Martensitic Steel Sheets of 1300 and 1500MPa Grades

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Super-high strength steel sheets of a strength exceeding 980 MPa have been used in reinforcement parts for automotive bumpers and door to meet strengthened collision safety standards and to decrease weight for the sake of emission reduction. A study has been conducted to improve the bending workability, resistance weldability, and delayed-fracture immunity required for the steel sheets used in parts produced through cold forming, such as bumper reinforcements. The study then led to the development of martensitic steel sheets of 1300 MPa and 1500 MPa grades. The newly developed steel has enabled the production of bumpers of 1300 MPa grade and 1500 MPa grade, the world's highest grades for cold worked bumper reinforcements, while also enabling 10 to 15% less weight compared with conventional bumper reinforcements.

Introduction

There has been a growing need for steel sheets and members of ultrahigh strength in satisfying stronger collision safety standards and the need for less weight for emission reduction purpose. Steel sheets of the ultrahigh strength level of more than 980 MPa are currently used to make reinforcement parts for automotive bumpers and doors.

This paper describes the martensitic steel sheets of 1300 and 1500 MPa grade, which have mainly been adopted in the use of the above applications.

1. Concept of steel sheet design

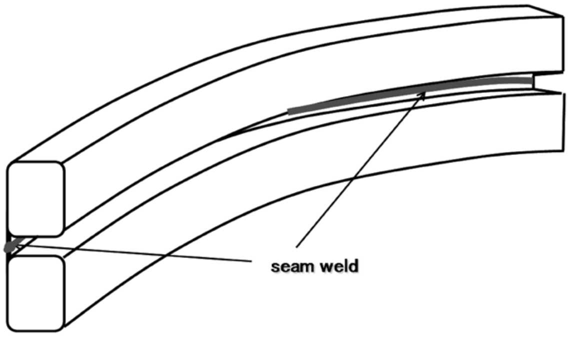


Fig. 1 Example of bumper reinforcements

Bumper reinforcements (hereinafter referred to as bumper R/F) represent the reinforcing parts attached to the front and rear of vehicles, which help absorb the impact in collisions. They typically have a hollow square cross section or B-shaped cross section as shown in **Fig. 1**. Steel sheet coils are cut to a specified length, pierced, roll formed or press formed, and then assembled into the final shape through seam welding or spot welding, etc.[1] In the case of roll forming, they are bent according to the shape of the front or rear side of the vehicle after the forming and seam welding processes. Steel sheets used in bumpers therefore require the following characteristics.

(1) Bending workability of the base material (roll formability)
(2) Resistance weldability (wide range of suitable current with seam welding and spot welding, strength of welded joints, and bending workability of seam welds)
(3) Delayed-fracture immunity (characteristics specifically required for high-strength steel)

1.1 Bending workability

In order to obtain excellent bending workability of the high strength of 1300 MPa and 1500 MPa grade martensitic steel, it is effective to form martensitic single phase structures, which provide uniformly high strength. However, martensitic structures as quenched can be brittle although of high strength, and therefore tempering is used to improve their ductility and toughness. Meanwhile, it is known that the bending workability is affected by the tempering temperature, and that it deteriorates in the tempering temperature range where so called low-temperature tempering embrittlement occurs.[2]

We therefore examined the effect of the tempering temperature on the tensile strength or bending workability (minimum bending radius) of 0.22% C martensitic steel sheets of 1.0 mm in thickness. **Fig. 2** shows the results. The results indicate that the same phenomenon occurs as described above, and that high strength and bending workability can be compatible in a tempering temperature range lower than that where the bending workability deteriorates.

1.2 Resistance weldability

High-tensile steel sheets have some problematic issues; that is, the suitable welding current range with spot welding (the current range after a specified nugget diameter is obtained until an expulsion,

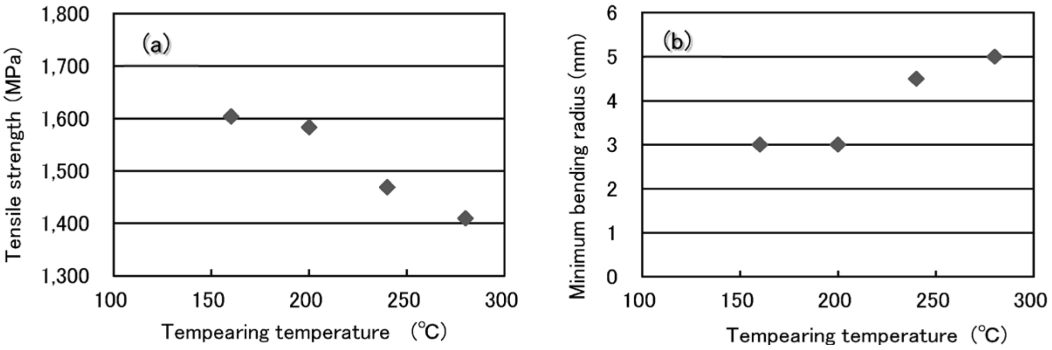


Fig. 2 Effect of tempering temperature on (a) tensile strength and (b) minimum bending radius

