JFE TECHNICAL REPORT
No. 19 (Mar. 2014)

Social Contribution through JFE Steel's Environment-Friendly Steel Products†

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Abstract:

JFE Steel makes a great contribution to environmental preservation through environment-friendly steel products, which make it possible to reduce required energy and CO_2 emission of transportation, and to reduce the resources and the weight of construction. This paper introduces typical high-end products of high strength steel plates for ships, construction and linepipes, advanced high strength steel sheets for automobiles, enhanced corrosion-resistant seamless pipes, and advanced electrical steel sheets.

1. Introduction

JFE Steel is making an important contribution to reduction of environmental loads by supplying to customers high performance functional steel materials developed by using JFE Steel's technologies, which enable energy saving and reduction of CO_2 emissions by weight reduction in transportation equipment and weight reduction, resource saving, and greater safety in steel structures by use of high strength materials. This paper presents an overview of the manufacturing technologies for those steel materials, together with their features as well.

As environment-friendly steel products in the field of steel plates, JFE Steel supplies high strength steel materials for ships and construction/industrial machinery which make it possible to conserve energy and reduce CO_2 emissions by weight reduction, high performance steel materials for building applications which reduce the weight of structures and achieve resource saving by use of high strength materials, and a high strength linepipe which aims at reducing environmental loads by enhanced safety. This paper introduces the microstructural/mechanical property control technology realized by the thermo-mechanical control process (TCMP), which is an original JFE Steel's technology, and the properties of these respective steel products. Among seamless pipe products, this paper introduces JFE Steel's lineup of martensitic stainless steel oil country tubular goods (OCTG), which can be used under severe corrosion environments characterized by high temperature/high pressure, and 13% Cr martensitic stainless steel pipes for linepipe.

In the field of steel sheets, reduction of CO_2 emissions from automobiles while traveling is progressing by reduction of the auto body weight, which is possible by using high strength (thinner gauge) automotive steel sheets. Because formability (elongation, hole expansionability) during press forming generally decreases when the strength of material is increased, the development of high-strength steel sheets (HITEN) with excellent formability is an urgent issue. This report discusses distinctive automotive high-strength steel products developed by JFE Steel and introduces the concept of material design and examples of application. Electrical steel sheets for motors of electric vehicles and hybrid electric vehicles (EV/HEV) and high Si steel sheets for high frequency equipment are also introduced.

† Originally published in *JFE GIHO* No. 32 (Aug. 2013), p. 8–17


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2. Steel Plate Products

2.1 High Strength Steel Plates Enabling Energy Saving in Large-Scale Transportation Equipment

2.1.1 High performance functional steel materials for ships: YP460 MPa class steel for large heat input welding

In the shipbuilding industry, increasing use of long-distance freight by containers has led to a rapid increase in the size of container ships in recent years[1]. Construction of ultra-large-scale container ships has begun recently, as seen in vessels exceeding 15 000 TEU (twenty-feet equivalent unit; ship capacity converted to 20-foot container units; see **Fig. 1**[2]). Because container ships are structured with wide openings, high strength and heavy wall materials are used in members such as hatch coamings and sheer strakes. In the YP390 MPa class (YP: yield point), plates with a maximum thickness of 65 mm or larger are now used[3]. In large container ships like those mentioned above, there is a rising need for steel materials with higher strengths which make it possible to reducing hull weight and improving construction efficiency by reducing plate thickness.

Electrogas arc welding (EWG), a high efficiency vertical welding method, is utilized in welding of the high strength, heavy thickness plates used in container ships. In large heat input welding, the microstructure of the heat-affected zone (HAZ) coarsens remarkably, leading to deterioration of the toughness of welded joints. In response to this problem, JFE Steel made further improvements in its "JFE EWEL™" technology for improvement of HAZ toughness in large heat input welding by advanced microstructure control, and developed a YP460 MPa class steel with excellent welded joints properties in large heat input welding[4]. The "JFE EWEL™" technology consists of minimizing the coarse grain HAZ region through control of TiN particles, refining the microstructure of the HAZ by using B and Ca, and improving the toughness of the matrix. The high HAZ toughness of the developed steel is achieved by minimization of the coarse-grained region and refinement of the internal microstructure.

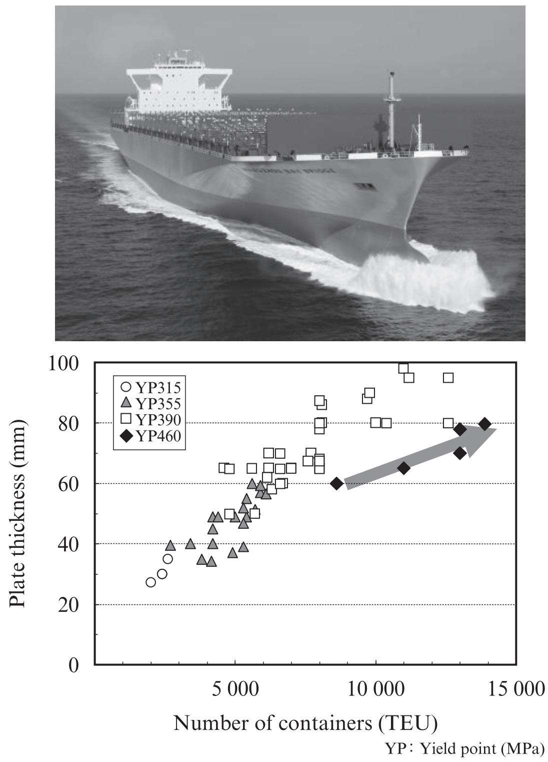

Fig. 1 Outlook of container ship and change of plate thickness and steel grades used for container ships

