Characteristics of 1180MPa Grade Cold-rolled Steel Sheets with Excellent Formability

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High-strength steel sheets are being used in recent years to improve crashworthiness and to decrease weight in order to reduce automobile emissions. Higher strength is desired particularly for automotive body frame members. In response to this demand, Kobe Steel has developed a 1180 MPa grade cold-rolled steel sheet with excellent formability. This paper introduces the guidelines for the microstructural control and typical characteristics of the steel sheet. The newly developed steel exhibits favorable practical characteristics of delayed-fracture resistance, spot weldability and conversion treatability, in addition to excellent strength and formability.

Introduction

High-strength steel sheets are being used in recent years to improve crashworthiness and to decrease weight in order to reduce automobile emissions.[1), 2)] Against this backdrop, Kobe Steel has been offering cold-rolled/galvanized steel sheets with their processabilities optimized for the shapes of parts,[3)-6)] and these sheets have been highly valued by customers.

Meanwhile, in the case of automotive body frame members, even higher strength is being pursued to protect passengers against collision. For example, a formability equivalent to that of low strength steel sheet is required for application to the complex shape parts typified by B-pillars. The formability of steel sheets, however, tends to decline with increasing strength in general, making it difficult to apply high-strength steel sheets of 1180 MPa grade or higher to complex shape parts.

To solve this problem, Kobe Steel conducted a study on high-strength steel sheets with excellent elongation (hereinafter referred to as "EL") and developed an 1180 MPa grade high-strength steel sheet with excellent formability to be used in automotive body frames. This was a world first.[7)] The steel sheet has an excellent EL approximately twice that of a conventional dual phase (DP) steel sheet. This paper introduces the concept of microstructure control for the newly developed steel and its main characteristics.

1. Concept of microstructure control for newly developed steel

The newly developed steel is used in high-strength sheets intended for application to complex shape parts and combines strength and excellent press formability. To suppress cracks during press forming, the hole expansion ratio (λ), an index of stretch-flangeability, is an important factor in addition to EL. It is generally difficult, however, to achieve both EL and λ together.

For the improvement of formability, it is known to be effective to add alloying elements such as C and Si. On the other hand, the addition of these alloying elements deteriorates the joint strength of spot welding[8)] and chemical conversion treatability,[9)] both being important practical properties of auto parts. In addition, the sensitivity to delayed fracture is increased in the case of high-strength steel sheet.[10)] Hence, it is also important to secure resistance against delayed fracture. To this end, various microstructure control measures have been developed to realize a steel sheet combining high strength, excellent formability and other practical properties.

Fig. 1 shows the mechanical properties of typical high-strength steel sheets of Kobe Steel. The company has established the production technology of high-strength steel sheets for cold working, including DP steel sheets,[2), 4), 11)] TRIP-aided bainitic ferrite (TBF) steel sheets[12)-14)] and martensite steel sheets.[15)] The newly developed steel exploits

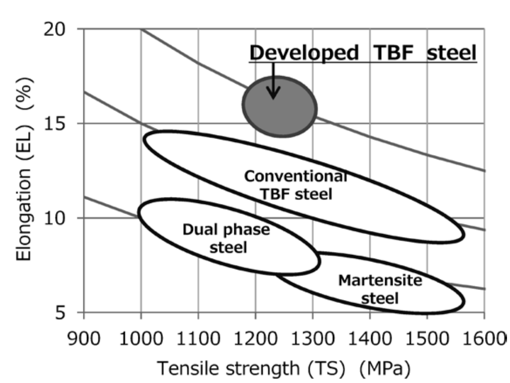

Fig. 1 Tensile strength and elongation of cold rolled steel sheets

the microstructure control technology for the conventional steel and, at the same time, applies the following microstructure control based on a further study on measures for improving the mechanical properties:

1) increasing the volume fraction of retained austenite by adjusting the additive amounts of the alloying elements (C and Si) and utilizing bainite transformation;
2) introducing martensite and refining retained austenite utilizing the transformation into martensite; and
3) introducing ferrite to provide a composite structure of soft and hard phases.

