JFE TECHNICAL REPORT
No. 10 (Dec. 2007)

Newly-Developed Ultra-High Tensile Strength Steels with Excellent Formability and Weldability†

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Abstract:

JFE Steel has developed and commercialized ultra-high tensile strength steel series from TS780 MPa to 1 470 MPa with excellent formability and weldability which reduces weight and increases safety in collision when they are applied to the reinforcement parts around a cabin. Those ultra-high tensile strength steels are developed by applying JFE Steel's own technology, continuous annealing line water-quenching facilities which greatly contribute to reduce alloy elements in the steel. Especially, the TS1180 MPa steel which is expected to expand in application, excels in elongation. It is 1.5 times larger than the conventional one which is the same level with 980 MPa, and strech-flangeability has also been achieved as the same level with TS980 MPa. It is remarkable work-hardenability and bake-hardenability make it possible to replace hot-stamping parts.

1. Introduction

In recent years, high strength steel sheets have been increasingly applied to automobile bodies to improve crashworthiness so as to secure the safety of the passengers in the automobile and improve fuel economy by reducing automobile body weight in order to reduce CO_2 emissions.

Up to 1990, application of TS440–590 MPa grade high strength steel sheets (TS: tensile strength) was studied as a substitute for conventional mild steel sheets. These steel sheets were improved to overcome problems such as difficulty of press formability, weldability, and corrosion resistance, and have played an important role as front end collision members such as the front side member and others which absorb energy by deforming in a collision.

From the beginning of the 1990s, ultra-high strength steel sheets of TS780 MPa grade and higher were studied. Conventionally, this type of ultra-high strength steel sheet had been applied in safety reinforcing parts located away from the cabin, such as bumper reinforcing materials, door impact beams, and the like, but in response to stricter safety and weight reduction requirements, this range has expanded to include pillars and their reinforcing materials and similar parts. This trend is also clearly shown by the ULSAB (Ultra Light Steel Auto Body) Project, which was carried out jointly by 32 steel makers in 15 countries beginning in 1994, and can be interpreted as the future direction for automotive structural members[1)].

To meet these needs, JFE Steel, as a total maker of automotive high tensile strength steels, carried out product development of automotive steel sheets which lead the world in responding to the diverse requirements of the automobile market[2,3)]. As part of this effort, the company commercialized high formability ultra-high strength steel sheets of grades TS780–1 470 MPa utilizing a low alloy composition design and control of the microstructure, making full use of the continuous annealing line with a water quench function (WQ-CAL) process shown in **Photo 1**[4)] .

This paper introduces JFE Steel's TS780–1 470 MPa grade cold-rolled steel sheets, which can contribute to further weight reduction and improved crashworthiness in automobile bodies. In particular, the basic concept of material design and properties are outlined, centering on TS980 MPa and TS1180 MPa grade steel sheets, which

† Originally published in *JFE GIHO* No. 16 (June 2007), p. 16–20

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Photo 1 West Japan Works (Fukuyama) No. 3 Continuous Annealing Line (WQ-CAL)

are enjoying increased application to body structural parts around the cabin.

2. Properties Required in Steel Sheets for Body Structural Part

High strength cold rolled steel sheets of TS780 MPa grade and higher are used in body structural parts around the cabin in order to secure crashworthiness. The properties which are considered necessary in these steel sheets for body structural parts are (1) press formability, (2) spring back characteristics, (3) spot weldability, and (4) delayed fracture resistance.

Where press formability is concerned, property requirements differ depending on the structural part where the sheet is to be used. For example, in parts where stretch-formability is a priority, as represented by the center pillar, a high elongation-type steel sheet with high ductility is applied, while a sheet with a high hole expansion property is applied in stretch-flanging applications such as members. In particular, the TS1180 MPa grade cold rolled steel sheet had been applied in members and reinforcing parts which are formed mainly by bending forming such as roll forming, but higher ductility becomes necessary when this sheet is applied to body structural parts around the cabin.

A property which is important in combination with press-formability is spring back. Although spring back occurs when high strength cold rolled steel sheets are press-formed, poor dimensional accuracy in parts resulting from spring back has a negative effect on the subsequent assembly and welding processes. In response, auto makers perform press-forming taking spring back into account in advance, but if deviations in material strength are large, the problem of spring back cannot be solved by this method. Therefore, high strength cold rolled steel sheets with minimal deviations in material strength are applied in order to improve spring back characteristics.

