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TS590～980 MPa Grade Low-Carbon Equivalent Type Galvannealed Sheet Steels with Superior Spot-Weldability*



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Synopsis:

High strength galvannealed (GA) sheet steels have been developed for the improvement of weight reduction, crash-worthiness and anti-corrosion properties of an auto body. In general, the strengthening of GA steel can be realized through the addition of alloy elements although Zn coating properties and spot weldability are affected at the same time. In this paper, the mechanical properties and spot weldability of newly developed 590–980 MPa GA steels are described. Excellent mechanical properties and crashworthiness comparable to those of dual phase steel have been obtained by adding Mo, Ti and Nb which are suitable alloying elements for strengthening the steels processed with continuous galvanizing line. Spot weldability, especially in terms of ductility ratio, has been remarkably enhanced through the reduction of carbon equivalent.

1 Introduction

Weight reduction of auto bodies is an increasingly important issue as a major factor in increase in motor vehicle fuel mileage. This is critical because the laws and regulations on CO_2 emissions are getting tighter to conserve the global environment. High strength sheet steels for auto bodies are being developed to reduce weight while enhancing crashworthiness.[1–6] Furthermore, galvanized (GI) sheet steels and galvannealed (GA) sheet steels are becoming more extensively used for auto bodies to improve corrosion resistance.[7–10] GA sheet steels with strengths exceeding 590 MPa have been developed for use as structural members in auto bodies.

Generally, sheet steel can be easily hardened by the addition of elements such as C, Si, Mn, and P. However, increasing the amount of elements such as C, Si, and Mn, which increase the quenching hardenability of steel, and of elements such as P and S, which embrittle the weld nugget, makes the sheet steels more susceptible to interfacial fracture at spot welded joints, as shown in **Fig. 1**. Thus, the addition of these alloying elements should be minimized to provide excellent spot weldability.[11,12] In addition, when readily oxidized elements such as Si and Mn are added, these elements tend to segregate and selectively oxidize at the steel surfacer during annealing, and degrades the wettability of the steel with molten Zn, causing bare spots and other surface defects in galvanizing.[8,9,13] The addition of P, which tends to segregate in the grain boundaries, hinders the grain boundary diffusion of iron atoms in the base steel. Since the diffusion process accelerates the formation of the Fe-Zn galvannealed layer, the galvannealing rate of sheet steels severely slows down by the hindering effect of P on the diffusion.[8,9,14,15]

This paper reports on new TS590–980 MPa grade GA sheet steels, that have excellent spot weldability by optimizing contents of alloying elements.

2 Concepts Applied to Chemistry Design

The chemistry of the steel was designed with a carbon equivalent less than 0.24% to strengthen the GA sheet steels while providing excellent spot weldability. The carbon equivalent (Pcm) is calculated by Eq. (1).[11,12]

$$\mathrm{Pcm} = \mathrm{C} + \mathrm{Si}/30 + \mathrm{Mn}/20 + 2\mathrm{P} + 4\mathrm{S} \quad \text{(mass\%)} \cdots (1)$$

The concepts used to design the alloy chemistry are as follows.

(1) C is effective for strengthen sheet steels, but it

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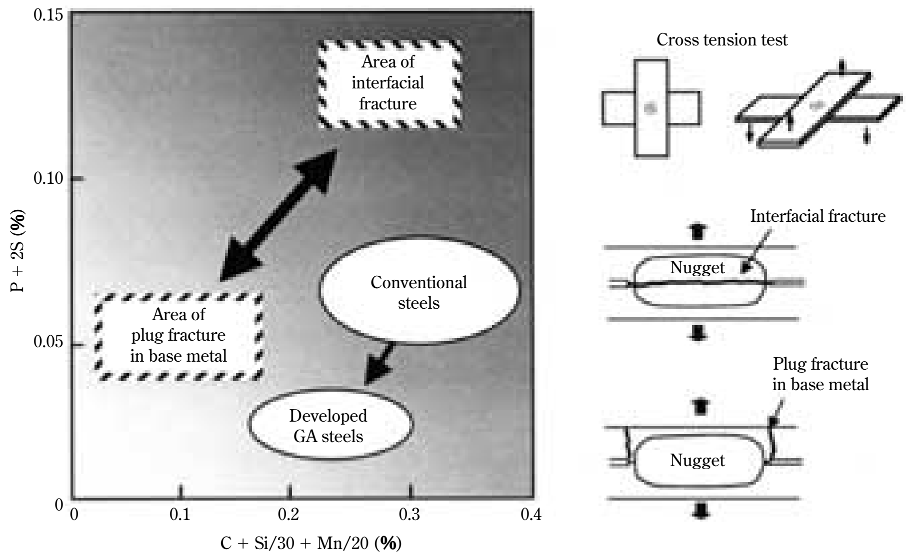


