Martensitic Steel Sheets of 1,700 MPa-Grade

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Abstract

The application of high-strength steel sheets to automotive parts is being considered to improve the collision safety of automobiles and reduce CO_2 emissions through weight reduction, and further strengthening is expected in parts that already use 1,470 MPa-grade steel sheets. The 1,700 MPa-grade steel sheet developed by Kobe Steel utilizes continuous annealing equipment with water quenching and has a martensite single-phase structure despite being a low alloy. This solves the application challenges associated with strengthening, such as bending workability, weldability, and delayed fracture resistance. One issue with water quenching is the deterioration of flatness due to thermal distortion during rapid cooling. This, however, has been improved by straightening with a powerful tension leveler, achieving flatness equal to or better than that of the 1,470 MPa-grade. This report introduces the concept of material design and the characteristics of steel sheets.

Introduction

High-strength steel sheets are seeing increasing use in automotive parts to improve collision safety and reduce emissions through weight reduction. Forming methods for automotive parts made of high-strength steel sheets include hot forming (e.g., hot stamping) and cold forming (e.g., press forming, roll forming). Roll-formed 1,470 MPa-grade high-strength steel sheet is used in components such as bumper reinforcements, cross members, and roof racks. This grade is also increasingly being used in press-formed parts such as A-pillars and car body parts that are more complex and require greater dimensional accuracy. Further, the need for steel sheets with even higher strength than 1,470 MPa is also now on the horizon.

To fulfill this projected demand for higher-strength components, Kobe Steel has developed a 1,700 MPa-grade martensitic steel. This steel uses a continuous annealing line with a water quenching system for rapid cooling. Further, it has the necessary workability, weldability, and delayed fracture resistance, which are the main issues in increasing strength. This paper introduces the design concept and main characteristics of the developed material. It also covers how we improved flatness, as this parameter affects the dimensional accuracy of parts, which is particularly crucial in car body applications.

1. Design concept of the developed steel

In roll-formed parts such as bumper reinforcements and roof racks, steel sheets are fed through multiple rolls to form the cross-sectional shape of the part through successive bending processes. As such, these steel sheets must exhibit bending workability. Delayed fracture due to residual stresses generated in the part during forming is also a concern. Therefore, it is necessary to design the material such that it has these characteristics on top of merely having a higher strength rating.

The proposed method of achieving these properties was to use a martensite single-phase microstructure that can achieve high strength with low alloying. The martensitic structure is formed by austenitizing the material via uniform heat treatment and then rapidly cooling it. Kobe Steel uses a continuous annealing furnace with a water quenching system. This inhibits the formation of soft microstructures such as ferrite and bainite during rapid cooling while precluding the need to add a high alloy content. This makes it possible to reduce elements with adverse effects in terms of weldability and delayed fracture, and it yields a composition with highly favorable properties. Details of the concept for achieving such properties are described next.

1.1 Strength

To protect vehicle occupants, parts such as bumper reinforcements must not undergo plastic deformation during a collision. As such, they must have a high yield strength as well as a tensile strength of at least 1,700 MPa.

Martensite structures are very hard because carbon is supersaturated in the interstitial sites of the solid solution.[1)] However, martensite exhibits low toughness and a low yield ratio in the as-quenched state.[2)] To ensure toughness and high yield strength, the developed steel was tempered at a relatively low temperature to achieve a tempered martensite single-phase structure.

1.2 Bend formability

The microstructural changes associated with tempering greatly influence bend formability, so appropriate processing is necessary. As the tempering temperature increases, the number density of needle-like cementite formations increases, reducing bending workability.[3] We therefore selected the temperature range for tempering so as not to deteriorate workability, thus achieving a design that ensures bending workability. Additionally, we adapted the steel composition to combat the issue that inclusions on the surface of the steel sheet act as stress concentration points during bending, which can initiate cracks and reduce bending workability.[4]

1.3 Delayed fracture

Delayed fracture, a phenomenon known to result from hydrogen embrittlement, occurs when a material subjected to tensile stress suddenly fails after some amount of time. The stages of delayed fracture are (1) hydrogen ingress, (2) hydrogen diffusion, (3) crack initiation, and (4) crack propagation.[5] We applied countermeasures against each of the stages from (1) to (4) to inhibit delayed fracture.