which is scattering of molten metal develops) decreases[3] and the cross tensile strength does not increase[4]. This phenomenon can also be observed in the same way with seam welding, which is another type of resistance welding. In order to expand the suitable welding current range, it is important to shift the expulsion development current to the high-current side, and it is effective to reduce the addition of the elements that increase the electric resistance of steel, including P, Si, Mn, etc.[5]

Table 1 Chemical composition of steels

(mass%)

C	Si	Mn	others
0.12〜0.26	tr〜1.4	0.5〜2.1	Ti,Nb,V,Cr,Mo,B,Cu,Ni

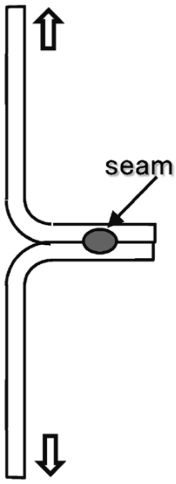


Fig. 3 Peel test of seam weld

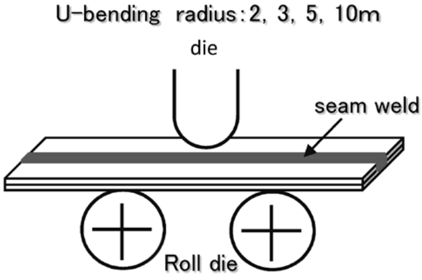


Fig. 4 Bending test of seam weld

The characteristics required in bumper R/Fs, which have a closed cross section manufactured by roll forming, include peel strength and bending workability of seam welds. The relationship between peel strength and bending workability of seam welds and the additive elements was therefore examined. Laboratory-melted steel with the chemical composition shown in **Table 1** was hot rolled, pickled, cold-rolled, and then heat treated in a salt bath to manufacture martensitic steel sheets of 1.2 mm in thickness. The heat treatment included being held at 900℃ for 90 seconds to austenitize, and being water quenched and then tempered at 200℃ for 360 seconds. The resulting steel sheets were then seam welded with two sheets overlapped, and the peel strength of the seam weld was measured using the test shown in **Fig. 3**. In addition, a U-bend test of the seam weld was conducted at a right angle to the weld line using dies of 2 mm, 3 mm, 5 mm, and 10 mm in tip radius, as shown in **Fig. 4**, thereby determining the minimum bending radius where no cracks were caused in the weld. The correlation between these measurements and the chemical composition was then determined using multiple regression analysis. **Fig. 5** shows the results of measuring the peel strength of seam welds and **Fig. 6** the results of measuring the minimum bending radius of seam welds in a correlation of Ceq1 and Ceq2, as determined by multiple regression analysis, respectively.

The peel strength of seam welds has a correlation of Ceq1=C+Mn/5+Si/13, thus indicating that it improves as Ceq1decreases. Meanwhile, the bendability of seam welds has a correlation of Ceq2=C+Mn/7.5, thus indicating that it improves as Ceq2 decreases.

1.3 Delayed-fracture immunity

It is well known that hydrogen embrittlement cracking tends to occur, i.e. the delayed fracture sensibility increases when the strength of steel is increased[6]. It is also agreed that the delayed-fracture immunity of steel sheets is affected not only by