Fig. 1 Effect of chemical compositions on fracture shapes of spot welded joint

degrades press formability and spot weldability, which are indispensable for the assembly of auto bodies. The carbon content was therefore suppressed as low as possible.

(2) Mn is effective for strengthening sheet steels through both solid solution hardening and transformation hardening,[16] but it degrades spot weldability and galvanizability. The manganese content was therefore suppressed to less than 2.5 mass%.

(3) Si and P can economically strengthen sheet steels, but both degrade galvanizability. Thus, their contents were suppressed to the extent possible.

(4) S degrades spot weldability as well as stretch flange ductility.[17] The sulfur content was therefore suppressed to less than 0.003 mass%.

(5) The most appropriate strengthening methods for producing high yield ratio (high-YR type) GA sheet steels should be precipitation hardening[18] and grain-refinement hardening.[19–21] Additions of Ti and Nb were used to strengthen by carbide precipitation because both elements can form carbides without degrading the galvanizability.[15] However, fine carbides such as TiC and NbC suppress recrystallization and grain growth during annealing after cold rolling.[19–22] Thus, the amounts of Ti and Nb added were determined by maintaining a balance between strength and ductility.

(6) Mo was adopted as a strengthening element for producing low yield ratio (low-YR type) GA sheet steels.[7–9] As shown in **Fig. 2**, sheet steels in a continuous galvanizing line (CGL) are heated to the ferrite-austenite dual-phase temperature range and then cooled. The cooling process is interrupted at about 500°C while the sheet steels are galvanized. After galvanizing, they are subjected to a galvannealing treatment. Therefore, in contrast to a continuous annealing line (CAL), the critical cooling rate required to obtain

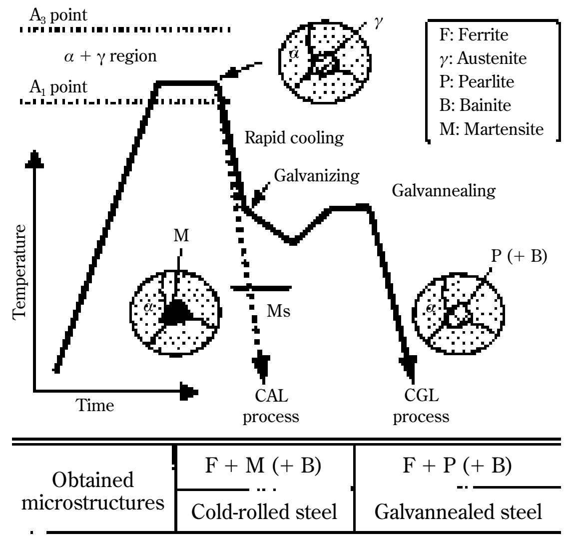


Fig. 2 Schematic illustration of formed microstructure by continuous annealing line, CAL and continuous galvanizing line, CGL in case of conventional C-Mn steels

a ferrite-martensite dual-phase microstructure is not achieved in a CGL process.[16] When conventional C-Mn sheet steels are being processed by CGL, the austenite phase is transformed into ferrite and pearlite and/or bainite during the cooling process. Therefore, it is difficult to produce steel that has the ferrite-martensite dual-phase microstructure required for obtaining a low yield ratio. Thus, to obtain this microstructure by CGL, it is necessary to determine a steel chemistry that can decrease the critical cooling to the feasible one in the CGL cooling process. Mo is effective to shift the nose of the pearlite and/or bainite transformation, which takes place at a relatively low temperature, to a longer time side in CCT diagram.