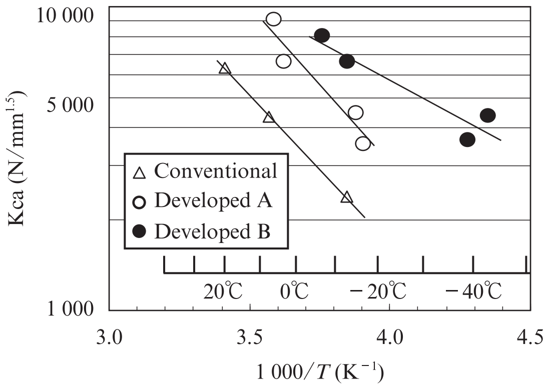

Fig. 2 Brittle Crack arrestability of YP390 MPa steels developed

To ensure the safety of large container ships, co-research is carried out in close cooperation with the governmental, industrial, and academic worlds, including large-scale experiments[5], and "Guidelines on Brittle Crack Arrest Design" (2009 ClassNK) were announced in 2009[6]. These guidelines are applied to hatch side coamings, etc. with plate thicknesses exceeding 50 mm in container ships for which crack arrest design is performed.

Against this backdrop, JFE Steel developed a YP460 MPa class steel with excellent characteristics in large heat input welding, responding to the larger size of vessels, and developed a higher toughness (crack arrestability improved) YP390 MPa and higher strength plates for large container ships (**Fig. 2**[7]). Application of the developed steel plates to actual ships is also progressing[4].

2.1.2 High performance functional steel materials for construction/industrial machinery: "JFE-HYD™960LE" and "JFE-HYD™1100LE"

Higher strength and higher toughness have been required in steel materials used in construction and industrial machinery in recent years, accompanying the trends to larger scale and more severe use environments. To meet these needs, JFE Steel developed "JFE-HYD™ 960LE" and JFE-HYD™1100LE" for construction and industrial machinery[8]. These are ultra-high strength steel plates with yield strengths of 960 MPa and 1 100 MPa, respectively, and provide excellent low temperature toughness. The combination of ausforming with a technology for morphological control of cementite by rapid tempering using HOP™ (Heat-treatment On-line Process; **Fig. 3**[9]), which is a proprietary technology of JFE Steel, achieves not only high strength but also excellent low temperature toughness and delayed fracture resistance. The heating rates in tempering by HOP™ are one to two orders of magnitude higher than those by conventional furnaces. As features of this process, the effective grain size is refined and uniform dispersion of fine cementite in the steel is achieved, as shown in **Photo 1**.

As a result of these microstructural control technologies, the developed steels have excellent low temperature toughness, as shown in **Fig. 4**, and also realize high delayed fracture resistance, which is critical for practical application of ultra-high strength steels. In addition, excellent weldability is also achieved by a low-alloy design.

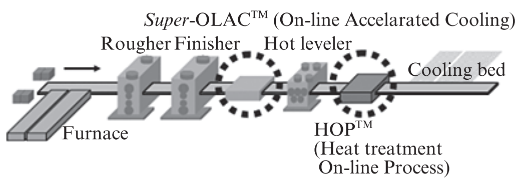

Fig. 3 Layout of online heat-treatment facilities of West Japan Works (Fukuyama)

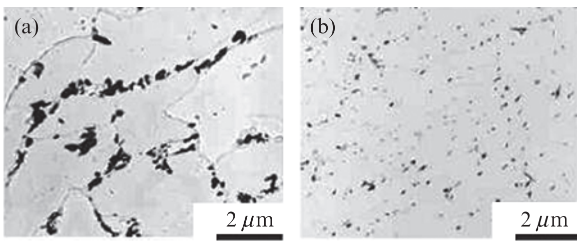

Photo 1 Uniform dispersion of fine cementite by rapid heating and tempering

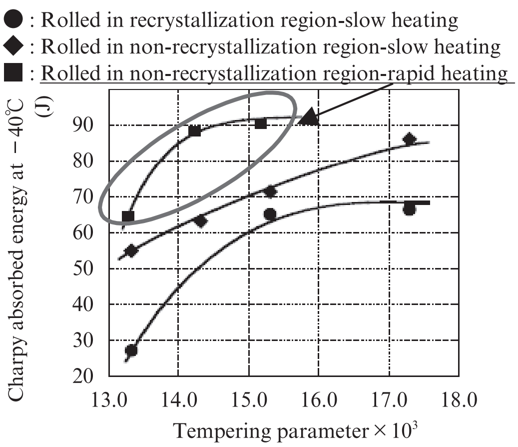

Fig. 4 Improvement of low temperature toughness by ausforming and rapid heating and tempering of HYD1100LE steel

The morphology and dispersion control technology of carbides and mechanical property control technologies by HOP™ are widely applied to JFE Steel's high strength steels with tensile strengths of 600 MPa and over, as exemplified by "JFE-HYD™960LE" and JFE-HYD™1100LE"[10].

2.2 High Performance Functional Steel Materials Enabling Resource Saving by Reduction of Structural Weight and Reduction of Environmental Loads by Enhanced Safety

2.2.1 High performance functional materials for building construction: Low YR550–780 N/mm² class high-strength steels

Large-span designs and multi-story designs in commercial spaces, offices, and hotels are common features of recent high-rise buildings being built mainly in urban districts. These design features require the use of high strength, heavy wall thickness steel materials. When high strength steel materials are used, it is generally possible to reduce the required section of members. Since this reduces the weight of steel materials and welding consumables used in the structure, and also reduces the burden of steel frame processing, transportation, and erection, high strength steel materials are adopted as the height of high-rise buildings increases, in which the sectional area of the members becomes larger. At present, steel plates up to tensile strength 590 MPa class (Ministry of Land, Infrastructure, Transport and Tourism approved steel material SA440) are mainly used considering base material performance and weldability, manufacturing costs, and other restrictions[11]. Japanese Industrial Standards (JIS) require a low yield ratio (YR: Yield strength to tensile strength ratio) of under 80% for steel plates used for building construction to ensure earthquake-proof properties. It becomes difficult to obtain a low yield ratio in high-strength steel plates with tensile strengths of over 600 MPa by the usual quenching and tempering[12]. Therefore, complex multiple heat treatments, such as reheat-quenching, intercritical reheat-quenching, and tempering (RQ-Q'-T) are usually applied to obtain low yield ratios in high strength plates of this type. Low YR, high tensile strength steels with high earthquake resistance 550–590 MPa class products