One countermeasure, designed to combat hydrogen ingress (stage 1), was to add elements that improve corrosion resistance[6] as implemented in a 1,470 MPa-grade steel sheet. To suppress hydrogen diffusion (stage 2), we increased the tempering temperature to form hydrogen traps created by carbides. And to suppress crack initiation and propagation (stages 3 and 4), we took measures to increase the formation of alloy carbides to inhibit grain growth and thus refine the crystalline grains. Laboratory studies confirmed the effects of these measures on delayed fracture resistance (**Table 1**).

We added alloying elements and adjusted manufacturing conditions to increase the tempered carbide in steels A and B and to refine the γ particle size in steels B and C. The delayed fracture resistance of the three steels was tested via the method shown in **Fig. 1** of U-bending, followed by immersion in hydrochloric acid.

Test specimens were steel strips with machined end faces and dimensions of 150 mm perpendicular to the rolling direction × 30 mm in the rolling direction. The strips were U-bent to a bending radius of 10 mm, with the bending ridge in the rolling direction. Stress was applied to each test specimen through a bolt such that multiplying Young's modulus by the amount of strain measured via strain gauge equals the specified stress. The specimens were immersed in 0.1N HCl for 200 hours and evaluated for fracture. Table 1 shows the results. Load stresses of 1,500 MPa and 2,000 MPa were applied to N=3 test samples for each condition. Those that did not exhibit fracture are indicated by ○, and those exhibited fracture are indicated by ×. Steel B has a finer original γ particle size than steel A and a higher carbide ratio than steel C. Delayed fracture occurred in steels A and C but not B, indicating that steel B has superior delayed fracture characteristics. These findings, which validate an improvement in delayed fracture resistance upon

Table 1 Effects of tempered carbide and grain refinement on delayed fracture resistance

Steel type	Corrosion resistance element	Tempered carbide	Prior gamma particle size	Thickness (mm)	TS (MPa)	Delayed fracture evaluation results	
						Bending radius：10R Applied stress：1,500 MPa	Bending radius：10R Applied stress：2,000 MPa
A	addition	increase	-	1.0	1,785	○×○	×××
B	addition	increase	fine	1.0	1,757	○○○	○○○
C	addition	-	fine	1.0	1,744	××○	-

○：No fracture　×：Fracture

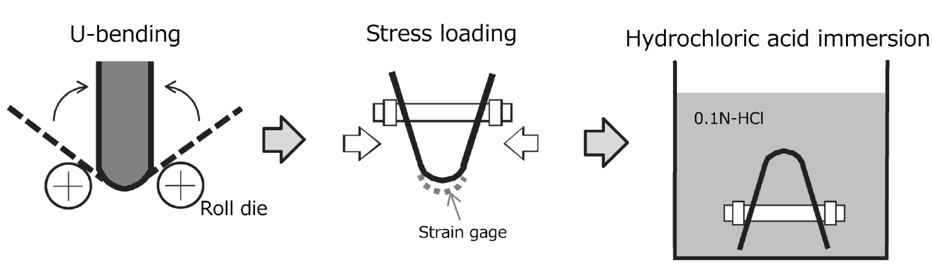


Fig. 1 Delayed fracture evaluation method using U-bending test pieces

increasing the tempered carbide ratio and refining the γ particle size, are reflected in the design of the developed steel.

2. Key properties of the developed steel

2.1 Mechanical properties and proper welding current range

Fig. 2 shows representative microstructures of the developed and conventional steels. The developed steel has a fine needle-like microstructure, indicating a uniform martensite single-phase microstructure. Further, the developed steel has a finer microstructure than the conventional steel, which testing confirmed as the superior microstructure in terms of delayed fracture resistance.

