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High Performance Steel Plates for Construction and Industrial Machinery Use —New Steel Plates for Construction and Industrial Machinery Use with High Strength and Superior Toughness Combined with Good Weldability and Formability—

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Abstract:

The requirements placed on steel plates for construction and industrial machinery use have diversified in recent years, as exemplified by low temperature toughness to enable use in cold districts and improved weldability by lowering the preheating temperature for welding. To meet these requirements, JFE Steel has developed new abrasion resistant steel plates, "JFE-EH360LE/EH500LE," and a new high strength steel plate, "JFE-HITEN780LE," with good weldability and low temperature toughness guaranteed at −40°C. In the developed steel plates, high hardness or high strength was achieved by selecting the optimum C content and hardenability (D_I), while reducing the carbon equivalent (C_{eq}) in consideration of weldability. Low temperature toughness at −40°C was improved in the developed steel plates by applying microalloying and thermo-mechanical control process (TMCP)/controlled heat treatment process technologies to refine prior austenite grains.

1. Introduction

The requirements placed on steel plates for construction and industrial machinery include excellent abrasion resistance, considering abrasion by ore, rock, or sand, and high strength, from the viewpoint of weight reduction in the equipment structure. For example, in parts such as dump truck beds and excavator buckets, high abrasion resistance is required. Because abrasion resistance has a strong correlation with the surface hardness of the steel plate[1)], abrasion resistant steel plates with high surface hardness are used in applications of this type. In parts such as crane booms and outriggers, high strength is required, and in many cases, steel plates with 780 MPa in tensile strength are used.

In recent years, the performance requirements for these steel plates for construction and industrial machinery use have diversified. For example, securing low temperature toughness to enable use in cold districts and improved weldability by lowering the preheating temperature for welding are required. Moreover, improved bending formability is also required in many cases.

To meet these requirements, JFE Steel has developed new abrasion resistant steel plates, "JFE-EH360LE/EH500LE," and a new high strength steel plate, "JFE-HITEN780LE," with good weldability and low temperature toughness guaranteed at −40°C. This paper describes the development details of these high

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performance steel plates for construction and industrial machinery use and the performance of the developed steels.

2. Development Details

2.1 Target Properties

The target properties for abrasion resistant steel plates and 780 MPa grade high strength steel plates for construction and industrial machinery use are shown in **Table 1** and **Table 2**, respectively. Considering actual use conditions, the plate thickness is set at a maximum of 32 mm for both abrasion resistant steel plates and high strength steel plates, and in consideration of weldability, the carbon equivalent (C_{eq}) is reduced corresponding to the standard and plate thickness. Moreover, in consideration of use in cold districts, Charpy absorbed energy at −40°C is guaranteed, depending on the standard.

2.2 Investigations for High Hardness and High Strength

In the abrasion resistant steel plates, first, improvement in the abrasion resistance of the plate, in other words, achieving high hardness in the plate, was studied. The hardness of steel plates is decisively determined by the C content and amount of martensite in the microstructure after quenching[2]. Accordingly, a composition design which simultaneously secures the C content for obtaining the target hardness and hardenability in order to achieve a full martensite structure after quenching is important.

The authors studied the effect of the C content on the hardness of the full martensite structure. As samples, steel plates with C contents of 0.10–0.32 mass% were used. Quenching was performed to these plates, and the surface Brinell hardness was measured after obtaining a full martensite structure (**Fig. 1**). It was found that the minimum C contents for obtaining HBW: 361 or higher or HBW: 477 or higher, which were the development targets for the hardness values of the abrasion resistant steel plates, were 0.14 mass% and 0.26 mass%, respectively.