Moreover, as the strength of steel sheets increases, the C content also generally increases. In steels with high C contents, spot welds are susceptible to embrittlement, encouraging internal fracture when tensile stress occurs, and weld strength is reduced. Accordingly, a low carbon equivalent (C_{eq}) composition design is necessary in order to secure adequate strength in welds.

In ultra-high strength steel sheets of TS1180 MPa grade and higher, delayed fracture is a concern in corrosive environments. To improve delayed fracture properties, a low C_{eq} composition design and tempered martensite microstructure control are effective[5].

3. Development Concept of High Strength Cold Rolled Steel Sheets

JFE Steel succeeded in commercializing ultra-high strength cold rolled steel sheets from TS780 MPa grade to 1 470 MPa grade utilizing the WQ-CAL, which was developed independently by JFE Steel and has the world's highest speed cooling capacity (>1 000°C/s). Steel sheets manufactured using the WQ-CAL have the following features.

(1) Full product line of high formability steel sheets in grades from TS780 MPa to 1 470 MPa capable of meeting a wide range of strength and formability requirements.

(2) Excellent spot weldability and delayed fracture resistance by low C_{eq} composition design.

(3) Excellent material quality stability by uniform water cooling using WQ and feedforward control.

The heat cycle of the WQ-CAL is shown in **Fig. 1.** The microstructural morphology (martensitic single phase microstructure, dual phase (DP) microstructure) can be controlled by annealing conditions. Furthermore, in the DP microstructure, it is also possible to control

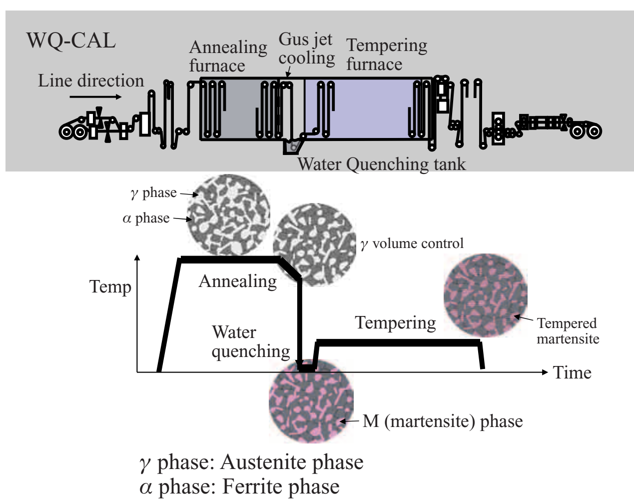

Fig. 1 Typical heat cycles of WQ-CAL, and schematic microstructures

Table 1 Line up of TS780–1 470 MPa grade cold rolled high strength steels

TS grade	JFE Steel Standard	JFS Standard*1	Type	Thickness (mm)	Mechanical properties*2				C_{eq}*4 (mass%)
					YP (MPa)	TS (MPa)	El (%)	λ (%)*3	
780	JFE-CA780Y2	JSC780Y	Low YR	1.4	430	810	22	30	0.15
	JFE-CA780SF		High λ	1.2	600	830	19	80	0.12
980	JFE-CA980Y2	JSC980Y	Low YR	1.2	610	1 010	18	30	0.18
	JFECA980SF		High λ	1.2	740	1 020	15	60	0.18
	JFE-CA980SF2	–	Super λ	1.2	900	1 020	7	100	0.09
1 180	JFE-CA1180Y2	JSC1180Y	Low YR	1.2	950	1 210	14	30	0.23
	JFE-CA1180SF	–	High λ	1.6	1 030	1 230	7	60	0.17
1 370	JFE-CA1370	–	–	1.6	1 130	1 450	7	60	0.23
1 470	JFE-CA1470	–	–	1.6	1 200	1 510	7	60	0.23

YP: Yield point, TS: Tensile strength, El: Elongation
*1 The Japan Iron and Steel Federation Standard
*2 Tensile specimen: Transverse direction, JIS No.5
*3 λ: Hole expanding ratio according to JFST 1001
*4 Carbon equivalent for spot welding: $C_{eq} = 1.5C + P + 3S$