Table 2 shows a comparison of the mechanical properties of the developed and conventional steels.

We evaluated the tensile strength properties by preparing JIS No. 5 test pieces and performing tensile testing per JIS Z 2241. Stretch-flangeability was evaluated via the hole expanding test specified in JIS Z 2256, and bending workability via the 90° V-bend test specified in JIS Z 2248.

The specimens were bent with the bending edge in the rolling direction. The smallest bending radius at which the bent surface did not fracture was divided by the sheet thickness (R/t) to serve as an index of bendability.

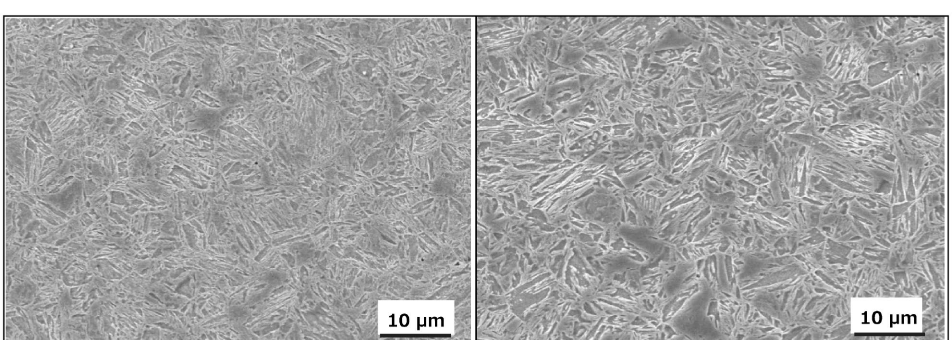
The developed steel has a high yield ratio, similar to the 1,470 MPa-grade steel. In addition to a tensile strength of at least 1,700 MPa, it also has a high yield strength, making it suitable for high-strength parts. The total elongation (El.), hole expandability (λ), and bending workability (R/t) are nearly the same as those of 1,470 MPa-grade steel, indicating that the application of the developed steel where 1,470 MPa-grade steel is used should be unproblematic in terms of formability.

Fig. 3 shows the appropriate welding current range. Spot weldability is a requirement for car body applications. As such, we performed spot welding using a 1.4 mm test sheet under the conditions in **Table 3** and evaluated the current range from the current at which the nugget diameter was $4\sqrt{t}$ (t: sheet thickness) to the current at which expulsion occurred. Although the expulsion limit current decreases with increasing strength, the developed steel has a wide current range of 7 to 10 kA. This is equivalent to the 1,470 MPa-grade steel, and it was confirmed that the same welding conditions could be used to ensure the specified nugget diameter.

2.2 Delayed fracture

Plastic strain and residual stress contribute to delayed fracture. As such, in automotive parts, there is concern about the occurrence of delayed fracture in cut edges machined during blanking and in formed parts, where a high degree of plastic strain is introduced. To confirm the resistance of the developed steel to delayed fracture in these locations, we applied U-bending and shearing processes to test samples to simulate the production of an automotive part.

Test specimens for testing U-bent parts were steel strips with machined end faces and dimensions of 150 mm perpendicular to the rolling direction × 30 mm in the rolling direction. The strips were U-bent



Developed steel (1,700 MPa-grade) | Conventional steel (1,470 MPa-grade)

Fig. 2 Microstructure of developed steel and conventional steel

Table 2 Mechanical properties of developed and conventional steels

	YS(MPa)	TS(MPa)	El.(%)	λ (%)	R/t
1,700 MPa-grade (Developed steel)	1,503	1,768	6	39	3.6
1,470 MPa-grade (Conventional steel)	1,332	1,544	6	47	3.5

