The Development of New High-strength Steel Sheets for Automobiles

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Improvement of fuel economy, crash worthiness and passenger safety are gaining increasing attention in the automobile industry. Kobe Steel has developed and has continued to produce a variety of high strength steels for automobiles including 590MPa class, dual-phase hot dip galvannealed steel and hot & cold rolled TRIP-aided steel. This article introduces some of our new products including a very ductile 980MPa class hot dip galvannealed steel and an ultra-high strength, cold rolled, steel with excellent delayed fracture resistance.

Introduction

Environmental concerns are growing year by year, forcing automobile manufacturers to reduce automotive body weights for higher fuel economy and lower CO_2 gas emission. In addition, regulations to protect passengers from collisions have become stricter, making automobile manufacturers develop lighter and safer bodies. High tensile strength steels (Hi-Tens) are effective in reducing the thicknesses and weights of automotive components and in increasing the strengths of parts. Their applications and uses are increasing, and Hi-Tens having even higher strengths are being developed.

We have focused on the development of Hi-Tens for automobiles since the late 1970s and have developed a 980MPa class, cold-rolled, complex steel with high ductility.[1)-4)] More recently we have developed several Hi-Tens with strengths higher than 590 MPa, which have won a high reputation from customers. Needs for Hi-Tens are diversifying with an expanding application field, and it is our priority to develop characteristic Hi-Ten products in response to those specific needs. This article introduces several Hi-Ten products which have been developed based on our own technological concepts.

1. Development of microstructure controlled Hi-Ten

The purpose of developing a Hi-Ten is to produce a steel having both high strength and good formability simultaneously. Hi-Tens with complex structures have a good balance of strengths and elongations and comprise the mainstream of steels having strengths higher than 590 MPa.

We have established the basic technologies of Hi-Tens with the development of a 980MPa class, cold-rolled, complex steel with high ductility described previously. The core technology is a dual phase microstructure in which hard martensitic phase is finely dispersed in soft ferritic matrix. We succeeded in controlling the volume fraction of phases, to stabilize the structure by rapid cooling, and to control hardness of the hard second phase by utilizing the heat cycle of our own continuous annealing line. Our complex Hi-Tens are produced based on this microstructure control technology. Lately we have commercialized 590-980MPa class, cold-rolled, complex steel sheets and 590-980MPa class, galvannealed alloy steel (GA) sheets.[5)-7)] **Figure 1** shows the automobile parts to which Hi-Tens are commonly applied. The parts include side members, pillars and cross members.

The application field of Hi-Ten is expanding widely and the requirements for the materials' formability are becoming stronger. Especially forming of seat-members, which are becoming stronger recently, requires not only the conventional strength-elongation properties, but also the stretch flangeability. In response to this requirement, we have developed a 980MPa class, cold-rolled steel sheet having high strength-elongation properties along with a good stretch flangeability. More advanced microstructure control technologies have been developed to improve the stretch flangeability. The ferritic phase was retained at the same level as conventional steel to retain elongation, and solid-solution strengthening elements were added to the ferritic phase. The annealing temperature of the

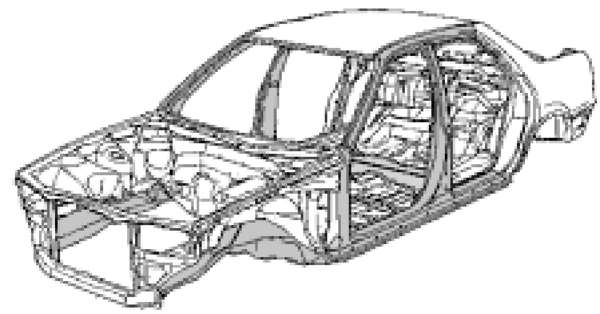

Fig. 1 Application of high strength steel sheet for body in white

martensitic phase was revised so that the difference in hardness between the ferritic and martensitic phases became smaller, which improved formability. **Figure 2** shows the elongations and stretch flangeabilities (λ value) of several steels. The steel developed by the method described above has a higher balance of elongation and stretch flangeability.

