# 590～980 -

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**Synopsis:**

## 1 I

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 **F . 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 we t0JTi .9(g)-1Tw[(as Si ai)434.9(ate)]TJ 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 graofg

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 **F[illegible]. 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 [illegible] **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 **F[illegible]. 4**.

Kawasaki Steel successfully developed the TS590–980 MPa grade, high strength GA sheet steels shown in [illegible] **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 C[illegible]

[illegible] **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-ng, and transf7i

| 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**2 | | | | | | | | | |
| | | | | | | | | | |
| | 590 | | | | | | | | |
| | | | | | | | | | |

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

ment of the martensite volume fraction.

## 4

### 4.1 F 7

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 ($\lambda$) in accordance with the method specified in JFS T 1001. The results are shown in

**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 $\lambda$ 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 C

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 **F . 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 G C

The phase structure of the Zn coating layer was analyzed. The $\Gamma$ 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 **F . 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

### 6.1 J

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

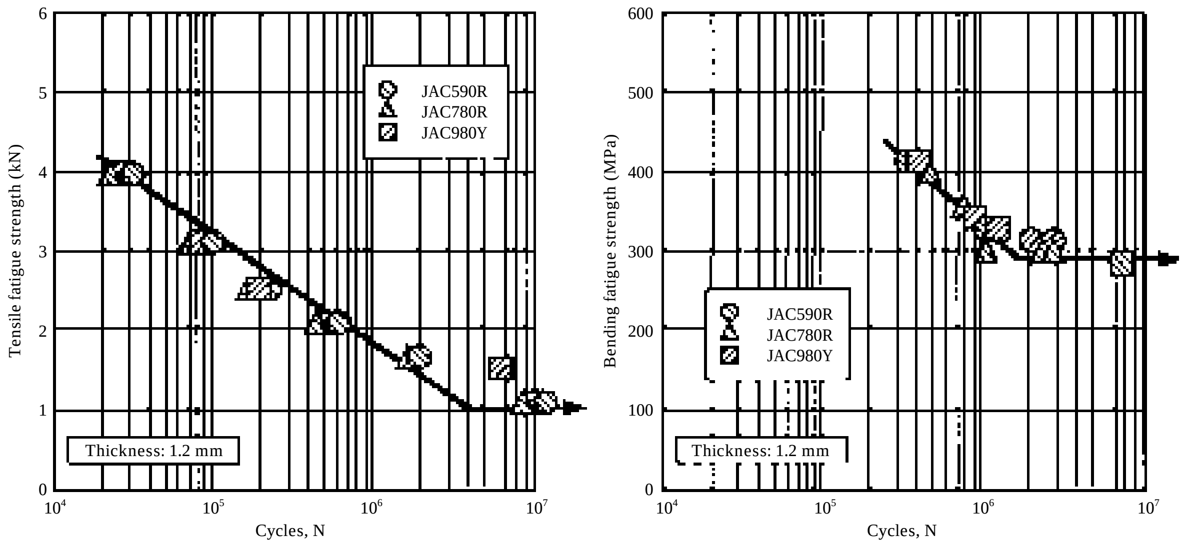


Fig. 8 Tensile and bending fatigue strengths of spot-welded GA sheet steels

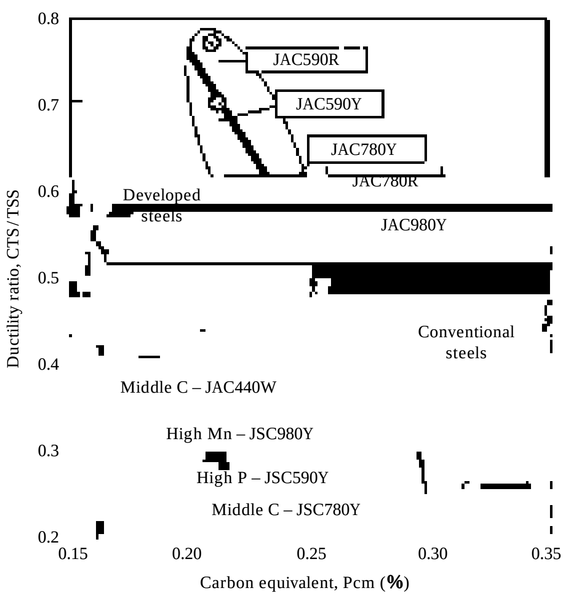


Fig. 7 Relationship between carbon equivalent, Pcm at welding current of 7.5 kA and ductility ratio, CTS/TSS

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 [illegible]

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 [illegible]

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

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


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