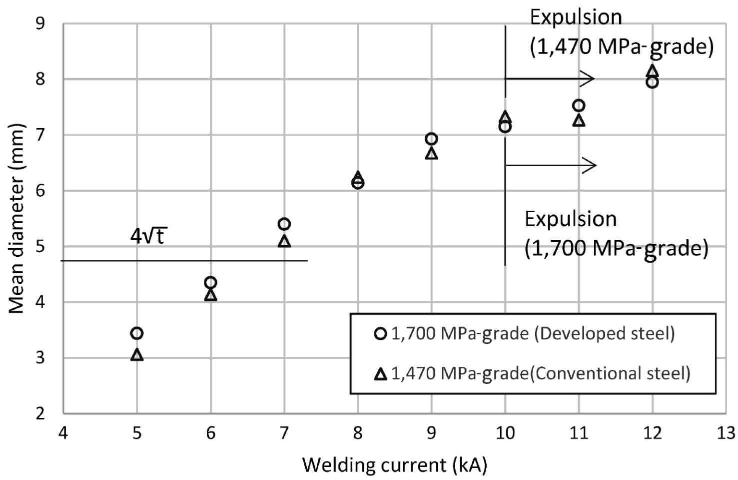


Fig. 3 Relationship between welding current and nugget diameter

Table 3 Spot welding condition

Electrode tip	1%Cr-Cu dome radius type
Tip diameter	6 mm
Electrode force	5.0 kN
Welding time	18 cycles/60Hz
Squeeze time	60 cycles/60Hz
Hold time	1 cycle/60Hz
Welding current	5-12 kA

Table 4 Delayed fracture test results for U-bending part

Steel	Grade	TS (MPa)	Thickness (mm)	Applied stress (MPa)	Evaluation results
Developed steel	1,700 MPa	1,798	1.2	1,700	○○○
Conventional steel	1,470 MPa	1,488	1.4	1,500	○○○

○ : No fracture × : Fracture

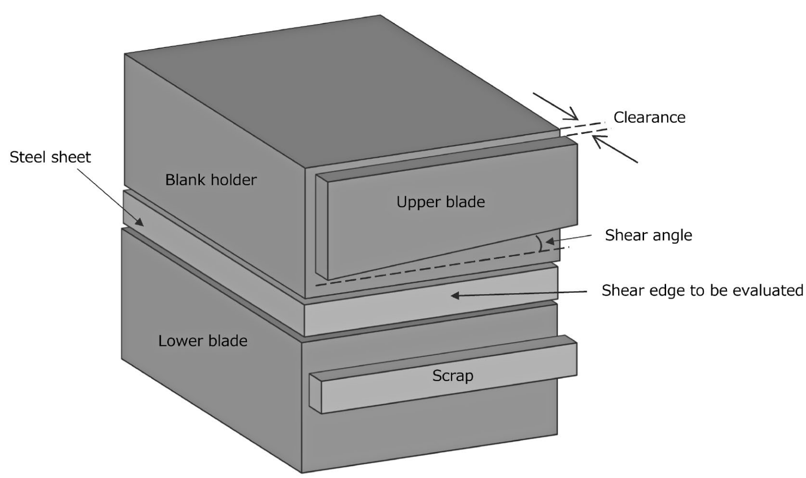


Fig. 4 Schematic diagram of shear processing

to a bending radius of 5 mm, with the bending ridge in the rolling direction. Stress was applied to each test specimen through a bolt such that multiplying Young's modulus by the amount of strain measured via strain gauge equals the specified stress. The specimens were immersed in 0.1N HCl for 300 hours and evaluated for fracture. **Table 4** shows the results; no fracture occurred at a stress of 1,700 MPa, or when strain was applied beyond the elastic limit.