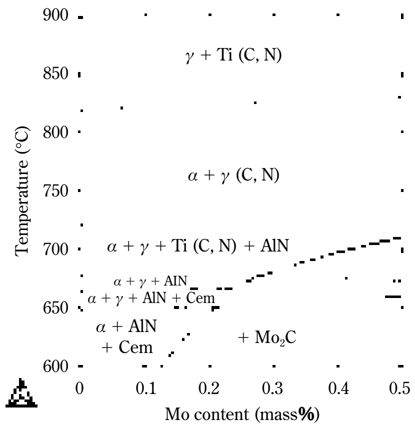
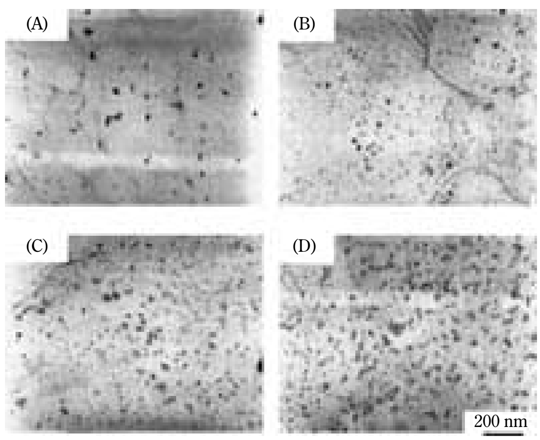


Fig. 3 Equilibrium state diagram of 0.07%C-2.0%Mn-0.02%Ti-0.10%Nb steel calculated by Thrmo-Calc (Nb (C, N) and MnS also are evaluated in region)



(A) Mo-free steel, (B) 0.07%Mo-added steel,
(C) 0.15%Mo-added steel, (D) 0.25%Mo-added steel

Photo 1 TEM micrographs of Mo-free steel and Mo-added 0.07%C-2.0%Mn-0.02%Ti-0.10%Nb steels

This nose shift relaxes the critical cooling rate to a slower level, and enables the production of steel with a ferrite-martensite dual-phase microstructure by CGL. Mo has another advantage in galvanizing process. Since Mo is more difficult to be oxidized than Si and Mn, its addition is effective to strengthening steel without sacrificing galvanizability.[7–9,23)] Further, the Thermo-Calc calculation result shown in **Fig. 3** indicates that a Mo-based carbide (Mo_2C) is likely to be formed in Mo-added steel. As revealed in the TEM micrographs shown in **Photo 1**, the volume fraction on fine precipitates increases with increasing Mo additions. These precipitates should contribute to strengthening steel, which is an additional benefit for using Mo. EDX analysis confirmed that the fine precipitates observed in Photo 1 are mostly Ti-Nb-Mo-based compound carbides, as shown in **Fig. 4**.

Kawasaki Steel successfully developed the

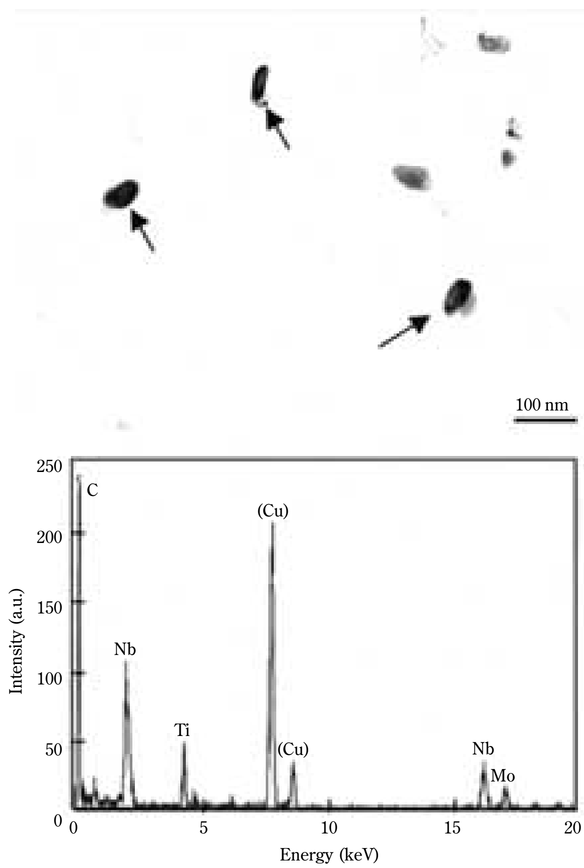


Fig. 4 TEM micrograph and EDX analysis result of 0.07%C-2.0%Mn-0.02%Ti-0.10%Nb-0.15%Mo steel

TS590–980 MPa grade, high strength GA sheet steels shown in **Table 1** by using the optimum combinations of limited types of elements such as Ti, Nb, and Mo that do not degrade spot weldability and galvanizability. Also, various strengthening mechanism such as precipitation hardening, grain-refinement hardening, and transformation structure hardening were fully utilized.