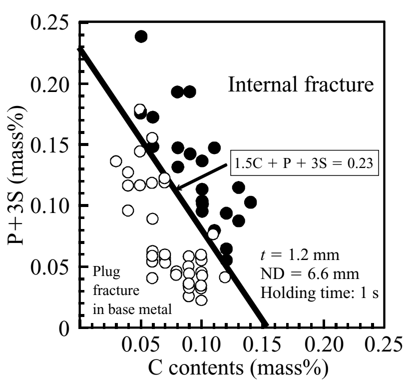

Fig. 2 Effect of C, P and S contents on fracture type of spot-welded joint in cross tension test (t: Thickness, ND: nuggest diameter)

the volumetric fraction and hardness of the hard second phase by optimizing the water quenching temperature and tempering temperature. Using equipment functions capable of realizing this kind of heat cycle, the ideal structural control was achieved and a technology for producing a wide range of strengths and specific properties corresponding to the application was established (**Table 1**).

The fact that a low C_{eq} composition design that reduces added elements, beginning with C, to the absolute limit is possible utilizing the WQ-CAL, and as a result, the soundness of welds, which is a concern in ultra-high strength steel sheets, is also an important strength of this technology. **Figure 2** shows the effect of added elements on the cross-tensile strength of spot welds[6]. Increases in the contents of C, P, and S encourage internal fracture in the cross-tensile test of welds, and thus reduce weld strength. In order to maintain a morphology in which fracture occurs in the nugget in ultra-high strength steel sheets of grades exceeding TS780 MPa, JFE Steel performs material design in which C_{eq} is strictly controlled within the range of the limit line ($C_{eq} \leqq 0.23$). JFE Steel also overcame the problem of delayed fracture in corrosive environments, which is a concern in ultra-high strength steel sheets of TS1180 MPa and higher, by a low C_{eq} composition design and control of the tempered martensite microstructure[5].

Spring back, which becomes an issue in press-forming of high strength steel sheets, is improved by minimizing strength deviations in the coil longitudinal direction and transverse direction by rapid and uniform cooling control, which is a strong point of the WQ-CAL. For coil-to-coil strength differences, strength fluctuations in TS780–1 470 MPa grade ultra-high strength steel sheets are reduced to the same level as in TS590 MPa grade cold rolled steel sheets by applying steelmaking technology which controls the chemical composition of the steel with high accuracy and controlling the factors associated with strength fluctuations in an integrated manufacturing process from hot rolling to continuous annealing.

4. Recent Condition of Development of Ultra-High Strength Cold Rolled Steel Sheets

4.1 TS980 MPa Grade Cold Rolled Steel Sheets Suitable for Auto Body Structural (Reinforcing) Parts and Seat Frame Materials

JFE Steel developed high formability TS980 MPa grade cold rolled steel sheets which respond to a wide range of recent requirements for automotive parts. To meet the specific property requirements of various parts, JFE Steel commercialized the three types of TS980 MPa

Table 2 Feature of mechanical properties of 3 types of TS980 MPa grade cold rolled steels and their application to automotive parts

Type	Mechanical properties			Applicable parts
	YP	El	λ	
Low YR	Low	High	Low	· Structural parts of body in white ex. Center pillar (Reinforcement)
High λ	Medium	Medium	Medium	· Bumper reinforcement · Seat frame, Seat rail
Extra high λ	High	Low	High	· Seat parts (Mechanical clinch)

grade sheets shown in **Table 2**, namely, a low yield ratio(YR) type, a high λ (hole expanding ratio) type, and an extra-high λ type. The low YR type is a high elongation DP microstructure steel sheet with a low yield point(YP) and high ductility for stretch-forming products such as pillar parts. The high λ type also has a DP microstructure, but has a high YP and an excellent balance of elongation and hole expansionability. This sheet is used in a wide range of products, including stretch-formed products, seat parts, and others. The extra-high λ sheet achieves a hole expanding ratio superior to that of TS440 MPa grade cold-rolled sheets, and is also suitable for mechanical clinching, which had been limited to mild steel, aluminum, and other low strength materials in the past. Taking advantage of this feature, this sheet realizes weight reduction in automotive seat frames and reduces the cost of manufacturing parts by making it possible to omit the welding process. As a result, it has become possible to apply this sheet in new fields[7)].