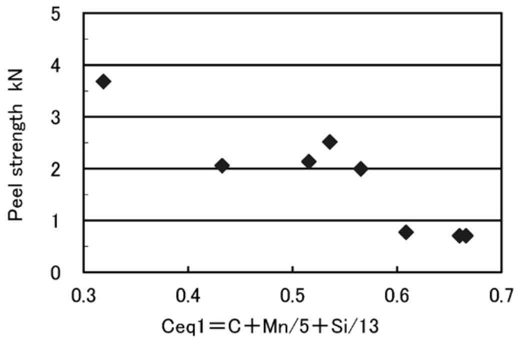


Fig. 5 Effect of chemical composition on peel strength of seam weld

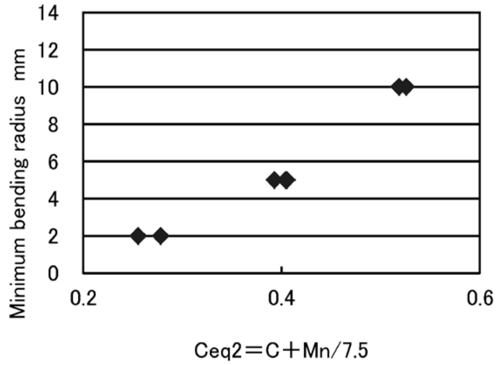


Fig. 6 Effect of chemical composition on minimum bending radius of seam weld

their strength but also their chemical composition, microstructure, etc. The delayed fracture of high-strength steel is a phenomenon wherein the hydrogen generated in connection with the corrosion reaction of the steel penetrates into it, and hydrogen embrittlement cracking of the steel occurs at a locally concentrated area in accordance with the tensile stress gradient. In other words, hydrogen embrittlement is understood to be a phenomenon caused by three different factors that are related to each other: (1) the penetrability of the hydrogen into the steel, (2) the diffusivity of the hydrogen in the steel, and (3) the hydrogen embrittlement sensibility of the structure of the steels.

Accordingly, effective measures to counteract each of the above factors involved in hydrogen embrittlement from the steel side to use include: (1) preventing the hydrogen from penetrating the steel by improving the corrosion resistance, (2) preventing the hydrogen from diffusing into the steel and concentrating in a tensile stress area by introducing trap sites, and (3) reducing the hydrogen embrittlement sensibility of steel itself through grain refining. The delayed-fracture immunity measures were used based on a laboratory examination conducted from the viewpoint as described above.

With martensitic structures it is known that not only the bendability but also the delayed-fracture immunity can be affected by the tempering temperature described above[7), 8)]. The results of the examination of this paper indicated that the delayed-fracture immunity also deteriorates within basically the same temperature range as the tempering temperature range in which the bending workability deteriorates, and that all the high strength, bending workability, and delayed-fracture immunity factors are compatible within a tempering temperature range lower than that temperature range.

Steel sheets typically get cut or pierced into a specified length or shape in being processed into a specific part. However, it is considered that delayed fractures tend to occur along the edge of such processed parts due to the very large plastic strain involved. This means that, of the three above described measures taken to counter delayed-fracture immunity, the measures to prevent the hydrogen from penetrating and diffusing into the steel are the most effective as the effect of the base metal structure control tends to be lost. Because of this an optimized composition design was adopted through selecting the applicable elements.

2. Characteristics of martensitic steel manufactured using an actual machine

The results of the laboratory examination were taken into account to manufacture 1300 MPa and 1500 MPa grade cold rolled steel sheets (thickness: 1.2 mm) using an actual machine. The qualities of appropriate bending workability, resistance weldability, and delayed-fracture immunity were taken into account in the design of the steel sheets, while also taking full advantage of the water quenching process that is a feature of Kobe Steel's continuous annealing line. **Fig. 7** shows a SEM image of the developed steel, and **Table 2** the mechanical properties. The bending workability included a 90° V-bend test and L-bend test (**Fig. 8**) in determining the minimum bending radius. **Table 3** shows the results. Both the 1300 and 1500 MPa grade steel sheets formed uniform martensitic single phase structures and featured favorable bending workability.

The spot weldability was evaluated through welding the test materials of 1.2 mm in thickness with a DR type electrode of 6 mm in tip diameter, a welding pressure of 4.1 kN, a welding time of 10 cycle/60 Hz, and welding current of 4 to 13 kA. **Fig. 9** shows the effect of the welding current on the tensile shear strength and cross tensile strength, respectively. **Table 4** shows the suitable welding current, and the nugget diameter, tensile shear strength, and cross tensile strength obtained within the range. The lower limit of the suitable welding