3 Cross-Sectional Microstructures

Photo 2 shows cross-sectional micrographs of two representative types of newly developed TS590 MPa grade, GA sheet steels (A) low-YR type GA sheet steel (JAC590Y), and (B) high-YR type GA sheet steel (JAC590R). JAC590Y, which is produced by adding Mo, has a dual-phase microstructure with martensite formed in the vicinity of ferrite grain boundaries. JAC590R, which is produced by adding Ti and Nb, has a finer microstructure the JAC590Y due to the large pinning effect on grain boundary that TiC and NbC have on grain growth process.

TS 780–980 MPa grade GA sheet steels are produced by combining optimized additions of Ti, Nb, and Mo with an optimized CGL operation. The high strength of these steels is achieved by grain refinement and adjust-

Table 1　Chemical compositions of GA and cold-rolled sheet steels

Steel	TS grade (MPa)	JFS Standard	Chemical compositions (mass%)					Hardening mechanism***
			C	Si	Mn	Special element	Carbon equivalent, Pcm**	
Conventional GA sheet steel	440	JAC440W	0.17	0.01	0.7	—	0.26	SS
Developed GA sheet steels	590	(JAC590Y)*	0.08	0.02	2.0	Mo	0.21	TR
		JAC590R				Ti, Nb		PP
	780	(JAC780Y)*	0.10	0.02	2.0	Ti, Nb, Mo	0.24	PP + TR
		(JAC780R)*						
	980	(JAC980Y)*	0.10	0.02	2.0	Ti, Nb, Mo	0.24	PP + TR
Conventional cold-rolled sheet steels	590	JSC590Y	0.08	0.03	1.7	P	0.32	TR
	780	JSC780Y	0.15	0.07	1.7	Ti	0.32	PP + TR
	980	JSC980Y	0.08	0.20	3.0	Ti, Nb	0.28	PP + TR

*( ): Not standardized
**Pcm = C + Si/30 + Mn/20 + 2P + 4S (mass%)
***SS: Solid solution hardening, PP: Precipitation hardening, TR: Transformation hardening

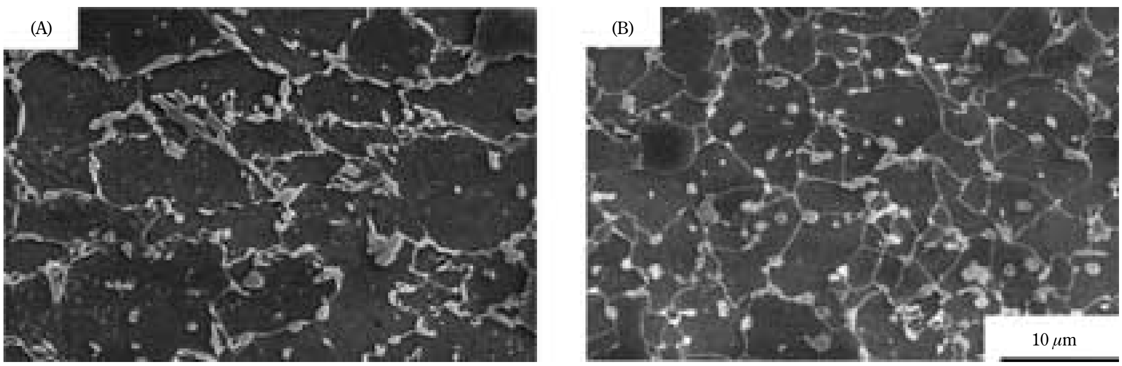


Photo 2　SEM micrographs of steel of (A) JAC590Y and (B) JAC590R etched in nital

ment of the martensite volume fraction.