Table 1 High strength steels fot buildings developed and application records of the steels

Grade	Designation	Manufacturing process	Thickness (mm)	Tensile test			Application record
				Yield strength (YS) (MPa)	Tensile strength (TS) (MPa)	Yield ratio (YR) (%)	
550 MPa Class	HBL385	TMCP	19–100	385–505	550– 670	≦80	approx. 100 000 tons
	HBL385-L		12– 19				
590 MPa Class	SA440	Heat treatment (Dual-phase region quenching)	19–100	440–540	590– 740	≦80	approx. 50 000 tons
	HBL440	TMCP	19– 50				
780 MPa Class	JFE-HITEN780T	Heat treatment (Dual-phase region quenching)	22–100	670–750	780– 930	≦85	approx. 1 000 tons
	HBL630-L	TMCP (HOP™)	12– 40				
	H-SA700	Heat treatment, TMCP	6– 50	700–900	780–1 000	≦98	

(a) Architectural rendering (b) Ultra-high strength concrete-filled welded box columns under construction

Fig. 5 New skyscraper planned to use low yield to tensile ratio (YR) 780 MPa grade steels

are widely used. To date, JFE Steel has a cumulative production record exceeding 120 000 tons of 550 MPa class steel materials and 46 000 tons of 590 MPa class steel materials (**Table 1**).

In the production of low YR 780 MPa class steel plates, application of multi-step off-line heat treatments had been considered indispensable until now. JFE Steel developed a new microstructural control technology and manufacturing process for these materials[13]. Excellent base metal mechanical properties for building structural use, together with excellent weldability and weld toughness, are achieved in the developed 780 MPa steel which has dual phase microstructure with bainite and fine M-A (martensitic-austenite constituent) phases by utilizing JFE Steel's *Super*-OLAC™ system and induction-heating type on-line heat-treatment process HOP™. The delivery record of 780 MPa class steels is still limited to approximately 600 tons as use as such began only recently, irrespective of low YR or high YR. Recently, however, 400 tons of the developed steel was adopted for ultra-high strength concrete-filled welded box columns in a new skyscraper being constructed as part of the Otemachi Plan in central Tokyo (**Fig. 5**[14])).

2.2.2 High performance functional steel for linepipe: High strength, high deformability linepipe JFE-HIPER™

The pipelines now being constructed are often run through severe environments, such as cold regions, seismic regions deepwater and sour gas environments. An example of pipe-laying in Canada is shown in **Photo 2**.

When pipelines are installed in permafrost ground or seismic regions, ground movement is likely to impose larger plastic deformation on the pipes. Pipeline engineers have recently developed a new pipeline design methodology called "strain-based design" for seismic regions and discontinuous permafrost regions[15]. The methodology is modeled on the new concept that pipelines require higher resistance against larger compressive and tensile strains. The microstructural control technology by the *Super*-OLAC™ and HOP™ process has been applied to the plates for X80 grade linepipes with excellent deformability, "JFE-HIPER™"[16]. One of the key technologies for improving deformability is dual-phase microstructural control. Steel plates with a bainite and M-A microstructure can be obtained by applying the HOP™ process after the accelerated cooling process. The pipes developed by applying the

Photo 2 Construction Scenery of long distance pipeline used X100 grade linepipes

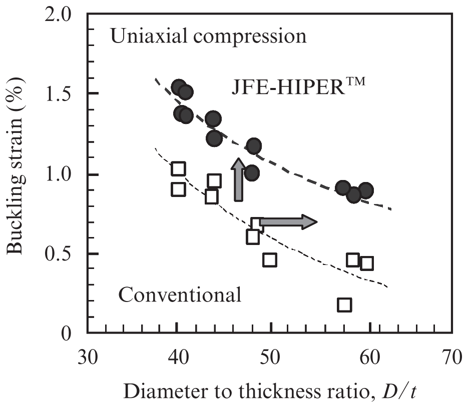

Fig. 6 Relationship between buckling strain of by axial compression and pipe diameter to thickness ratio (D/t)

HOP™ process are X70–X100 grade under the American Petroleum Institute (API) standard.

Figure 6 shows the relationship of maximum buckling strain, which is one of the parameters related to the deformability of pipes, and the pipe diameter (D) to thickness (t) ratio (D/t). Buckling strain decreases as the D/t ratio increases. "JFE-HIPER™" has higher strength with higher deformability, thus providing a safety margin with the same pipe dimensions or enabling a material weight reduction by thickness reduction while maintaining the same buckling strength as the conventional pipe. "JFE-HIPER™" has a production record exceeding 20 000 tons as land linepipes not only in Japan, but also in China[17] and North America[18], centering on the X65–X80 classes. Also including X100, expansion of application to projects in the earthquake region of eastern Siberia (Russia) and elsewhere is expected.

3. Seamless Pipes and Tubular Products: High Cr Seamless Steel Tubes with High Corrosion Resistance

When general-purpose seamless carbon steel tubes are used in oil and gas fields under wet CO_2 gas environments, mesa corrosion may occur, resulting in perforation of the tube during service[19]. The American Petroleum Institute (API) has standardized 13% Cr martensitic stainless steel tubes (API-13Cr) as oil country tubular goods (OCTG) for use in wet CO_2 environments. Since 13% Cr steel tube has excellent CO_2 corrosion resistance, it is in high demand in the world. As one of the leading mills which can supply API L80-13Cr, JFE Steel has a large record of sales for oil and gas fields around the world.