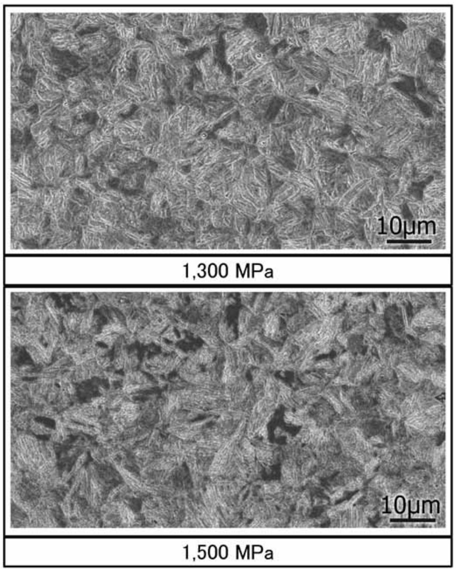
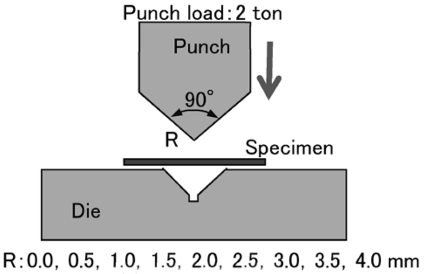


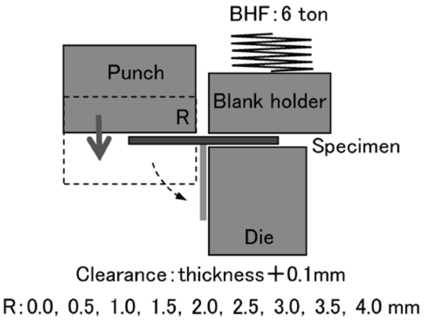
Fig. 7 SEM image of developed steels

Table 2 Typical mechanical properties of developed steels

Developped steel	YS (MPa)	TS (MPa)	EL (%)
1300 MPa	1,180	1,370	7
1500 MPa	1,280	1,570	6



(a) V-bend test



(b) L-bend test

Fig. 8 Experimental procedure of (a) V-bend test and (b) L-bend test

Table 3 Typical bendability of developed steels

Developped steel	90°V bend test Minimum bend radius		L bend test Minimum bend radius	
	Long.	Trans.	Long.	Trans.
1300 MPa	3.0	3.5	2.0	2.0
1500 MPa	3.5	4.5	2.5	3.5
DP980 MPa	1.0	2.0	1.0	1.5

Rmin: Minimum bend radius
Thickness: 1.2 mm

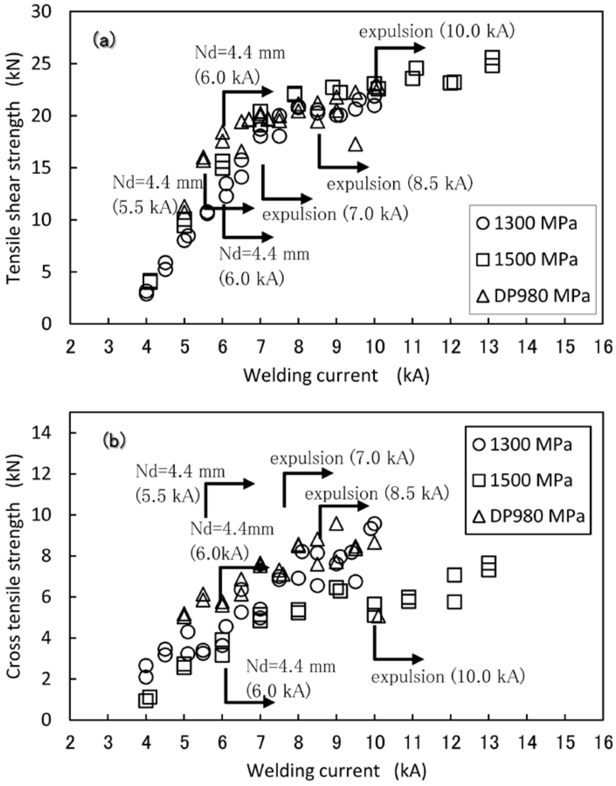


Fig. 9 Effect of welding current on (a) tensile shear strength and (b) cross tensile strength in developed steels

current range in this evaluation had the current value where the nugget diameter becomes equal to the minimum nugget diameter of 4.4 mm ($4\sqrt{t}$) in accordance with the requirements of JIS Z 3140, Class B. The list also includes results of evaluating high-ductility type DP steel sheets of 980 MPa grade.