4 Mechanical Properties

4.1 Formability

JIS Z 2204 No. 5 test specimens were taken from a commercially produced GA coil, their direction being transverse to rolling direction, and tested. The yield point (YP), tensile strength (TS), and elongation (El) were measured by the methods specified in JIS Z 2241. Stretch flange ductility was evaluated by measuring a hole expansion ratio (λ) in accordance with the method specified in JFS T 1001. The results are shown in **Table**

Table 2　Mechanical properties of GA and cold-rolled sheet steels

Steel	JFS Standard	Thickness (mm)	YP (MPa)	TS (MPa)	El (%)	λ (%)	Tensile fatigue limit stress (MPa)	Plane bending fatigue limit stress (MPa)
Conventional GA sheet steel	JAC440W	1.4	302	460	33	47	430	230
Developed GA sheet steels	(JAC590Y)*	1.4	359	603	30	64	500	255
	JAC590R	1.4	440	621	26	55	505	262
	(JAC780Y)*	1.2	531	785	21	30	605	334
	(JAC780R)*	1.2	670	800	19	27	610	336
	(JAC980Y)*	1.2	602	988	15	18	640	342
Conventional cold-rolled sheet steels	JSC590Y	1.4	301	623	30	62	580	309
	JSC780Y	1.2	500	834	21	31	655	390
	JSC980Y	1.2	625	1035	16	22	680	420

*( ): Not standardized
Tensile test specimens were prepared in a form of No. 5 specimen in accordance with JIS Z 2204
Hole expansion ratio was obtained by method of JFS T 1001
Tensile and plane bending fatigue limit stress on as-annealed sheet steels were obtained by methods of JIS Z 2273 and JIS Z 2275

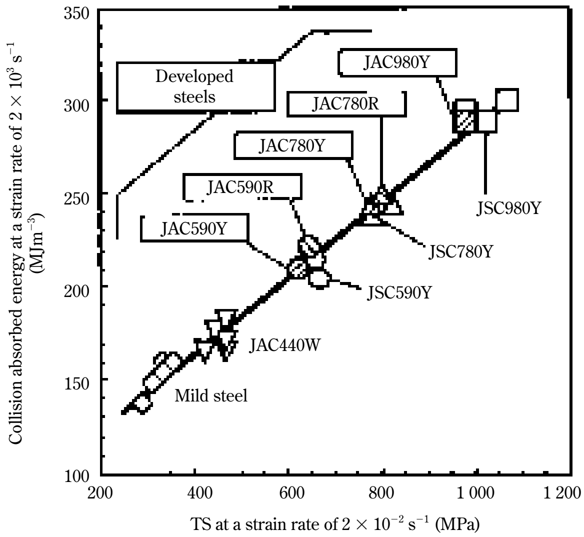


Fig. 5 Relationship between tensile strength at a low strain rate and collision absorbed energy at a high strain rate

2. By optimizing the amounts of alloying elements such as C and Mn that markedly increase the Pcm value, as stated in Section 2, and by lowering unavoidable impurities such as P and S to the extent possible, low-YR type GA sheet steels produced by CGL exhibited El and λ values equivalent to those of low-YR type cold rolled sheet steels produced by CAL. High-YR type GA sheet steels, which were produced by mainly utilizing precipitation hardening and grain-refinement hardening, exhibited excellent El that was nearly equal to that of the low-YR type GA sheet steels.

Table 2 also shows the tensile fatigue limit stress and plane bending fatigue limit stress for the base sheet steels measured by the methods specified in JIS Z 2273 and JIS Z 2275. The newly developed GA sheet steels have a fatigue limit stress that is higher than that of JAC440W, which is a widely used, conventional GA sheet steel. This improvement in fatigue property clearly demonstrates the effect of strengthening of steel.

4.2 Crashworthiness

Absorbed energy at a high strain rate of $2 \times 10^3 s^{-1}$ was measured in a non-coaxial, Hopkinson pressure bar type, high-speed tensile tester. A conventional tensile tester was used to measure the TS at a low strain rate of $2 \times 10^{-2} s^{-1}$. The relation between these two measurements is shown in **Fig. 5**. The absorbed energy values of the newly developed GA sheet steels fall on an identical line to those of conventional low-YR type cold rolled sheet steel (JSC590Y, JSC780Y, JSC980Y), which have excellent crashworthiness. The results of these experiments confirm the excellent crashworthiness of the newly developed GA sheet steels, and suggest that the absorbed energy is not greatly affected by the difference in YR, but rather is dependent on the static TS measured at a low strain rate.