On the other hand, with the drilling environments in oil and gas fields becoming progressively more severe, even API-13Cr steel tubes cannot meet such severe corrosion environments in some cases. In contract, 22% Cr duplex stainless steel tubes or higher high alloy tubes are used in oil and gas wells with such corrosive environments. However, due to the low strength of duplex stainless steel tubes and high alloy steel tubes, it was necessary to secure the high strength required in OCTG by cold drawing. In this case, both cost and the delivery schedule are still problems. Therefore, a new OCTG which possesses high corrosion resistance superior to that of API-13CR and is also more economical than duplex stainless steel had been demanded.

To meet these requirements, JFE Steel developed and began sales of martensite-based stainless steel pipes with a new composition that improves CO_2 corrosion resistance and sulfide stress cracking (SSC) resistance while also realizing high strength as a candidate for alternative material selection. As shown in **Table 2**, JFE Steel's lineup of Cr seamless steel pipes for OCTG includes JFE-11CR-110ksi-grade steel pipes[20], JFE-HP1-13CR-95ksi-grade and 110ksi-grade steel pipes[21], JFE-HP2l-13CR-95ksi-grade and 110ksi-grade steel pipes[21], JFE-HP2-13CR-M-95ksi-grade steel pipes and JFE-UHP™-15CR-125ksi-grade steel pipes[22], JFE-UHP™-17CR-110ksi-grade and 125ksi-grade steel pipes[23,24]. Taking advantage of this extensive lineup, JFE Steel is making proposals of material selection matched to the conditions of actual wells presented by oil and gas producers. As a distinctive feature of these products, high strength is realized while also stabilizing the passivation film so as to withstand severer corrosion environments by adding Cr, Mo, Ni, Cu, and other alloying elements and optimizing the manufacturing condi-

Table 2 JFE Steel's lineup of Cr seamless pipes for OCTG

Material grade	Specified minimum yield strength / Chemical composition	80 ksi (552 MPa)	85 ksi (586 MPa)	95 ksi (655 MPa)	110 ksi (758 MPa)	125 ksi (862 MPa)	140 ksi (965 MPa)
13CR	0.2C-13Cr	■	■	■			
11CR	0.01C-11Cr-2Ni				■		
HP1-13CR	0.04C-13Cr-4Ni-1Mo			■	■		
HP2-13CR	0.04C-13Cr-5Ni-2Mo			■	■		
HP2-13CR-M	0.01C-12.5Cr-6Ni-2Mo			■			
UHP™-15CR	0.03C-15Cr-6Ni-2Mo-1Cu-Nb					■	
UHP™-17CR	0.03C-17Cr-4Ni-2.5Mo-1W-1Cu				■	■	

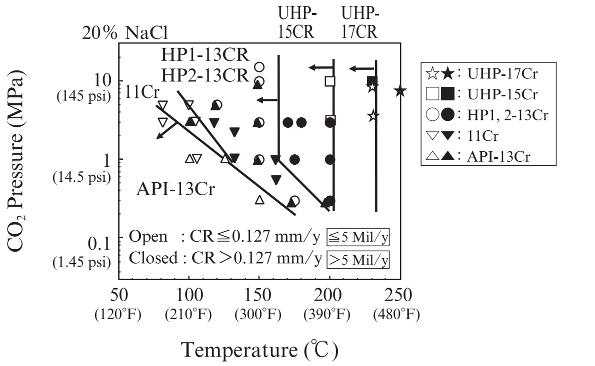

Fig. 7 Domain map of CO_2 corrosion-resistance in JFE steel's OCTG

tions. As a result, these pipes possess the required strength and realize improved CO_2 corrosion resistance and improved SSC resistance.

As one example, **Fig. 7** shows data for CO_2 corrosion in a 20% NaCl solution environment. Comparing the upper limit temperatures at which use is possible under a condition of CO_2: 3 MPa, API-13Cr steel tubes can be used at 100°C, but in contrast to this, the upper limit temperatures for the JFE Steel lineup are 160°C for HP Series 13Cr, 200°C for UHP™-15CR, and up to 230°C for UHP™-17CR[23].

Based on the same technological concept, 13% Cr martensitic stainless steel material is used in seamless steel pipes for linepipes. The conventional types of steel for linepipe applications are carbon steel, which is used in combination with a corrosion inhibitor, or a duplex stainless steel-based linepipe material. As a candidate for alternative material selection, JFE Steel has developed a 13% Cr-based linepipe material which shows appropriate CO_2 corrosion resistance and is a more economical option than duplex stainless steels. The basis of the composition design is stabilization of the passivation film by optimizing the addition of Mo and Ni, and optimization of the amounts of C, N, and Ti to secure weldability and intergranular stress corrosion cracking resistance (IGSCC resistance) [25]. This material has now been standardized by Det Norske Veritas (DNV) as DNV-13CR. An increasing number of applications in which DNV-13CR is used in actual fields for offshore pipeline applications can be seen.

4. Steel Sheet Products

4.1 Advanced High Strength Steels Enabling Automotive Weight Reduction

4.1.1 440 MPa bake hardenable high strength steel for automotive outer panels: UNIHITEN™

The first quality requirement for outer panels of automobiles is external appearance. Application of high strength steels to outer panels is difficult because the surface distortion that occurs in press forming is proportional to the yield strength of steel sheets. Bake hardenable (BH) steel sheets, which are hardened by using the heat of the painting/baking process, were developed as a solution to this problem. In BH sheets, the strength of the sheet is low during press forming, but increases as a result of bake-hardening in the paint-baking process. Recently, 340 MPa class BH steel sheets are continuing to become the main stream in this application.

UNIHITEN™ is a new high strength BH steel sheet developed by JFE Steel. Before press forming, its yield strength is held to the same low level as 340 MPa class, but after paint-baking, it displays yield strength equal to that of the general 440 MPa class. As a result, dent resistance was successfully improved by 20% in comparison with the 340 MPa class BH steel sheets[26] (**Fig. 8**).