Figure 3 shows the development of this product line based on the elongation-hole expansionability (El-λ) balance. In comparison with the conventional materials, the El-λ balance has been greatly improved in these three types of TS980 MPa cold rolled steel sheets. Generally, DP microstructure-type high strength steel sheets display a trade-off correlation between the hole expanding ratio and elongation, in that λ tends to deteriorate when El is improved. However, JFE Steel's high-λ type TS980 MPa grade sheet is based on a DP microstructure, but by reducing the strength difference between the ferrite and martensite phases and optimizing the volumetric ratio of martensite, it is possible to maintain high hole expansionability, on the same level as that in TS590 MPa grade cold rolled steel sheets, while also maintaining satisfactory elongation. This is considered to be because the reduction of the hardness difference between the phases suppresses the occurrence of initial micro voids in the vicinity of the shear plane during punching, and also suppresses formation and consolidation of micro voids during hole-expanding forming, while the presence of ferrite maintains appropriate ductility[8,9)].

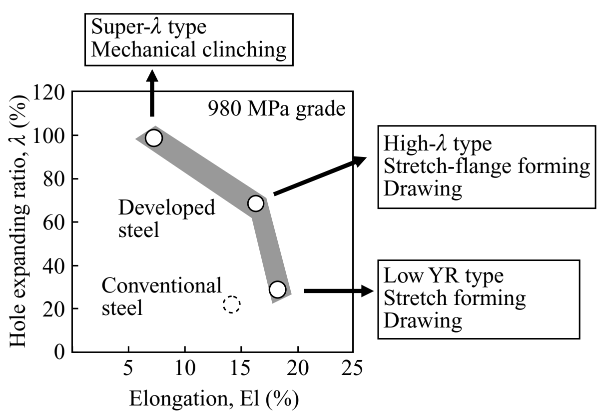

Fig. 3 Typical El(elongation)-λ balance of newly developed TS980 MPa grade ultra-high strength steels

4.2 TS1180 MPa Grade Cold Rolled Steel Sheet Suitable for Automobile Body Structural Parts

In response to the need for weight reduction in automobile body structural parts, JFE Steel developed a TS1180 MPa grade high strength cold rolled steel sheet with excellent press formability. As shown in **Table 3**, in comparison with the conventional TS1180 MPa grade high strength cold rolled steel sheet, elongation is increased by more than 1.5 times, and the newly-developed sheet shows El-λ equal to that of general TS980 MPa grade high tensile strength steel. Because the developed sheet

Table 3 Feature of mechanical properties of newly developed TS1180 MPa grade cold rolled steel compared with conventional one

	JFE Steel Standard	Thickness (mm)	Mechanical properties		
			YP (MPa)	TS (MPa)	El (%)
Newly developed	JFE-CA1180Y2	1.2	950	1 210	14
Conventional	JFE-CA1180SF	1.6	1 030	1 230	7

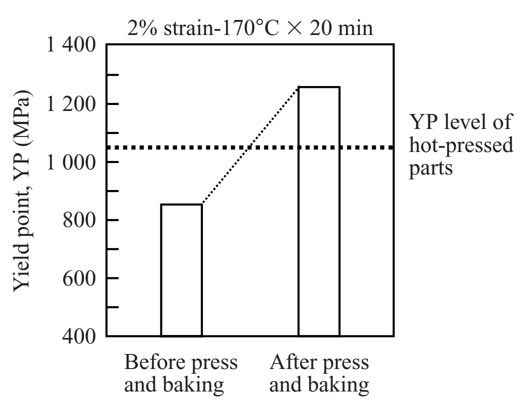

Fig. 4 Change of YP of newly developed TS1 180 MPa grade ultra-high strength steel