Examples of the microstructures of the newly developed steel and conventional TBF steel sheet are shown in **Fig. 2**. The newly developed steel includes ferrite existing in the matrix, which consists of bainite and martensite, and contains finely dispersed retained austenite. The newly developed steel has an excellent uniform deformability, thanks to the transformation induced plasticity (hereinafter referred to as "TRIP")[16] of retained austenite and the introduction of soft ferrite phase. In addition, the matrix consisting of bainite and martensite realizes high strength. Furthermore, the finely dispersed retained austenite reduces the void formation at the hard/soft interface between a very hard martensite, formed by the transformation of the retained austenite during deformation, and a soft phase,[12] suppressing the deterioration of the local deformability represented by the hole expansion ratio λ.

The typical mechanical properties of the newly developed steel are compared with those of the DP steel sheets (980 MPa grade and 1180 MPa grade) in

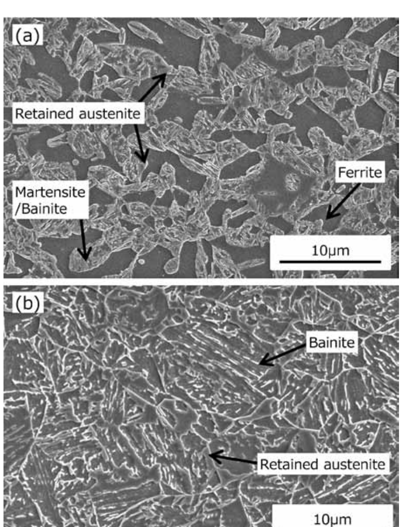

Fig. 2 Microstructure of (a) developed TBF steel, (b) conventional TBF steel

Table 1 Mechanical properties of developed TBF steel and dual phase steels

Steel	Grade	YP (MPa)	TS (MPa)	EL (%)	λ-value (%)
Developed TBF steel	1180MPa	946	1,222	18	40
Dual Phase steel	1180MPa	910	1,185	10	51
Dual Phase steel	980MPa	640	1,020	17	25

※Specimen Thickness : 1.4mm
※Tensile Test : JIS Z 2241 (JIS Z 2201 #5 Specimen in Transverse directions)
※Stretch flanging (Hole expanding) test
Hole expanding ratio : λ-value obtained by method of JIS Z 2256

Table 1. The newly developed steel has very well balanced properties of TS, EL and λ, thanks to the improved uniform deformability and the suppressed deterioration of local deformability.

2. Main properties of newly developed steel

2.1 Formability

The press forming of thin steel sheets is roughly classified into 4 modes, namely, stretch flanging, bending, stretching and deep drawing. The λ value, which is the index of stretch-flangeability, is as described above. The following describes the results of a study on the bendability, stretchability and deep drawability of the newly developed steel.

Fig. 3 shows the typical properties of the minimum bending radius (R) of the 90° V-bending test conducted on the newly developed steel sheet, 980 MPa grade steel sheet and 1180 MPa grade DP steel sheet. In the bending test, a specimen (100×40 mm) was placed on a die such that the bending direction was vertical to the rolling direction, and a 90° punch with a tip radius (R) of 0 to 5.0 mm was pressed on the specimen. The minimum bending radius for no crack occurrence was taken as the index. Due to its high strength, the developed steel exhibits a bendability lower than that of the 980 MPa grade DP steel sheet; however, its bendability is equivalent to that of the 1180 MPa grade DP steel sheet. The finely dispersed retained austenite is considered to have suppressed the local concentration of strain, inhibiting the occurrence of voids, the origin points of cracks.