Generally speaking, many BH steel sheets up to 340 MPa class use a control method that retains a trace amount of solute C, while being based on an IF (interstitial free) steel, which is a single-phase ferritic steel. However, if strength is increased further by this method, increased yield strength is unavoidable. Therefore, in a paradigm shift, JFE Steel developed UNIHITEN™ based on a DP (dual phase) steel sheet which displays the BH property but has a low yield ratio. **Figure 9** shows the relationship between the yield point (YP) and volume fraction of the second phase when the C content was adjusted, comparing a conventional 590 MPa class DP steel with trace addition of V, a 2.2% Mn steel which was based on the previous steel but contained Mn in place of V, and the developed steel, in which Mn was reduced and B, etc. were added in order to secure ferrite grain growth so as to obtain the proper grain size and the BH property. **Photo 3** shows representative microstructures of the respective steels as observed by scan-

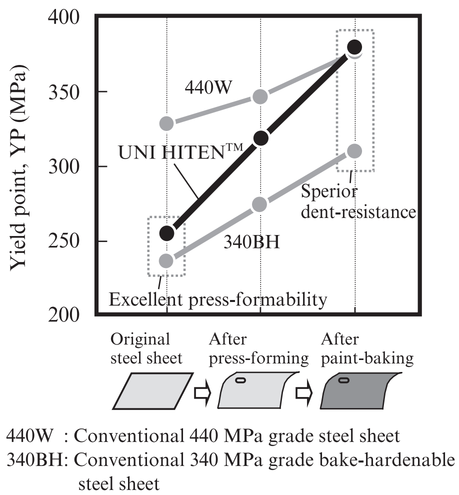

Fig. 8 Change in yield point (YP) of panel steels during car production process

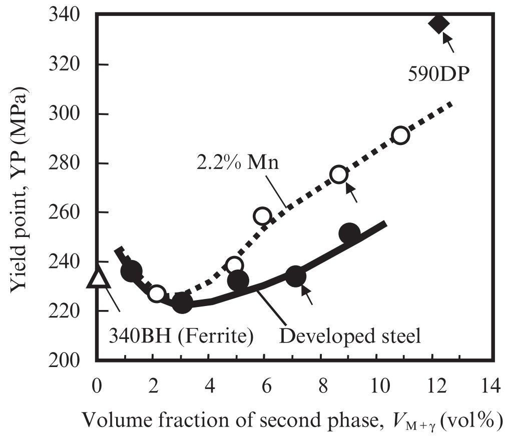

Fig. 9 Relationship between yield point (YP) and volume fraction of second phase

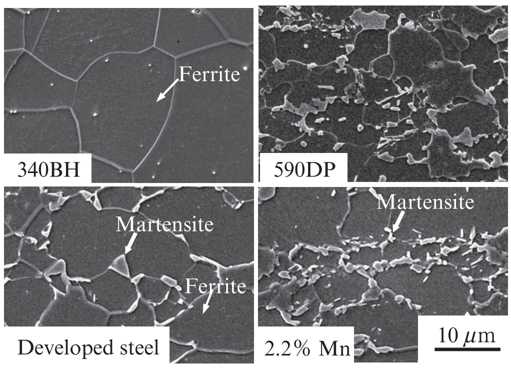

Photo 3 Scanning electron micrographs showing microstructures of conventional and developed steels

ning electron microscope (SEM)[26]. In the developed steel, in addition to coarsening of the ferrite grains, it can be understood that the second phase is uniformly and coarsely dispersed and the developed steel shows a lower YP, equivalent to 340 MPa, over a wide range of volume fractions of the second phase. In the developed steel, the volume fraction of the second phase is controlled in the low YP range by actively utilizing narrow range control of C.

UNIHITEN™ has a low yield point equivalent to that of the conventional 340 MPa, and high elongation (El) and *n*-value (strain hardening coefficient) in comparison with the conventional 440W. Furthermore, because work hardening (WH) and BH are high when 2% pre-strain is given to the sheet, the yield point (YP) after press-forming and paint-baking of automotive panels was greatly increased in comparison with 340 MPa.

UNIHITEN™ has been used in the doors and hoods of the automobiles shown in **Photo 4**. Mass production of cold-rolled UNIHITEN™ began in 2010, and mass production of galvannealed (GA) began in 2011. In doors, a weight reduction of 1.1 kg per vehicle is achieved by reducing the material thickness of the steel sheets. Due to the large size of outer panels, the weight reduction effect of reducing the thickness of these parts

Photo 4 Application of UNI HITEN™ ; (a) Rear door, (b) Hood

is large. Thus, application of UNIHITEN™ is expected to make an important contribution to CO_2 emission reduction.

4.1.2 Cold-rolled and GA HITEN for auto body frame: WQ high strength and high strength, high formability GA HITEN

In order to protect the passengers in an automobile, the cabin must not deform in case of a collision. To meet this requirement, 980 MPa class and higher cold-rolled and GA ultra-high strength steels have been applied recently.

JFE Steel developed the continuous annealing line, which is necessary for production of ultra-high strength steel sheets, and was among the first to commercialize ultra-high strength products in the 1970s[27]. In conjunction with progress in forming technology utilizing computer aided engineering (CAE)[28], these products has been successively adopted in bumper reinforcements and door impact beams, seat frames, body parts, and so on, contributing to auto body weight reduction. More recently, application of ultra-high strength steels to underbody parts, in which rust resistance is necessary, has also begun, and development and commercialization of high strength, high formability GA steel sheets is progressing.