The tensile shear strength of the 1300 and 1500 MPa grade steel sheets is almost the same as that of the 980 MPa grade steel sheets but the cross tensile strength tends to decrease in the order of the 980, 1300, and 1500 MPa grade steel sheets. The

Table 4 Suitable welding current for developed steels, and their nugget diameter, tensile shear strength and cross tensile strength

Developped steel	Suitable welding current (kA)	Nugget diameter (mm)	Tensile shear strength ($\times 10^3$N)	Cross tensile strength ($\times 10^3$N)
1300 MPa	6.0～8.5	4.4($4\sqrt{t}$)～7.0	12.0～21.0	4.0～8.0
1500 MPa	6.0～10.0	4.4($4\sqrt{t}$)～7.5	15.0～23.0	3.0～6.5
DP980 MPa	5.5～7.0	4.4($4\sqrt{t}$)～6.5	15.0～20.0	5.0～7.0

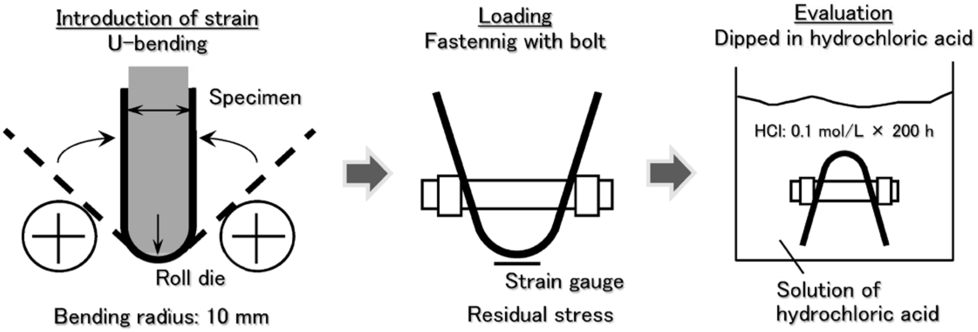


Fig.10 Experimental procedure of delayed-fracture immunity test

results agree with those of a study made by Oikawa, et al.[9], revealing that the tensile shear strength get saturated above 1,100 MPa and the cross tensile strength saturated around 590 to 780 MPa, with a decreasing tendency as the strength of the steel sheets increases in the case of the 780 MPa grade steel sheets.

The suitable welding current range is as wide as 2.5 kA for the 1300 MPa grade steel sheets and 4 kA for the 1500 MPa grade steel sheets, whereas it is 1.5 kA for the 980 MPa grade steel sheets. In addition, the nugget diameter obtained at the upper limit of the suitable welding current range is larger than that of the 980 MPa grade steel sheets. For this reason the cross tensile strength obtained at the upper limit of the suitable welding current range of the 1300 and 1500 MPa grade steel sheets is almost the same as that of the 980 MPa grade steel sheets. This then means that the practical weldability would appear to be almost the same as that of the 980 MPa grade steel sheets.

The delayed-fracture immunity was evaluated using a U-bend test (dipped in hydrochloric acid) as shown in **Fig.10**. To examine the crack initiation, strip test pieces were U-bent with a bend radius of 10 mm, and then dipped in 0.1 mol/L of hydrochloric acid for 200 hours, while loading stress of 1,300 MPa for the 1300 MPa grade steel sheets, and stress of 1,500 MPa for the 1500 MPa grade steel sheets. Note that strip test pieces are usually tested with their edges machined. However, some strip test pieces as shear cut and without their edges machined were also tested as generally steel sheet formed parts have cutting edges. The test results revealed that, both the 1300 and 1500 MPa grade steel sheets exhibited no cracks with both test pieces with the edge machined and as shear cut and without the edge machined, and thereby indicating that the delayed-fracture immunity is favorable.

The developed sheets make it possible to manufacture, by cold forming, bumpers from both 1300 and 1500 MPa grade steel sheets, the world's highest level of strength as a bumper R/F. Furthermore, they can be reduced by 10 to 15% of their weight when compared with conventional bumper R/F parts.

Conclusions

Kobe Steel commercialized 1180 MPa grade cold rolled sheet steels, and has already produced and distributed them for use in bumper R/Fs. In response to the need for further higher levels of strength, this paper has introduced the newly developed 1300 and 1500 MPa grade martensitic steel sheets. The developed steel sheets have been adopted by some customers for use in making roll formed bumper R/Fs, and have started to be produced commercially.

A constantly important issue in the automobile industry is satisfying both better collision safety and less weight. The requirement with automotive body use is the application of 980MPa, 1180 MPa, and 1470 MPa grade steel sheets. The even high level of strength of up to 1,700 MPa is a challenge that will be addressed in the future.

Kobe Steel will continue to strive to develop materials that can contribute to the needs of even higher level of strength and better workability.

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