Fig. 4 shows the typical stretch formability of

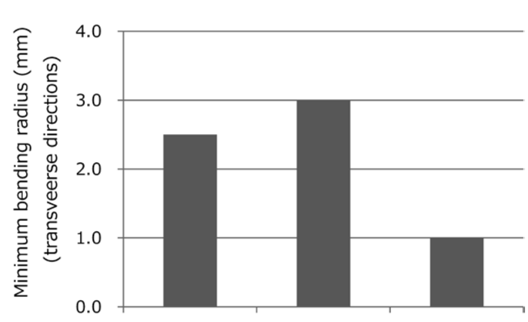

Fig. 3 Bendability of developed TBF steel and dual phase steels

the newly developed steel sheet, 980 MPa grade DP steel sheet and 1180 MPa grade DP steel sheet. The specimens were held with a blank holder force of 196 kN and formed with the die into the blank shape shown in **Fig. 5**. The stretch formability was evaluated by the maximum forming height of the stretch deformation with suppressed blank influx from the flange. The newly developed steel exhibits a maximum forming height equivalent to that of 980 MPa grade DP steel sheet, which is an effect of the improved EL achieved by the microstructure control described above.

Fig. 6 shows the typical properties of deep drawability for the newly developed steel sheet, 980 MPa grade DP steel sheet and 1180 MPa grade DP steel sheet. The specimens were held with a blank holder force of 196kN and formed with the die into the blank shape shown in **Fig. 7**. The deep drawability was evaluated by the maximum forming height of deep drawing deformation accompanying blank influx from the flange. The newly developed steel shows a maximum forming height superior to that of the 980 MPa grade DP steel sheet. This is considered to be attributable to the excellent deep drawability achieved by the strain-induced transformation of retained austenite.

Fig. 8 shows a forming limit diagram (FLD), comparing the newly developed steel with 980 MPa grade DP steel sheet having a thickness of 1.4 mm. The newly developed steel shows a forming limit equivalent to that of the low strength 980 MPa grade DP steel sheet, demonstrating its excellent press formability.

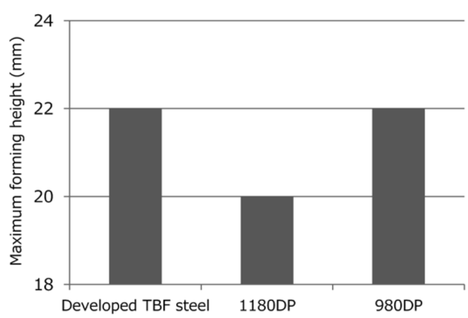

Fig. 4 Stretch formability of developed TBF steel and dual phase steels

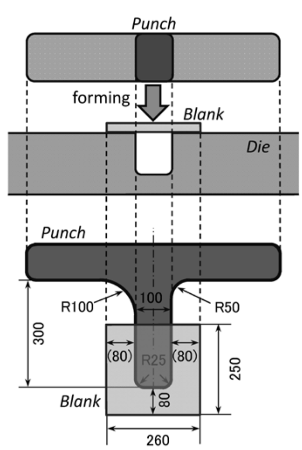

Fig. 5 Schematic illustration of measurement apparatus for stretch formability

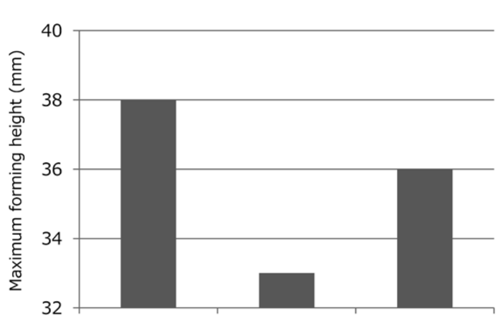

Fig. 6 Deep drawing formability of developed TBF steel and dual phase steels

2.2 Delayed-fracture resistance

The delayed-fracture resistance was evaluated by the occurrence of cracks on the specimens, stressed by U bending and bolt tightening and immersed in hydrochloric acid (**Fig. 9**). The results are shown

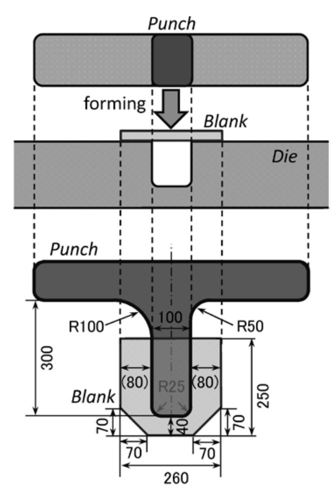

Fig. 7 Schematic illustration of measurement apparatus for deep drawing formability