JFE Steel offers a lineup of cold-rolled ultra-high strength steel sheets for the auto cabin which includes precipitation hardened steel, DP steel, martensitic steel, and TRIP steel, corresponding to the required strength

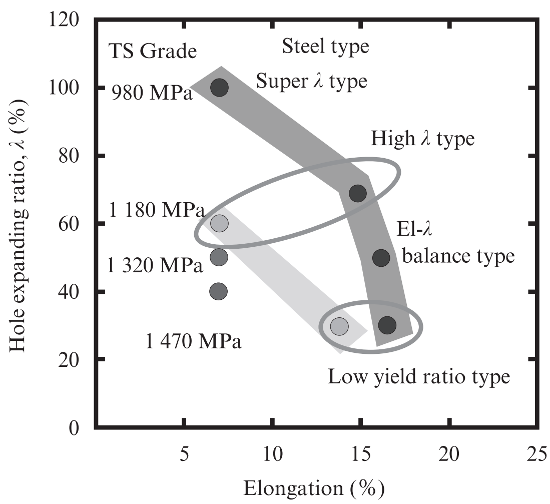

Fig. 10 El-λ balance of WQHITEN

and other properties. Among these, DP steel is manufactured mainly using the water quenching type continuous annealing line (WQ-CAL). As important features of these materials, DP steels are (1) available in a wide range of tensile strengths from TS780 to 1 470 MPa class with different balances of elongation (El) and stretch flangeability (λ), (2) possess excellent spot weldability and delayed fracture resistance due to their low carbon equivalent composition design[29], and (3) have stable material quality thanks to uniform cooling and feed-forward control. The El-λ balance of these products is shown in **Fig. 10**.

In particular, the above-mentioned features are utilized in the 980 MPa class, which has enjoyed a remarkable expansion of applications in recent years. For example, the requirements in body frame applications include not only elongation and bending formability, but also corrosion resistance after painting, spot weldability, etc. The low YR type, which offers this combination of properties, is mainly used in this application. In seat frame parts, the El-λ balance type and high λ type are applied, depending on the shape. The ultra-high λ type is a steel sheet that was developed for application of a mechanical joining method (TOX joining method) in the seat frame assembly process. As a distinctive feature, because this sheet possesses extremely high local ductility, it is resistant to cracking even under severe forming like that in the TOX method[30].

A low YR type and high λ type are also available in 1 180 MPa class WQ HITEN. Since the low YR type has extremely high elongation for this strength grade and also enables drawing forming, it is applied in door impact beams like that shown in **Photo 5**[31], as well as other parts. Although door impact beams were conventionally manufactured by hot stamping, the same performance was successfully realized by cold press forming of WQ HITEN with a deeper cross-sectional shape than that of conventional parts. While delayed fracture is usually a concern with steels of this strength level and higher, this steel has been applied without problems by utilizing a delayed fracture prediction technology established by JFE Steel[32].

Cold-rolled 1 320 MPa class and 1 470 MPa class are steel sheets which make the maximum use of the features of the WQ-CAL and possess the highest levels of tensile strength (TS) among practical steels for automotive use. Excellent bending formability, spot weldability, and delayed fracture resistance are realized in these steels by using a martensitic steel with a single-phase microstructure and reducing C to the absolute minimum. These products are contributing to auto weight reduction as bumper reinforcements and steel tube door beams.

Next, the relationship between the TS and El of JFE Steel's high strength, high formability GA steel sheets is shown in **Fig. 11**. JFE Steel's lineup of GA HITEN also covers a wide range of TS grades from 590 to 1 180 MPa and includes conventional type, high El type, and high El-λ type products so as to support various forming modes. The high El type has 3–5% higher total elongation in comparison with the low YR type, and shows approximately the same ductility as the low YR type with a TS level one rank lower. With the high El type, 780 MPa class has been adopted in hard-to-form parts[33], continuing from 590 MPa class, and is contributing to weight reduction. The high El-λ type has λ values approximately 40–50% higher than those of the low YR type while maintaining the same El as the high El type; 590 MPa class is comparable to the λ of the 440 MPa class, and 980 MPa class is comparable to the λ of the 590 MPa class. In the future, these products are expected to be applied to hard-to-form parts in which use of high strength steels has not progressed due to poor stretch flangeability.

Photo 5 Application of WQ HITEN (1 180 MPa Grade, Door impact beam)

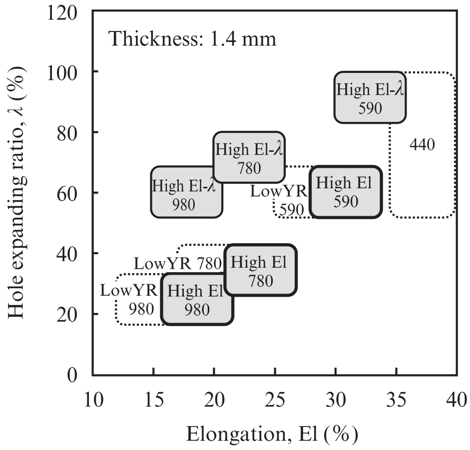

Fig. 11 El-λ balance of high performance GA HITEN

4.1.3 Hot-rolled high strength steel for chassis and frame: NANOHITEN™ and SB HITEN

Hot-rolled steel sheets are mainly used in automobile chassis parts such as suspension arms, etc. since the thickness of these part is large in comparison with that of body structural parts. In addition to formability (hole expansionability, etc.), strength, and stiffness, the properties required in chassis parts also include durability against fatigue and corrosion. TS440–590 MPa class materials are frequently used at present, but development of a 780 MPa class material with higher strength

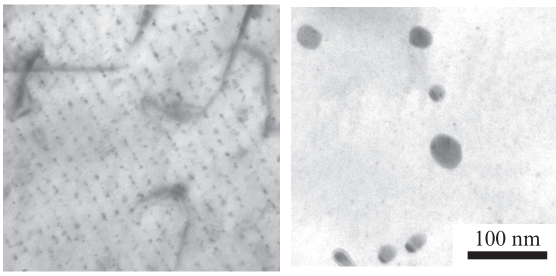

Photo 6 Carbides morphology in precipitation-strengthened steels; (a) NANOHITEN™, (b) Conventional steel

Photo 7 Application of NANOHITEN™

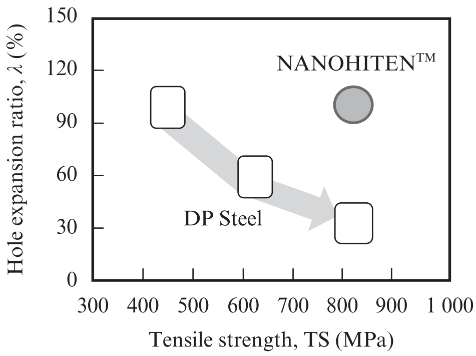

Fig. 12 Hole expanding ratios of NANOHITEN™ and dual phase steel

had been desired.