Hardenability was studied with a maximum plate thickness of 32 mm, which was the development target, using the hardenability index D_I (defined in Eq.(1))[3,4] as an index of hardenability, considering a full martensite structure is obtained stably.

$$D_I = D_{IC} \times MF_{Si} \times MF_{Mn} \times MF_{Cr} \times MF_{Mo} \times MF_{Ni} \times MF_V \times MF_B \times MF_{Cu} \times 25.4\ (\text{mm}) \cdots (1)$$

$D_{IC} = (C/10)^{1/2} \times (1.70 - 0.09N)$
N: Austenite grain number
$MF_{Si} = 0.70Si + 1$
$MF_{Mn} = 3.33Mn + 1$
$MF_{Cr} = 2.16Cr + 1$
$MF_{Mo} = 3.00Mo + 1$
$MF_{Ni} = 0.36Ni + 1$
$MF_V = 1.75V + 1$
$MF_B = 1.3$ (With B addition)
$= 1.0$ (Without B addition)
$MF_{Cu} = 0.35Cu + 1$

Small cylindrical test pieces (3 mmϕ × 10 mm) were taken from a steel contains 0.14–0.15 mass% of C and various alloy elements including Cr, Cu, Ni, Mo, V, Ti, and B appropriately. Using a heat treatment simulator (Formastor; manufactured by Fuji Electronic Industrial Co., Ltd.), the samples were heated to above the Ar_3 point, then cooled under cooling rates of 0.5–40°C/s to investigate the critical cooling rate for obtaining a full martensite structure with the various chemical composi-

Table 1 Target properties of new abrasion resistant steel plates “JFE-EH360LE/EH500LE”

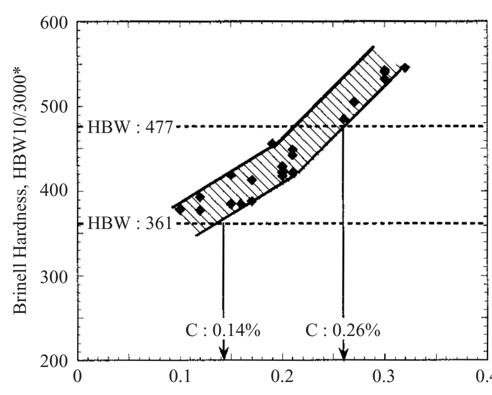
Grade	Thickness (mm)	Surface hardness, HBW10/3000	C_{eq}* (mass%)
JFE-EH360LE	6 –19	361–440	≦0.40
	19.1–32		≦0.43
JFE-EH500LE	6 –19	477–556	≦0.55
	19.1–32		≦0.58

Charpy absorbed energy value is guaranteed at −40°C.
* C_{eq} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5

Table 2 Target properties of new high strength steel plates “JFE-HITEN780LE”

Grade	Thickness (mm)	YS (MPa)	TS (MPa)	C_{eq}* (mass%)
JFE-HITEN780LE	6 –19	≧685	780–930	≦0.40
	19.1–32			≦0.43

Charpy absorbed energy value is guaranteed at −40°C.
* C_{eq} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5



*With 10 mmϕ ball subjected to a load of 3 000 kgf

Fig. 1 Effect of C content on surface hardness

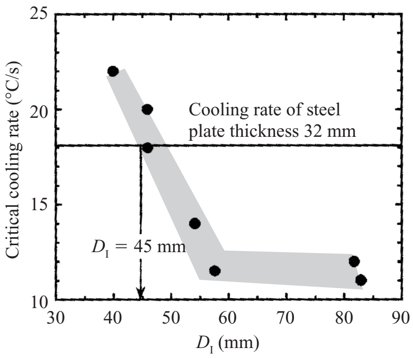


Fig. 2 Relationship between D_I and critical cooling rate to obtain martensitic structure

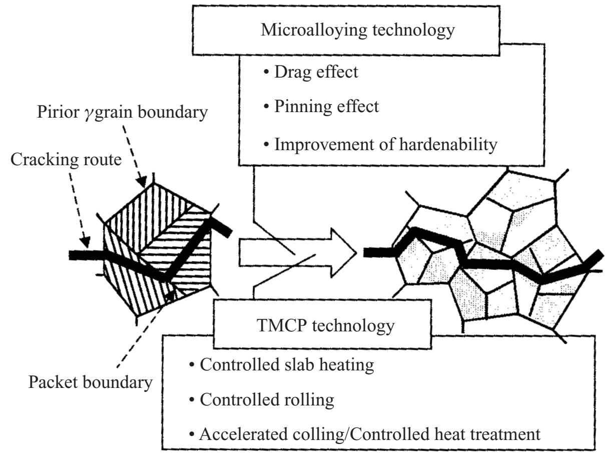


Fig. 3 Effects of microalloying and TMCP technology on refinement of packet size

tions. At this time, the D_I of the steels used in the investigation was set at 40–83 mm.