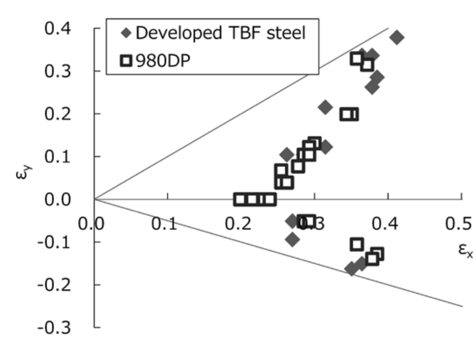

Fig. 8 Forming limit diagram of developed TBF steel and dual phase steel

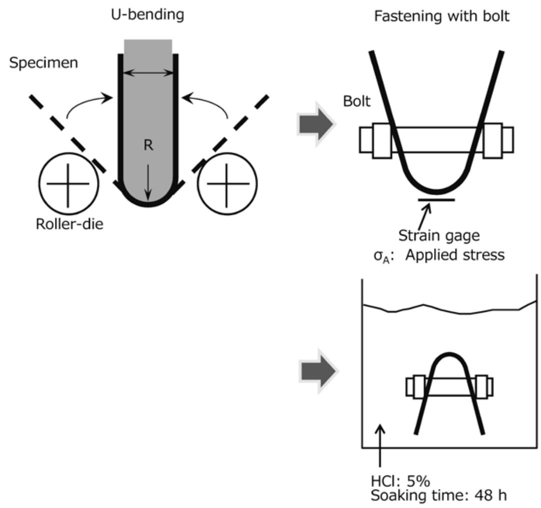

Fig. 9 Test procedure of delayed fracture resistance

Table 2 Delayed fracture properties of newly developed steel

Steel	Applied stress (MPa)	Bending radius 5 mm	Bending radius 10 mm
Developed TBF steel	1,000	○	○
	1,500	○	○
	2,000	○	○

○:No fracture、×:Fracture

in **Table 2**. In the newly developed steel, no crack occurred even in the most severe test condition and exhibited excellent delayed fracture resistance. The retained austenite, finely dispersed in the newly developed steel, is considered to have occluded hydrogen, suppressing the crack generation due to hydrogen.[17)]

2.3 Spot weldability

In general, the steel sheets utilizing retained austenite require higher compositions compared with DP steel sheets, making welding nuggets harder and an interfacial fracture more likely to occur. This tendency is more remarkable especially when the nugget diameter is small, which decreases the weld joint strength. Although high electric current is effective in increasing the nugget diameter, expulsion (i.e., scattering of molten metal) becomes inevitable in the case of high composition steel, making it difficult to secure a proper current range to yield stable and favorable weld joint strength. The newly developed steel has been designed to have as low a composition, as possible, to secure weldability. In addition, a further study was conducted on the welding conditions for suppressing expulsion. In this study, a low current is energized in the first stage of two stage energization to mitigate the volume expansion of molten metal associated with the rapid rise in temperature that occurs upon the energization of high current and thus to suppress the expulsion.

As for the weld joint strength, steel sheets having a thickness of 1.2 mm were welded to evaluate tensile shear strength (TSS) and cross tensile strength (CTS). **Fig.10** shows the relationship between the welding current and TSS, while **Fig.11** shows the relationship between the welding current and CTS. In the case of the newly developed steel, the TSS satisfies the specified load of 8.78kN (JIS Z 3140 A-class) at the welding current of 5.0 kA or higher, enabling a wide appropriate range of 3.5 kA or higher to be secured for the current up to expulsion. In the cross tensile test, it was difficult to secure sufficient joint strength due to the small nugget diameter resulting from the low current condition, which caused interfacial fracture. On the other hand, increasing the welding current to expand the nugget diameter improved the fracture mode to a plug shape, which resulted in a favorable CTS. It was also possible to secure an appropriate current range of 1.5 kA or higher, indicating that a favorable welded joint can stably be formed.