NANOHITEN™ is a hot-rolled steel sheet which was developed for these applications and has the following distinctive features[34].

(1) Ferrite single-phase microstructure with excellent formability.
(2) Precipitation-strengthened by carbides refined to the size of several nanometers (**Photo 6**).
(3) Extremely high thermal stability of carbides.
(4) Possible to omit addition of solid solution hardening elements such as Si, etc. because sufficient strength can be obtained by refinement of carbides.

NANOHITEN™ shows a high hole-expanding ratio in comparison with the conventional dual-phase steels, as shown in **Fig. 12**, which reflects the above-mentioned features (1) and (2). That is, in DP steels, microvoids are generated from the interface between the soft phase and the hard phase around punched holes due to the large difference in the deformation capacities of the soft phase and the hard phase, and if the strength of the material is increased, the hardness difference between the phases (i.e., difference in deformation capacity) also increases, causing a large decrease in hole expansionability. However, this phenomenon can be avoided with NANOHITEN™, which consists of a single phase of ferrite.

Moreover, because Si is not added to NANOHITEN™, reflecting feature (4), this material has excellent surface properties in comparison with general hot-rolled high strength steels. This is also advantageous for fatigue strength, as fatigue performance is influenced by surface irregularities.

The outstanding formability and durability of 780 MPa class NANOHITEN™ have been highly evaluated, and this material has been adopted in many applications, centering on chassis parts such as the suspension lower arm shown in **Photo 7**.

The strength of NANOHITEN™ can be increased by increasing the content of fine carbides. At present, high strength up to 1 180 MPa class has been successfully obtained. A high yield ratio (YS/TS) may also be mentioned as a distinctive feature of precipitation-strengthened steels. For example, the YS of 1 180 MPa class NANOHITEN™ is approximately the same as that of 1 470 MPa class material for hot stamping. Thus, in addition to chassis parts, expanded application to auto frame parts, in which impact energy absorption is an issue, can be expected.

Furthermore, reflecting feature (3), NANOHITEN™ can also be applied advantageously to warm forming, in which steel sheets are heated to 200–700°C for forming. Therefore, an expanded range of applications can be expected by use of NANOHITEN™ in combination with this new forming method[35].

On the other hand, in the frames of trucks, etc., steel materials must satisfy both fatigue strength and the static strength to withstand the weight of the truck bed. In particular, many punched holes are made in frames for weight reduction, but the fatigue strength of the hole parts becomes a problem. Moreover, since comparatively thick steel sheets with thicknesses exceeding 3 mm are required in this application, uniformity of the microstructure in the sheet thickness direction is also necessary.

JFE Steel's 780SB is a product that was developed assuming applications of this type. Non-uniformity of the microstructure, which causes roughness at the edges of punched holes, was greatly reduced by using bainite in the strengthening phase, thereby improving the fatigue strength of punched holes. In addition to fatigue strength, improvement of the uniformity of the microstructure also resulted in improved formability, namely, elongation and hole expasionability.

These properties of 780SB have earned a high evalua-

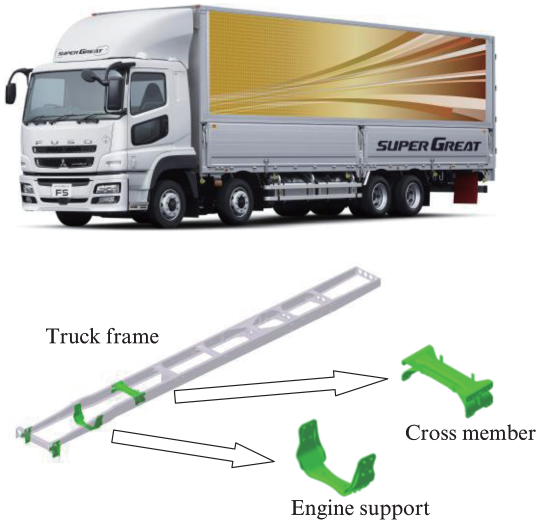

Photo 8 Application of 780SB

tion, and this product has been adopted in the cross members and engine supports of large trucks [36] (**Photo 8**).

4.2 Electrical Steel Sheets Contributing to High Efficiency in Electrical Machinery

4.2.1 Electrical steel sheets for EV/HEV motors: JNE, JNP, and JNEH

Since the 1990s, auto makers have promoted the development of low fuel consumption vehicles such as electric vehicles (EV) and hybrid electric vehicles (HEV) from the viewpoint of CO_2 reduction, and the market is being expanded. Because the drive motor plays a key role in EV/HEV, low iron loss and high magnetic flux density are required in the electrical steel sheets used as motor core materials. Addition of Si is effective for reducing iron loss in electrical steel sheets from the viewpoints of increasingly electrical resistivity and reducing magnetic anisotropy. Approximately 3% Si is added to high grade electrical steel sheets, but because Si is a nonmagnetic element, magnetic flux density is reduced due to a decreased in saturation magnetization. For this reason, it was difficult to produce materials with excellent performance in terms of both magnetic flux density and iron loss by the conventional technique of Si addition.