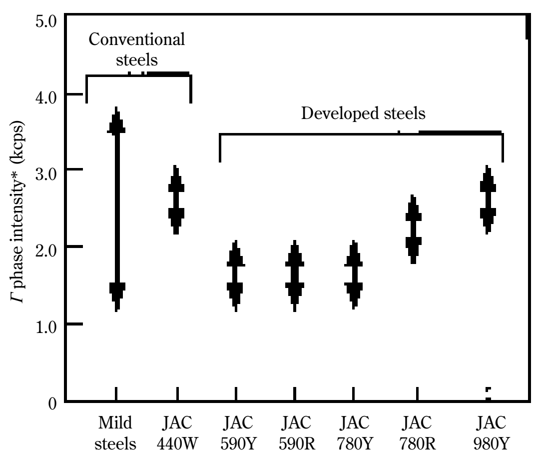
5 Properties of Galvannealed Coating

The phase structure of the Zn coating layer was analyzed. The Γ phase in the Zn coating layer[24] is generally believed to adversely affect the anti-powdering property of GA sheet steels. The intensity of the associated X-ray diffraction peak was measured. The results is shown in **Fig. 6**. The intensity of the X-ray diffraction peaks of the newly developed GA sheet steels indicates that they have coating layers with properties comparable to those of conventional GA sheet steels made of mild steel and JAC440W.

6 Spot Weldability

6.1 Strength of Spot Welded Joints

Spot welding was performed primarily using the welding conditions shown in **Table 3**. The welding cur-



Steel	JFS standard	t*** (mm)	Coating weight (gm⁻²)	Fe content (mass**%**)
Developed	(JAC590Y)**	1.2	45/46	10/11
	JAC590R	1.2	53/50	11/11
	(JAC780Y)**	1.2	49/47	10/10
	(JAC780R)**	1.2	46/47	10/9
	(JAC980Y)**	1.2	46/50	10/10
Conventional	JAC440W	1.4	48/47	11/11

*: Γ phase intensity = Γ (222) + Γ (444) {d = 2.59Å}
**( ): Not standardized
***t: Thickness of GA sheet steels

Fig. 6 Γ phase intensity in Zn coating layer of GA sheet steels

Table 3 Spot welding conditions

Electrode shape	Welding current (kA)	TS grade of steel (MPa)	Electrode force (kN)	Time schedule (cycle)			
				Squeeze	Upslope	Weld	Hold
DR, 6ϕ	7.5	440–590	3.1	25	3	16	25
		780–980	4.0	25	3	14	1

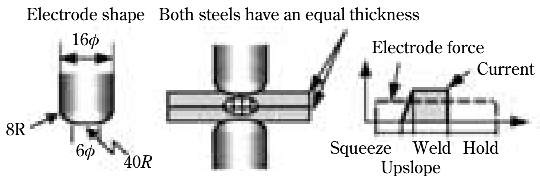


Table 4 Spot weldability of GA and cold-rolled sheet steels

(Welding current: 7.5 kA)

Steel	JFS Standard	Carbon equivalent, Pcm (%)	Thickness (mm)	JIS Z 3140 A-Standard (min)		TSS (kN)	CTS (kN)	Dn (mm)	Db (mm)
				TSS (kN)	Dn (mm)				
Conventional GA sheet steel	JAC440W	0.26	1.4	11.7	5.0	14.0	6.9	5.8	0
Developed GA sheet steels	(JAC590Y)*	0.21	1.4	11.1	5.0	16.5	11.6	5.9	7.5
	JAC590R	0.21	1.4	11.1	5.0	16.6	12.8	5.7	6.5
	(JAC780Y)*	0.24	1.2	8.8	4.7	15.2	8.7	5.6	5.8
	(JAC780R)*	0.24	1.2	8.8	4.7	15.5	8.8	5.5	5.7
	(JAC980Y)*	0.24	1.2	8.8	4.7	16.9	8.4	5.4	6.6
Conventional cold-rolled sheet steels	JSC590Y	0.32	1.4	11.1	5.0	15.2	4.6	5.5	0
	JSC780Y	0.32	1.2	8.8	4.7	15.6	3.9	5.6	0
	JSC980Y	0.28	1.2	8.8	4.7	16.0	4.8	5.6	5.8

*( ): Not standardized
TSS, CTS: Tensile shear stress and cross tension stress at spot welded joint measured by method of JIS Z 2273
Dn: Diameter of nugget measured by visual observation
Db: Diameter of button measured by peel test

rent was 7.5 kA, which causes neither interfacial fracture in tensile shear tests nor expulsion. An optical microscope was used to measure the nugget diameter (Dn) after welding and the button diameter (Db) after peeling tests of spot welded joints. Also, the tensile shear strength (TSS) and cross tension strength (CTS) of the spot welded joints were measured. The results are shown together in **Table 4**.