Figure 2 shows the relationship between the critical cooling rate and D_I. In order to obtain a full martensite structure after hardening under the cooling rate conditions for the thickness of 32 mm, which was the target maximum thickness, it was found that $D_I \geqq 45$ mm is necessary.

Accordingly, as the composition design of the abrasion resistant steel plates, C contents of 0.14% or more and 0.26% or more are necessary in order to obtain a high surface hardness HBW: 361 or higher or HBW: 477 or higher, respectively, and it is necessary to secure D_I of 45 mm or more while also reducing C_{eq} in consideration of weldability. As the manufacturing process, application of controlled heat treatment, in which the cooling rate during quenching and the stop temperature of quenching, etc. are controlled appropriately is effective for preventing delayed fracture and quenching cracks, which occur easily in high hardness steels such as abrasion resistant steel plates, and manufacturing plates with reduced heat treatment strain.

On the other hand, in order to satisfy both high strength and good weldability requirements in high strength steel plates, it is necessary to achieve high strength with a lower C_{eq}. The authors therefore investigated the effect of the C content and D_I on tensile strength. The results revealed that it is possible to satisfy both high strength of the 780 MPa class and good weldability requirements by selecting an appropriate C content and D_I and, furthermore, applying microalloying technology using micro-addition of elements such as Nb, Ti, V, etc. and a TMCP process with the on-line accelerated cooling device, *Super*-OLAC[5], which was developed and applied practically by JFE Steel originally.

2.3 Investigations for Improvement of Low Temperature Toughness

In martensitic steels, the fundamental unit of microstructure controlling toughness is a packet, and it is known that the packet size is reduced accompanying refinement of the prior austenite grain size[6]. In the present research, as shown in **Fig. 3**, prior austenite grains in martensitic steel were refined applying microalloying and TMCP technologies.

Microalloying elements, represented by Nb, Ti, and V, contribute to refinement of austenite grains through a drag effect due to solid solution atoms and a pinning effect due to precipitates. Furthermore, by dissolving in austenite, these elements also have the effect of improving hardenability. Based on the alloy design which is capable of obtaining these effects, refinement of austenite grains by slab reheating temperature control and controlled rolling/controlled heat treatment was studied as the manufacturing process.

Photo 1 shows the results of observation of the prior austenite grains in martensitic steel with the chemical composition in **Table 3**. By applying the above-mentioned austenite grain refining technologies, prior austenite grains, which were conventionally coarse, with a size on the order of 40–50 μm, were successfully refined to approximately 20 μm or less. **Photo 2** shows the cracking paths in the Charpy impact test with steel plates having the prior austenite grain size shown in Photo 1. Tests of the observed test pieces were performed at −196°C, which is the lowest possible temperature in the Charpy impact test. The photos show cross-sections of the microstructure of the fracture surface when brittle fracture was caused intentionally. In comparison with the conventional steel, irregularities in the fracture surface are fine in the developed steel. This shows that the size of the packet, which is the microstructural unit that controls toughness, has become smaller. Based on this result, it can be confirmed that refinement of packets has been achieved in the developed steel accompanying refinement of the prior austenite grains. The relationship between the prior

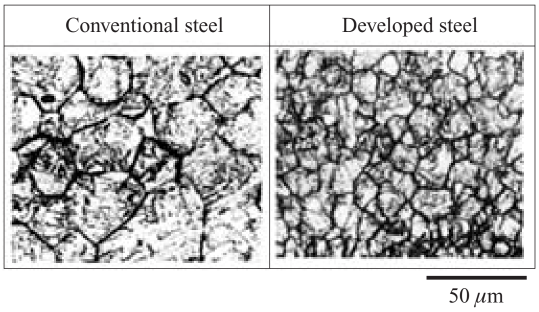


Photo 1 Prior austenite grains of developed and conventional steels

Table 3 Chemical compositions of developed and conventional steels (mass%)