To overcome this problem, JFE Steel developed the JNE series, which has an improved balance of magnetic flux density and iron loss in comparison with the conventional JN series, by optimizing the contents of added alloying elements such as Si, Al, etc. and reducing impurities in the steel, and to support higher motor torques, the company developed the JNP series, which has higher magnetic flux density than the JNE Series, by utilizing texture control technology[37,38]. To respond to the need for higher speed in EV/HEV motors, JFE also developed

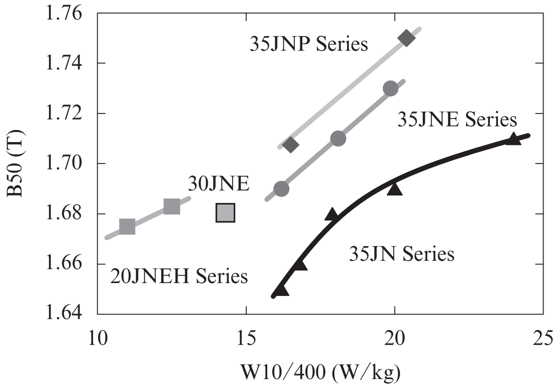

Fig. 13 Magnetic properties of electrical steel sheets for EV/HEV

a series of thin-gauge electrical steel sheets (JNEH Series), in which high frequency iron loss is reduced by producing thinner gauge sheets[39]. **Figure 13** shows examples of products in JFE Steel's lineup of electrical steel sheets for EV/HEV. These materials have been adopted in many EVs/HEVs, as they offer an excellent magnetic flux density-iron loss balance in comparison with conventional electrical steel sheets and can make an important contribution to high efficiency in motors.

4.2.2 High Si steel sheet for high frequency machinery: Super Core™

In case Si is added to steel, it is known that iron loss decreases as the amount of Si addition increases, and when Si addition reaches 6.5%, magnetostriction becomes virtually zero and magnetic permeability and iron loss show their most favorable values[40]. However, with increasing Si addition, the elongation of the material decreases rapidly, and it becomes difficult to manufacture high Si steel sheets by cold rolling. Therefore, in the conventional highest grade electrical steel sheets, Si addition had been limited to approximately 3.5%.

To solve this problem, JFE Steel developed a manufacturing technology for high Si steel sheets by the chemical vapor deposition (CVD) process as an alternative to rolling and succeeded in mass-production of 6.5% Si steel sheets for the first time in the world[41]. Due to their low magnetostriction, 6.5% Si steel sheets are extremely effective for realizing low noise in electrical machinery. As shown in **Fig. 14**, a remarkable noise reduction effect was confirmed in comparison with amorphous and grain oriented electrical steel sheets[42]. Excellent properties as a core material for high speed motors can also be expected since 6.5% Si steel sheets display low high frequency iron loss. **Figure 15** shows the characteristics of model motors (IPM motor, 4 poles, distributed winding, maximum output: 2 kW) using the 6.5% Si steel sheet, a JFE Steel thin-gauge electrical steel sheet (20JNEH1200), and a 3% Si steel (35A230)

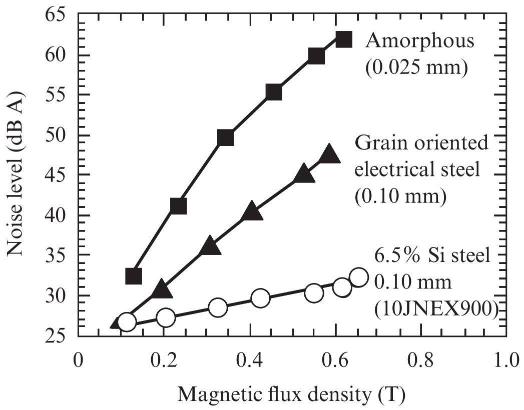

Fig. 14 Audible noise of test reactors

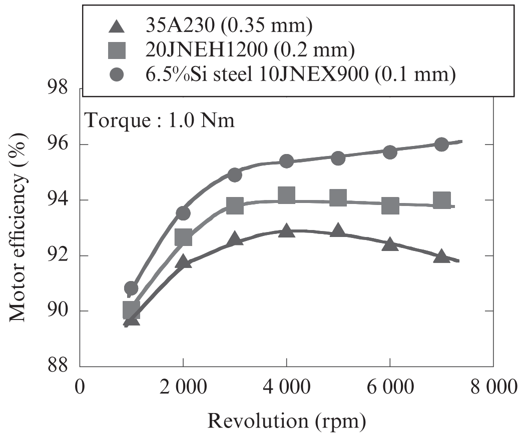

Fig. 15 Influence of kind of materials on efficiency of high speed motor

with a sheet thickness of 0.35 mm[43]. From this, it can be understood that a further increase in efficiency in comparison with the thin-gauge electrical steel sheet can be achieved by using the 6.5% Si steel sheet, and this effect also increases with motor speed.

Using the CVD process, JFE Steel also developed HF core, in which high frequency iron loss is reduced by optimizing the concentration gradient of Si in the sheet thickness direction[44]. High expectations are placed on HF core as a core material for high speed motors other than reactors, as this material displays low ion loss characteristics superior to those of the 6.5% Si steel sheet in the frequency range over 5 kHz, while also offering outstanding formability.

5. Conclusion

In the field of steel plates, the features of steel products developed by JFE Steel by applying its state-of-the-art TMCP technology were discussed. These materials can contribute to weight reduction in transportation and to enhanced safety in structures. Among steel sheet products, the features of JFE Steel's automotive high-strength steels, which can contribute to body weight reduction by enabling use of higher strength (thinner gauge) sheets, were described, and the concepts of material design and examples of application were introduced. In the field of seamless steel pipes, martensite-based stainless steel pipes were taken up, and oil country tubular goods (OCTG) and steel pipes for linepipe, which can be used in severe corrosion environments, were introduced. Finally, as advanced electrical steel sheets, electrical steel sheets for EV/HEV motors and high Si steel sheets for high frequency machinery were discussed.

In the future, JFE Steel will continue to contribute to reducing environmental loads through the supply of high performance functional products using advanced material quality control technologies.

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