The test specimens for evaluating the delayed fracture resistance of sheared ends were sheared to 15 mm × 30 mm, with the longitudinal direction perpendicular to the rolling direction. The test pieces were immersed in 0.1 N HCl for 24 hours, after which the end faces were inspected for fracture via visual inspection or a microscope. **Fig. 4** depicts the shearing setup. To evaluate the end face perpendicular to the rolling direction, we examined the end of the steel sheet sandwiched between the lower blade and the blank holder after cutting. The shear angle was 0°, and clearances were 5, 10, 15, 20, and 25%. **Table 5** shows the evaluation results. Three tests were performed for each condition. No fractures were observed under any of the conditions, confirming that the specimens had good resistance to delayed fracture.

Table 5 Delayed fracture evaluation results for sheared ends

Steel	Grade	TS (MPa)	Thickness (mm)	Evaluation results				
				CL=5%	CL=10%	CL=15%	CL=20%	CL=25%
Developed steel	1,700 MPa	1,755	1.0	○○○	○○○	○○○	○○○	○○○

○：No fracture ×：Fracture

3. Improving the flatness of steel sheets

Water quenching reduces the flatness of martensitic steels due to the thermal strain caused by rapid cooling. Flatness is an issue with car body parts such as pillars, which must exhibit high dimensional accuracy. As such, we cover Kobe Steel's flatness correction method at the end of this paper.

Kobe Steel has introduced a tension leveler with high correcting capacity that can correct the poor flatness of high-strength steel sheets after annealing. We have already established correction technology that ensures both favorable material properties and good flatness in 1,470 MPa-grade martensitic steel sheets for car body parts, which require exceptional dimensional accuracy. Since it is anticipated that 1,700 MPa-grade steel sheets will also be used for car body parts, the correction technology developed for 1,470 MPa-grade steel was applied to 1,700 MPa-grade steel to improve flatness. **Figs. 5** and **6** depict the change in flatness and appearance after correction using the tension leveler. The maximum warpage height of a steel sheet, cut to a length of 500 mm in the rolling direction, when placed on a flat surface, was used as a flatness index.

The results confirm that shape correction using the tension leveler reduced the warpage height and achieved good flatness. The flatness of our developed steel and the 1,470 MPa-grade steel is approximately equal in the longitudinal direction. Furthermore, water quenching causes deformation and large residual stresses in the sheet surface. This residual stress causes a high degree of deformation when blanks are cut from the coil. We confirmed that this residual stress can be sufficiently reduced through correction via a tension leveler. Further, the 1,700 MPa-grade steel developed is characterized by low deformation when cut.

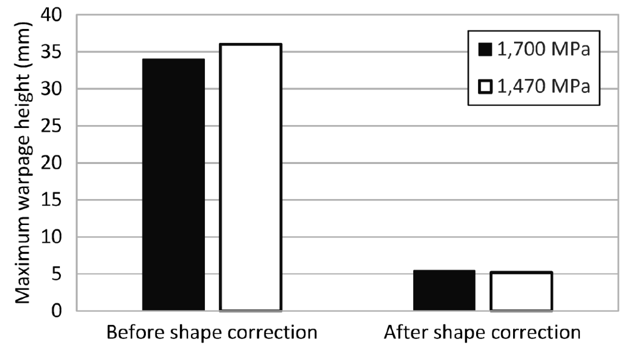


Fig. 5 Flatness measurement results

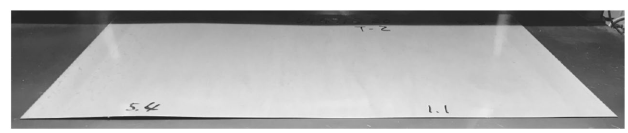


Fig. 6 Appearance of steel sheet after shape correction

Conclusions

Kobe Steel has developed a 1,700 MPa-grade martensitic steel to meet the need for even higher strength in demanding applications. This paper introduces the composition, microstructure control concept, main properties, and flatness correction method of this new steel. This steel features excellent bend formability, delayed fracture resistance, and flatness after shape correction.

Kobe Steel will continue developing materials that meet the expanding needs of car body applications, including demands for even higher strength.

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