	C	Si	Mn	P	S	Others	C_{eq}*	D_I (mm)
Developed steel	0.15	0.41	1.20	0.013	0.002	Nb, V, Ti, etc.	0.39	46
Conventional steel	0.15	0.34	1.44	0.020	0.006	Cr, Ti, B	0.45	48

* $C_{eq} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5$

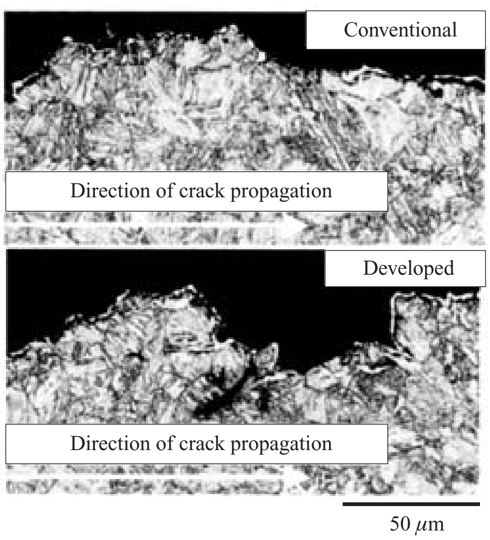


Photo 2 Cracking paths of developed and conventional steels

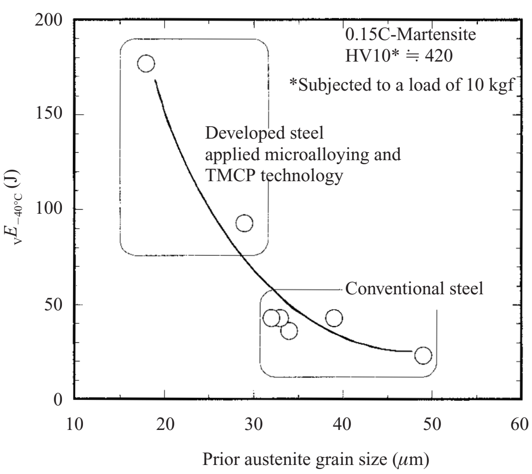


Fig. 4 Influence of prior austenite grain size on Charpy impact energy at −40°C

austenite grain size and low temperature toughness was investigated using 0.15 mass% C steel plates with a martensitic structure. The results are shown in **Fig. 4**. It was confirmed in advance that the hardness around the plate center-of-thickness position, where Charpy impact test pieces were taken, was substantially uniform in all of the steel plates, at approximately HV10: 420. As shown in Fig. 4, low temperature toughness improved accompanying refinement of the prior austenite grains. In the developed steel, a prior austenite grain size of 30 μm or less was obtained, and low temperature toughness improved remarkably.

3. Performance of Developed Steels

3.1 Abrasion Resistant Steel Plates for Construction and Industrial Machinery Use, "JFE-EH360LE/500LE"

Table 4 shows the typical chemical compositions of the developed abrasion resistant steel plates, "JFE-EH360LE" and "JFE-EH500LE." The maximum C contents, C_{eq}, and D_I values were selected considering the balance of plate surface hardness and weldability, and microalloying elements were added to achieve refinement of prior austenite grains. **Figure 5** shows the results of y-groove cold cracking tests of the developed steels. "JFE-EH360LE" is free of cracking at preheating temperature of 25°C and has excellent weldability. "JFE-EH500LE" has good enough weldability as the highest grade of hardness in abrasion resistant steel plates currently in use, its cracking stop temperature is 75°C. **Figure 6** shows the hardness and toughness of the developed steels. The developed steels has extremely good low temperature toughness as abrasion resistant steels, while also showing the same level of hardness as the conventional steels.

"JFE-EH360LE" and "JFE-EH500LE" are the first abrasion resistant steels in the world to guarantee toughness at −40°C. In addition to enabling use in cold districts, the life duratation of parts is also extended as a result of their improved impact damage resistance.