Various properties other than strength and formability are required to expand the application of High-Tens. Above all weldability is one of the most important characteristics. Generally, alloying elements added in large amounts to strengthen steel tend to deteriorate weldability. We have developed alloying compositions with lower carbon content, which increase strength without sacrificing weldability. These compositions were utilized in the development and commercialization of low C 780, 980MPa class, cold-rolled and GA sheets with high weldability.[8)]

Retained austenite is effective when high elongation is required. The transformation induced plasticity (TRIP) of retained austenitic phase increases elongation significantly, however, it decreases stretch flangeability. The cause of the decrease in stretch flangeability is explained as follows. The microstructure of conventional retained austenitic steel has both polygonal ferritic phase and blocky austenitic phase on grain boundaries. The structure tends to cause voids at the interface between the phases due to stress concentrations which occur when the material is worked after transformation of the austenitic phase into hard martensitic phase. On the other hand, fine austenitic phase can be dispersed homogeneously in ferritic grains when the structure before annealing is martensitic.[9)-11)] We have established a process to obtain this structure by forming martensitic phases during hot rolling and by annealing the structure directly. This process enabled the development of a steel sheet having both high elongation and stretch flangeability. The high flangeability is thought to be achieved by the fine dispersion of austenitic phase, which reduces formation of voids at the ferritic interface at the time of forming.[12)]

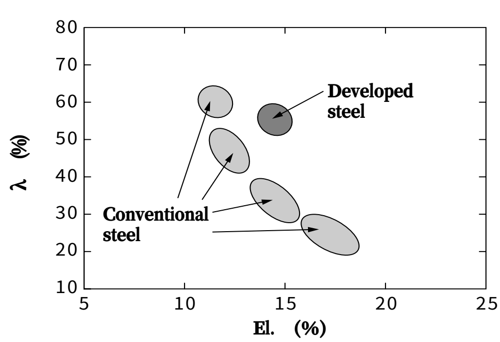

Fig. 2 Elongation and λ value combination of 980MPa grade cold rolled steel

The latest development of our structure controlled Hi-Ten has been described. A variety of quality design and production technologies have been utilized for the development of our Hi-Tens. The technologies which have been accumulated and improved during our long history of Hi-Ten development include development, control, evaluation and production of microstructures that assure good formability, including elongation and flangeability.

The following introduces our 980MPa class, galvannealed, alloy steel sheet and our ultra-high strength, cold rolled, steel sheet with sub-micron structure.

1.1 980MPa class galvannealed alloy steel sheet

1.1.1 Quality design approach

We have developed low yield-ratio galvannealed alloy steel sheets including 590MPa class and 780MPa class GA steel sheets. The basic concept of the alloy design was to obtain ferrite + martensite complex structure with low alloying element concentrations to ensure formability and weldability. The same concept is applied to the design of 980MPa class alloys.

The design concept of increasing strength while retaining elongation is as follows:

1) Mn is an effective solid-solution strengthening element; however, its addition should be minimized to retain ductility of ferritic phase.
2) Cr and Mo increase quench hardenability and are effective in increasing the volume fraction of martensitic phase. C is effective in hardening the martensitic phase. However, excessive additions of those elements cause deterioration of ductility and weldability. The total addition of those elements should be restricted to the minimum quantity that gives sufficient strength.

Table 1 shows an example of the chemical composition of an alloy developed on the basis of

Table 1 Chemical compositions of 980MPa grade hot dip galvannealed steel

(mass%)

Steel	TS grade	C	Si	Mn	P	Other element
Developed steel	980 MPa	0.14	0.01	2.30	0.007	Cr, Mo
Conventional steel	780 MPa	0.11	0.01	2.00	0.007	Cr, Mo

this design concept. The steel sheets of this alloy are currently produced in volume with stable properties.

1.1.2 Formability

Table 2 shows comparison of mechanical properties between the developed steel and conventional steels. The developed steel has a high elongation, and other properties comparable to conventional cold-rolled steel. **Figure 3** shows a forming limit diagram. The developed steel shows value comparable to that of cold-rolled steels and has a good formability.

1.1.3 Spot-weldability

Weldability of the developed steel is compared to that of the conventional cold-rolled steel. Sheet samples with 1.4 mm thickness were welded under conditions shown in **Table 3**. **Figure 4** shows the relation between the tensile shear strength and button diameter of the welding joint measured after fracture. The critical diameter for button fracture is higher for the developed steel compared to the cold-rolled steel. **Figure 5** shows cross-tension strengths. The developed steel retains high strengths from the low current region and shows button fractures up to high current region without showing fracture within nugget. The strength increases with increasing current, with small scatter, until expulsion. The developed steel has a wider range of current between button fracture and expulsion compared to the conventional cold rolled steel. This is considered to be due to the alloy design which minimizes the amount of alloying element for strengthening.

