA	5.5kA	8.0kA
	1mm	6.0kA	5.5kA	8.0kA

Table 4 summarizes the results of tests aimed at evaluating the practical spot weldability, in which the newly developed 590MPa grade and 980MPa grade materials were welded under the conditions of a smaller electrode tip diameter (6mm) and lower applied pressure (3,430N), compared with the conditions shown in Table 3. In addition, the welding was performed with or without a gap (1mm) in between the welded sheets. The table also includes the current values for the specified nugget diameter (5.4mm), JIS-A grade specification (13.5kN) and for expulsion. For all the cases, the electric current range in which both the specified nugget diameter and JIS-A grade specifications are satisfied without causing expulsion is above 1.5kA. This indicates that the newly developed materials not only have favorable workability, but also produce high welding joint strength in a consistent manner.

Conclusions

New galvannealed steel sheets of 590 - 980MPa grade with elongations as high as 1.3 times those of the conventional materials have been developed. The concepts of their microstructure control and main properties have been introduced. The newly developed materials are characterized not only by their excellent elongations, but also by superior bendability, spot weldability and coating quality, which are sufficient to satisfy customer needs. Kobe Steel regards these newly developed materials as a high-elongation type among the high-strength GA steel sheets. In response to customer needs, Kobe Steel has a lineup of products including, in addition to the above, steels with improved weldability and steels of high YS type. On the other hand, recent customer requirements for material properties have become much more stringent than they were several years ago, so Kobe Steel will continue striving to improve the characteristics of materials to resolve issues that the customers may have and thus expand the application of high-strength steel sheets.

References

1) Y. KURIYAMA et al., *Journal of Society of Automotive Engineering of Japan*, Vol.55, No.4 (2001), p.51.
2) S. KOBUKI, *TOYOTA Technical Review*, Vol.52, No.1 (2002), p.8.
3) K. SHIBATA, *NISSAN Technical Review*, No.50 (2002), p.26.
4) Y. FUTAMURA et al., *R&D Kobe Steel Engineering Reports*, Vol.57, No.1 (2007), p.109.
5) M. NAKAYA et al., *R&D Kobe Steel Engineering Reports*, Vol.50, No.1 (2000), p.75.
6) Y. OMIYA et al., *R&D Kobe Steel Engineering Reports*, Vol.52, No.3 (2002), p.10.
7) M. KAMURA et al., *R&D Kobe Steel Engineering Reports*, Vol.51, No.2 (2001), p.79.
8) M. KAMURA et al., *IBEC2002, Proceedings of the 2002 IBEC and ATT Conferences on CD-ROM*, (2002), 2001-01-3094.
9) M. KAMURA et al., *SAE Technical Paper* (2003), 2003-01-0522.
10) X. M. CHEN et al., *SAE Technical Paper* (2004), 2004-01-1048.
11) X. M. CHEN et al., *SAE Technical Paper* (2005), 2005-01-0354.
12) Y. FUTAMURA et al., *R&D Kobe Steel Engineering Reports*, Vol.57, No.2 (2007), p.11.
13) M. MIYAHARA et al., *R&D Kobe Steel Engineering Reports*, Vol.35, No.4 (1985), p.92.
14) T. TAMURA et al., R&D Kobe Steel Engineering Reports, Vol.52, No.3 (2002), p.6.
15) Y. TANAKA et al., *R&D Kobe Steel Engineering Reports*, Vol.42, No.1 (1992), p.20.
16) J. IWAYA et al., *JOURNAL OF THE JAPAN SOCIETY FOR TECHNOLOGY OF PLASTICITY SOSEI-TO-KAKO* (Journal of JSTP), Vol.35, No.404 (1994), p.1122.
17) S. NOMURA et al., *Technical Commission on Resistance Welding* (1981), RW-192-81.