In the TSS and nugget diameter measurements, all of the newly developed GA sheet steels and conventional sheet steels satisfied the JIS-A grade standards. In the peeling tests, however, except for JSC 980Y, the conventional cold rolled sheet steels (JSC590Y and JSC780Y) and conventional GA sheet steel (JAC440W) with high Pcm values caused interfacial fracture (Db: 0 mm). In contrast, all of the newly developed GA sheet steels caused plug fracture, owing to the suppressed Pcm values, and exhibited excellent spot welded joint strength. The ductility ratios (CTS/TSS) of the newly developed GA sheet steels exceeded 0.5, demonstrating excellent spot weldability that is superior to that of JAC440W.

The correlation between nugget hardness and carbon equivalent (in this case, as defined by $Ceq = C + Si / 40 + Cr / 20$ mass%)[25] and the relation between C content and TSS or CTS[26] have been already reported, but the relation between the ductility ratio and carbon equivalent has not been reported much. We summarized the relation between the ductility ratio and Pcm of the newly developed GA sheet steels and conventional sheet steels. The result is shown in **Fig. 7**. The ductility ratio is not so dependent on the base metal structure, YR, or strength level. It is rather linearly correlated to Pcm. This result indicate that Pcm is an effective index for forecasting the ductility ratio, as well as the fracture mode, which is characterized by either an interfacial fracture or plug fracture in the base metal of a spot welded joint as shown in Fig. 1.

6.2 Fatigue Properties of Spot Welded Joints

It is well known that fatigue strength of spot welded joints between high strength steel effectively improved by increasing TS of the base metal.[27–29] The tensile fatigue and plane bending fatigue properties were investigated on three representative steel grades selected out of the newly developed GA sheet steels: JAC590R, JAC780R, and JAC980Y. The *S*-*N* curves for these steels