1.1.4 Dynamic strength characteristic

Crash test specimens were prepared by bending strips of sheet into hat shaped cross-section. **Figure 6** shows the cross section of the specimens. The hit point interval of spot welding was 50 mm. The axial lengths of the specimens were 300 mm for axial crash test and 1,000 mm for three point bend crash test. A plumb bob was dropped on specimens from a constant height under conditions shown in **Table 4**. The crash load was measured by a load cell placed under the specimen and the displacement was measured by a laser displacement gauge. Absorbed energies up to 50 mm displacement were calculated from the load-displacement curves and the results are shown in **Figure 7**. The developed steel has an increased

Table 2 Mechanical properties of steels

Steel	TS grade	YP (MPa)	TS (MPa)	El. (%)
Developed steel	GA 980 MPa (GA980)	660	1,030	15
Conventional steel	Cold-rolled 980 MPa (CR980)	621	1,051	17
	GA 780 MPa (GA780)	445	832	20

Thickness : 1.2 mm, JIS No.5 specimen

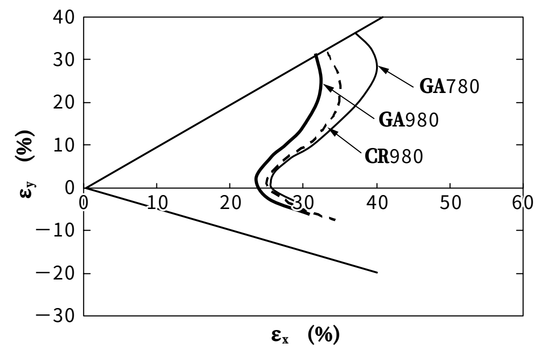

Fig. 3 Forming limit diagram of GA 980MPa grade steel

Table 3 Spot welding conditions

Electrode tip	Dome type Cu-Cr, Tip diameter : 6 mm
Electrode force	4,410 N
Welding time	16 cycle (16 Hz)
Welding current	5-20 kA
Cooling water	3 l/min (Upper : 1.5 l/min, Lower : 1.5 l/min)

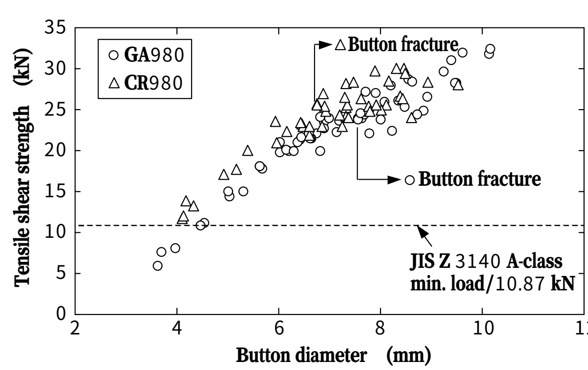

Fig. 4 Relation between tensile shear strength and button diameter

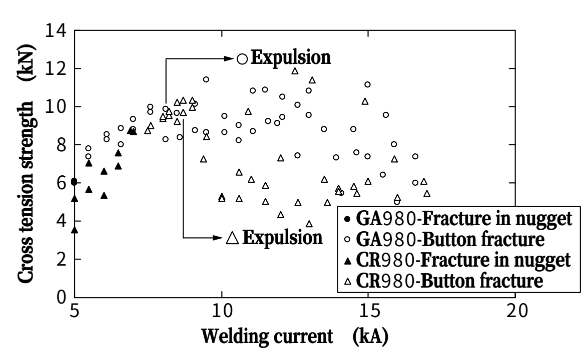

Fig. 5 Effect of welding current on cross tension strength

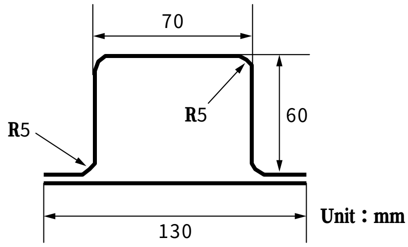

Fig. 6 Cross section of crash test specimen

Table 4 Crash test condition

	Axial crash	Crash bending
Weight	2,843 N	1,667 N
Impact speed	50 km/h	50 km/h
Displacement	max.150 mm	max.150 mm (span : 900 mm)

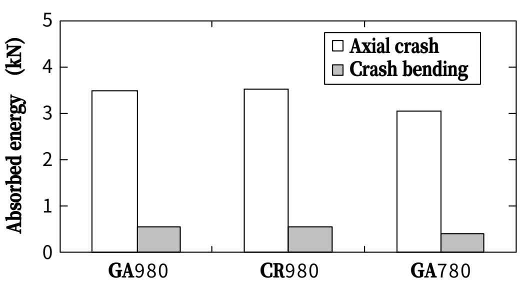

Fig. 7 Absorbed energy on dynamic crash test

absorbed energy due to increase in tensile strength and is expected to increase the strength of automobile parts.