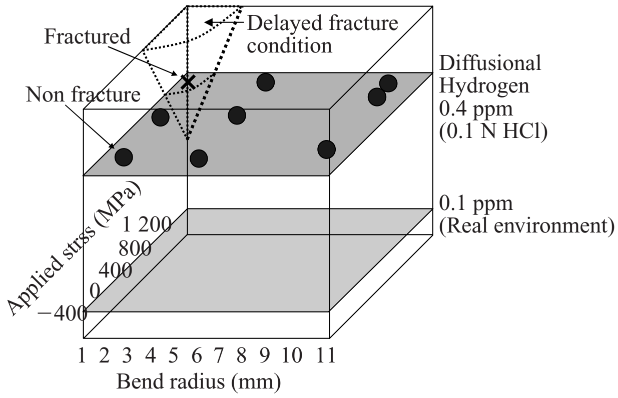

Fig. 5 Delayed fracture condition of the newly developed TS1 180 MPa grade ultra-high strength steel

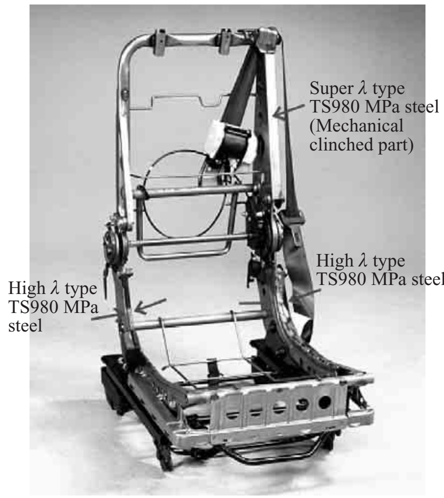

Photo 2 Automotive seat frame to which newly developed TS980 MPa grade steels were applied

Photo 3 Applied example for center pillar reinforcement of TS980 MPa steel (lor YR type) (Formed by the experimental stamping tools in JFE Steel)

displays high work hardening due to work strain during press forming and a large increase in strength due to bake treatment, the strength of manufactured parts is on the same level as that of hot press parts (**Fig. 4**), which means that it is possible to use these parts as a substitute for hot press parts.

In general, TS1180 MPa grade high strength cold rolled steel sheets are used in bumpers, reinforcing parts, and other parts which are produced mainly by bending forming, for example, by roll forming. However, because a higher order of press forming becomes necessary when these materials are applied to body structural parts around the cabin, the drawing property was a problem. JFE Steel developed a steel sheet which possesses a combination of high elongation and hole expansionability by control of the microstructure using its unique WQ-CAL, thereby realizing satisfactory press formability. Because adoption of the WQ-CAL method enables a low C_{eq} design, this sheet also has excellent delayed fracture characteristics and weldability. In addition to the material properties of the steel sheet itself, it is generally thought that work strain, load stress, and diffused hydrogen from the environment influence delayed fracture. **Figure 5** shows a delayed fracture danger region map for the developed 1 180 MPa grade steel. Under ordinary use conditions for pressed automotive parts, the developed steel is considered to have an adequate margin of safety with respect to delayed fracture.

5. Examples of Application of Developed Steels

An example in which the developed steels were applied as automotive seat frame parts is shown in **Photo 2**. In the back side frame, which is a distinctive feature of this seat, the extra-high λ type (Super λ type) TS980 MPa steel sheet was applied. In this part, a box structure is produced from one sheet by bending, followed by mechanical clinching. The high λ type TS980 MPa sheet is used in the cushion side frame parts.

Photo 3 shows the results when a center pillar outer part was press-formed with an experimental die using the newly-developed low YR, TS980 MPa steel sheet. This example shows that application to drawn parts with severe forming requirements is fully possible.

Because the newly-developed TS1180 MPa steel sheet has crashworthiness equal to that of hot press materials, application of cold-press forming to parts which were conventionally produced using a hot press is being studied.

6. Conclusions

This paper has described the features and examples of application of TS980 MPa and TS1180 MPa grade ultra-high strength cold rolled steel sheets with excellent formability, which contribute to weight reduction and improved crashworthiness in recently developed automobiles.

(1) The developed steels have outstanding properties and are available in a full product line with advantageous material properties suited to the particular part in which the material will be used, ensuring customer satisfaction.

(2) The newly-developed TS1180 MPa steel sheet has elongation more than 1.5 times higher than that of the conventional TS1180 MPa sheet, and also has elongation and hole-expansionability equal to those of general TS980 MPa sheets. Because this sheet displays high work-hardening due to work strain during press forming and a large increase in strength due to bake treatment, use as a substitute for hot press parts is possible.

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