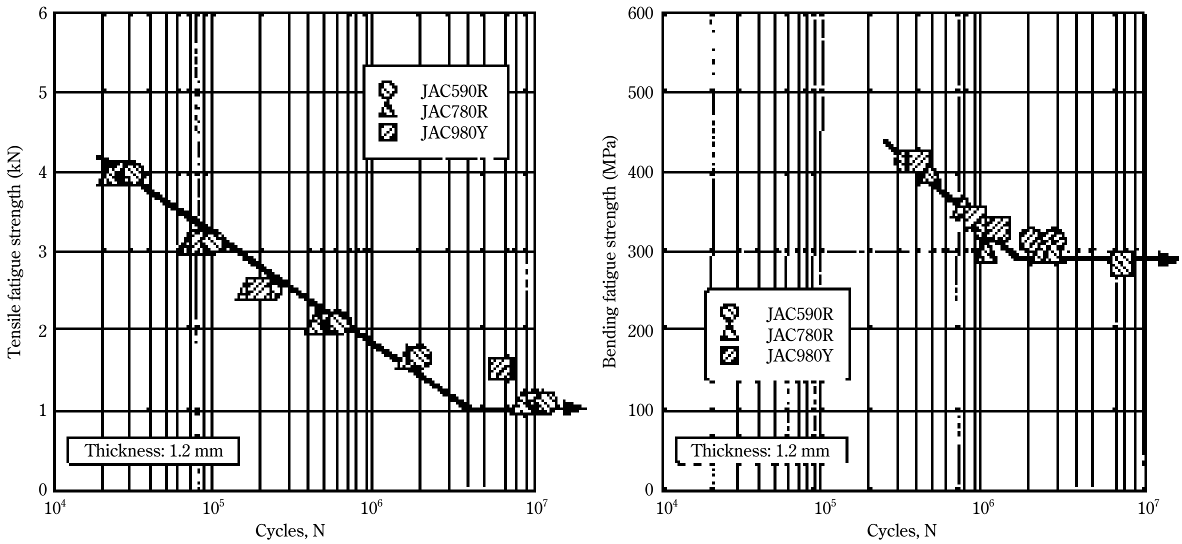


Fig. 8 Tensile and bending fatigue strengths of spot-welded GA sheet steels

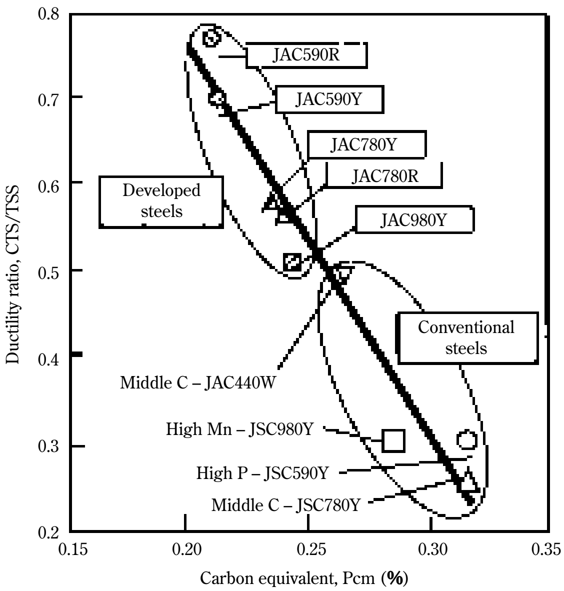


Fig. 7 Relationship between carbon equivalent, Pcm at welding current of 7.5 kA and ductility ratio, CTS/TSS

are shown in **Fig. 8**. These steels have different strengthening mechanisms, strength levels, and Pcm values, but all three of these steel grades are nearly equal in tensile fatigue strength and plane bending fatigue strength. As previously known, it was confirmed again that fatigue properties are not improved by strengthening base metals.

The starting points of fatigue cracks were mostly corona bonded areas in the spot welded joints. As with conventional high strength sheet steels, when performing spot welding on the newly developed GA sheet steels it is necessary to optimize welding current and to select the tempering treatment current and other welding conditions in accordance with the properties of each type of sheet steel.[25,29)]

7 Production Performance and Typical Applications

TS590 MPa grade GA sheet steels produced by Kawasaki Steel are mostly used to fabricate auto parts, as shown in **Fig. 9**. TS590 MPa grade GA sheet steels are mainly produced in the gage range of 1.0 to 2.3 mm, and their main applications are structural members and their reinforcement of auto bodies. Currently, they are produced at a rate of several thousand tons per month.

It is expected that the GA sheet steels grades over TS590 MPa will be widely adopted by automakers, and their production will increase accordingly.

8 Conclusions

Newly developed TS590–980 MPa grade low-carbon-equivalent type GA sheet steels have excellent formability, galvanizability, and spot weldability. The features of these new high strength GA sheet steels are:

(1) Ti, Nb, and Mo were employed as strengthening elements. Grain-refinement hardening by fine precipitates was combined with transformation hardening by a second phase. Although these sheet steels are produced by the CGL process, their formability is equivalent to that of conventional TS590–980 MPa grade low-YR cold rolled sheet steels.

(2) The galvanizability of these sheet steels is comparable to that of conventional GA sheet steels made of mild steel and JAC440W because of the lowered Si and P contents.

(3) Spot weldability, such as indicated by the fracture

Applied example
(1) Cowl side panel (2) Side sill (3) Side member (4) Cross member (5) Pillar (6) Reinforcement (7) Gasoline tank mounting (8) Others

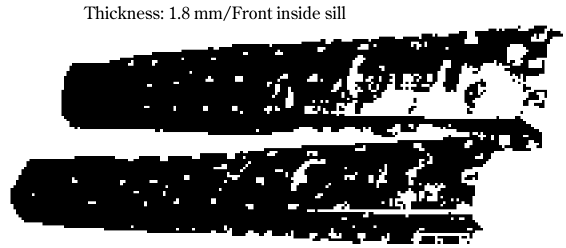


Fig. 9 Applied examples for automotive parts of newly developed 590 MPa grade GA sheet steels

mode at welds, and the ductility ratio are superior to that of JAC440W due to the lower carbon equivalent.

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