1.2 Ultra-high strength cold rolled steel sheet with sub-micron structure

Ultra-high strength, cold rolled steel sheets exceeding 980 MPa are utilized in stiffening members including bumpers and door impact beams.[13] Recent enforcements of regulations for collision safety are promoting use of ultra-strong materials for automobile body construction. In addition to the application of Hi-Tens, heat treatment technologies such as hot-stamp and induction-hardening are being applied to ultra-strong members.[14] The main issue in applying an ultra-high strength steel sheet is the delayed fracture. In case of steel, the delayed fracture susceptibility increases rapidly with strengths above 1,180 MPa.

We have developed an ultra-high strength, cold-rolled, steel sheet in collaboration with Shinshu University. The development is based on a new structure (TBF: Trip-aided Bainitic Ferrite[15)-17)]) which ensures high formability and improved delayed fracture resistance. The following introduces the development concept and property examples of this steel.

1.2.1 Microstructure design concept

A dual phase structure containing hard martensitic phase is utilized for ultra-high strength steel over 980MPa class for the purpose of obtaining strength and ductility. It is advantageous to utilize the transformation induced plasticity (TRIP) of retained austenitic phase in order to further increase ductility for higher formability. However, the delayed fracture susceptibility is increased in dual phase structures because cementites are precipitated at the prior-austenite grain boundaries after annealing. In the case that blocky austenitic grains exist at boundaries between ferrite and bainite, the retained austenite tend to transform into hard martensite during forming, making the steel brittle. Newly developed steel sheets having TBF structure have both the delayed fracture resistance and good ductility and are expected to expand the applications of ultra-high strength steel sheets, which enable further strengthening of automobile bodies. The features of those steels are as follows.

- The matrix phase consists of bainitic ferrite laths with a high dislocation density and does not contain carbide. The structure ensures high strength with improved delayed fracture resistance.
- Fine retained austenite exists between the bainitic ferrite laths, improving ductility by their TRIP effect.

Photo 1 shows a TEM micrograph of a TBF steel experimentally manufactured in our production line. Both bainitic ferrite of less than 1 μ m thick laths with high dislocation density and film-like austenite existing between the laths are observed. The photo shows that the TBF steel is characterized by a much finer unit cell compared to conventional steels strengthened by complex structures.

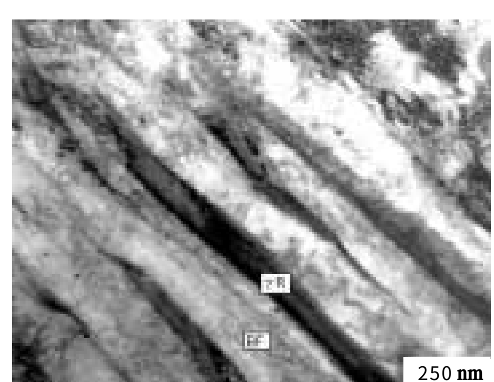

Photo 1 TEM micrograph of 1,470 MPa TBF steel

1.2.2 Properties of developed steels

Table 5 shows an example of mechanical properties of the developed steel. As a comparison, the properties of a 1,470MPa class steel having dual-phase (DP) are also shown. The developed steel has about 1.5 times higher elongation compared to the DP steel.

It has been reported that delayed fractures of steel sheets are affected not only by strengths but also chemical compositions and microstructures. Various methods have been suggested for the improvement of delayed fracture resistance.[18] Degrees of forming, residual stress and corrosion behavior in actual environment are also important factors for practical applications. Considering those factors, delayed fracture performances were evaluated on U-bent specimens submerged in a hydrochloric acid solution. As shown in **Figure 8**, rectangular shaped specimens were bent to U shape in the direction perpendicular to the rolling direction with radius of either 10 mm or 15 mm. Stresses were applied from 1,000 to 2,000 MPa, as confirmed by strain gauges, and observed for up to 48 hrs of immersion in 5% hydrochloric acid solution to determine if cracks occurred. **Table 6** summarizes the result of the immersion test. When compared to a DP steel with the same strength, the developed steel remains without cracking for longer hours especially for smaller bending radii and for higher residual stresses. Those performances of the developed steel are due to the matrix phase of bainitic ferrite without carbide as described above, and to hydrogen absorption effect of finely dispersed retained austenite.[19]

The latest developments in our Hi-Ten products have been described. The following describes a variety of needs for Hi-Tens and introduces our status of Hi-Ten development for environmental protection.