2.4 Chemical conversion treatability

Fig.12 shows an example of chemical conversion treatability; phosphate coatings on the surfaces of the newly developed steel and mild steel sheet.

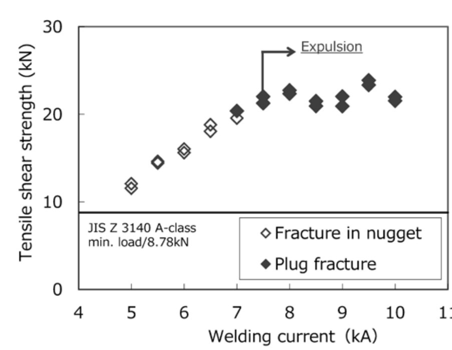

Fig.10 Relationship between tensile shear strength of spot welded joints and welding current

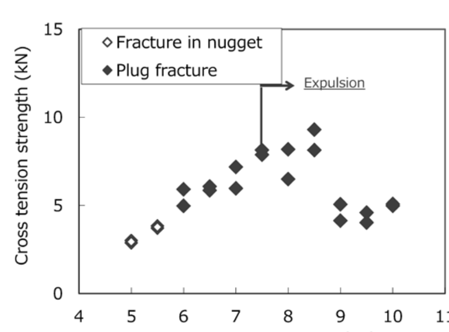

Fig.11 Relationship between cross tension strength of spot welded joints and welding current

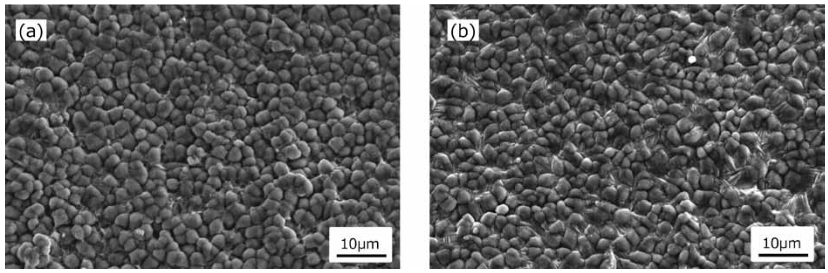

Fig.12 SEM image of phosphate coating on a) developed TBF steel, b) conventional mild steel

These coatings were formed by immersing respective sample steel sheets into a phosphate-treating agent, PALBOND-L3065, manufactured by Nihon Parkerizing Co., Ltd. Although the chemical conversion treatability generally declines as the amount of added Si increases, the newly developed steel exhibits no lack of hiding (poor formation of phosphate crystals). The grain size and forms of crystals are equivalent to those of mild steel, indicating favorable chemical conversion treatability. This is the result of applying the improvement of the practical characteristics and the improvement of the production technologies of high-Si steel sheets, accumulated through Kobe Steel's research over many years.[18)]

Conclusions

This paper has introduced the concept of microstructure control and the main characteristics of the newly developed 1180 MPa grade cold-rolled steel sheet with excellent formability. The newly developed steel not only has favorable strength and formability but also exhibits excellent delayed fracture resistance and chemical conversion treatability, enabling the stable formation of spot welds having sufficient joint strength.

Kobe Steel positions the newly developed steel as a high formability product in its cold-rolled high-strength steel sheet menu. In addition to the high-λ-type TBF steel sheet, the company also has a lineup including ultra-high-strength martensite steel.

Meanwhile, high-strength steel sheets will continue to be applied to automotive frames, and customers' needs for the material properties are expected to become even more stringent. Against this backdrop, Kobe Steel will strive to contribute to body weight reduction and collision safety improvement by exploiting the technologies accumulated so far, including the 1180 MPa grade cold rolled steel sheet with excellent formability introduced in this paper, to further improve the formability and practical properties of steel sheets.

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