Table 5 Mechanical properties of developed steel

Steel		YP (MPa)	TS (MPa)	El. (%)
Developed steel	TBF1470	1,059	1,495	11
Conventional steel	DP1470	1,313	1,527	7

Thickness : 1.2 mm, JIS No.5 specimen

2. Development status of Hi-Tens for a variety of needs

2.1 Globalization

Automobile manufacturers are producing vehicles with the same specifications worldwide through alliances and restructuring. The materials used for the vehicles have to be supplied on a global basis. We provided Hi-Ten manufacturing technologies to Pro-Tec Coating Co. in Ohio, a partnership of U.S. Steel and Kobe Steel, and have established a system of supplying the low yield ratio type GA

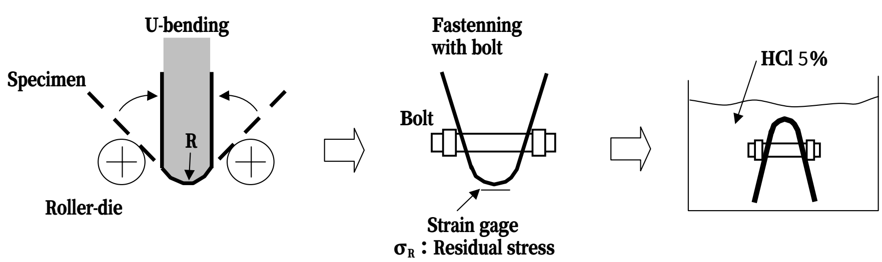

Fig. 8 Experimental procedure of delayed fracture resistance test

Table 6 Effect of bending radius, residual stress and time on delayed fracture performance

Steel	Bending radius (mm)	Residual stress (MPa)	Time in 5%-HCL 1 h	4 h	8 h	24 h	48 h
TBF1470	10	1,000	○○○	○○○	○○○	○○○	○○○
		1,500	○○○	○○○	○○○	○○○	○○○
		2,000	○○○	○○○	○○○	○○○	○○×
	15	1,000	○○○	○○○	○○○	○○○	○○○
		1,500	○○○	○○○	○○○	○○○	○○○
		2,000	○○○	○○○	○○○	○○○	○○×
DP1470	10	1,000	○○○	○○○	○○○	○○○	○○○
		1,500	○○○	○○○	○○○	○××	×××
		2,000	○○○	○○○	○○×	○××	×××
	15	1,000	○○○	○○○	○○○	○○○	○××
		1,500	○○○	○○○	○○○	○××	×××
		2,000	○○○	○○×	○××	×××	×××

○ : No fracture, × : Fracture

steel sheet of 590-980MPa class with the same specifications in both Japan and the USA. We are establishing a supply system for our new product, 780MPa class, TRIP-type GA steel sheet which has an excellent elongation property.

2.2 Linkages to application technologies

With the recent advancement of heat treatment technologies, Hi-Tens are finding applications not only in reinforcement members but also in structural members of vehicles. We have developed heat-treatable, cold-rolled steel sheets which have original strengths ranging from 440 to 590 MPa, which can be increased up to 1,470 MPa by induction heating and cooling after forming into final shapes.[20)]

2.3 Further improvement of Hi-Ten quality

As described previously, alloying elements are increasingly added to steel products for higher strengths. In case of Hi-Ten, Si and Mn are commonly added to improve strength-formability balances. However, those elements, when added in over-abundance, tend to form oxide on the surface, deteriorating important characteristics of phosphatability and corrosion resistances after painting. A cold rolled steel with excellent phosphatability and paint adhesion has been developed by controlling the state of surface oxides and by reduction of surface micro-cracks.[21)]

3. Future development

As the globalization of automobile industry progress further, more versatility will be required of the materials. Hi-Tens need to be developed for easier productions and forming. It is a subject of future R&D to develop materials which can exert stable quality performances neither with high levels of fabrication and forming technologies, nor with stringent manufacturing process control. On the other hand, the need for lighter bodies will increase and applications of Hi-Tens are expected to expand in response to those needs. Required properties will have to be clarified for each part, and developments of materials with higher performances need to be accelerated. We will continue to pursue microstructure controls to achieve both high strengths and good formability.

Conclusions

With enforcement of regulations for environmental protection and crash worthiness, technologies to reduce vehicle weights will progress and Hi-Tens will expand their applications. We will continue to develop high performance Hi-Ten products and application technologies that meet the requirements of automobile and parts manufacturers and thus contribute to environmental protection and crash worthiness.

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