Table 4 Typical chemical compositions of JFE-EH360LE and JFE-EH500LE (mass%)

Grade	C	Si	Mn	P	S	Others	C_{eq}*
JFE-EH360LE	0.15	0.41	1.20	0.013	0.002	Nb, V, Ti, etc.	0.39
JFE-EH500LE	0.26	0.31	1.33	0.010	0.002	Nb, V, Ti, etc.	0.53

* $C_{eq} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5$

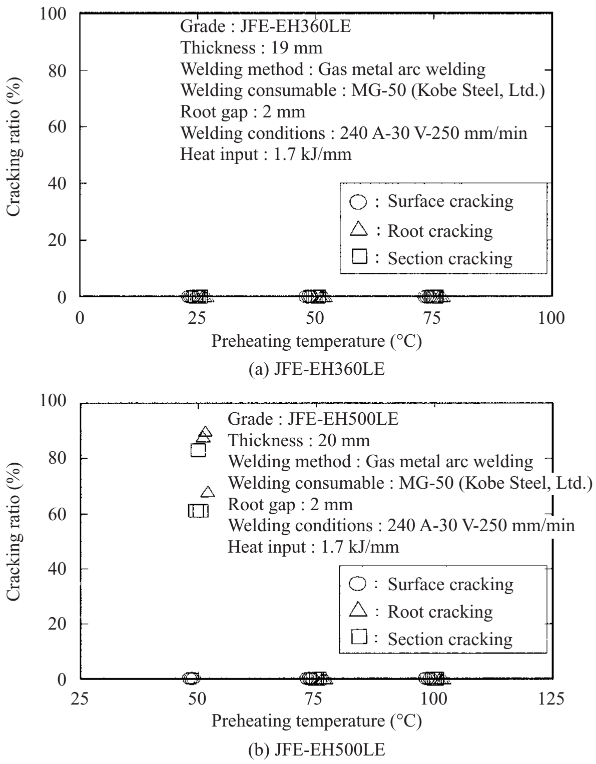


Fig. 5 y-groove cold cracking test results

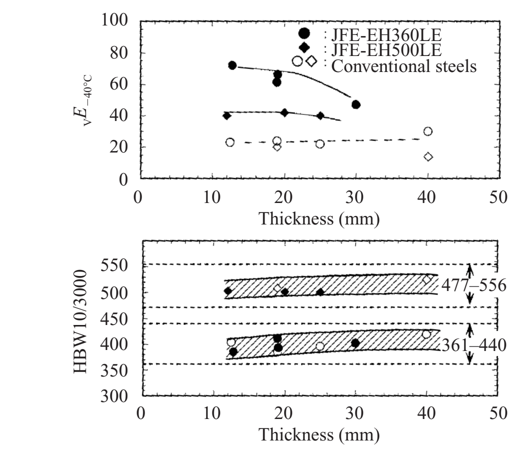


Fig. 6 Brinell hardness and Charpy impact test results of JFE-EH360LE and JFE-EH500LE

3.2 High Strength Steel Plate for Construction and Industrial Machinery Use, "JFE-HITEN780LE"

Table 5 shows the typical chemical composition of the developed high strength steel plate "JFE-HITEN780LE." In this developed steel, the low temperature toughness of 780 MPa grade high strength steel plate was markedly improved by applying microalloying technology and the thermo-mechanical control process, as represented by JFE Steel's *Super*-OLAC[5], and controlled heat treatment technology.

Table 5 Typical chemical composition of JFE-HITEN780LE (mass%)

C	Si	Mn	P	S	Others	C_{eq}*
0.15	0.38	1.18	0.012	0.002	Nb, V, Ti, etc.	0.39

* $C_{eq} = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5$

Figure 7 shows the strength and low temperature toughness of the developed steel. Is has an adequate strength as 780 MPa high tensile strength steel, combined with toughness significantly exceeding that of conventional steel plates. Moreover, as shown in **Table 6**, this steel also provides excellent formability, showing no cracking at a bending radius of 1.5 times the plate thickness, in the more severe 200 mm width bending test. In the results of a y-groove cold cracking test, as shown in **Fig. 8**, the developed steel has excellent weldability, with no cracking at a preheating temperature of 25°C.

The developed steel is the first in the world to guarantee toughness at −40°C, in the field of steel plates for construction and industrial machinery use enabling use in cold districts, and also offers excellent performance

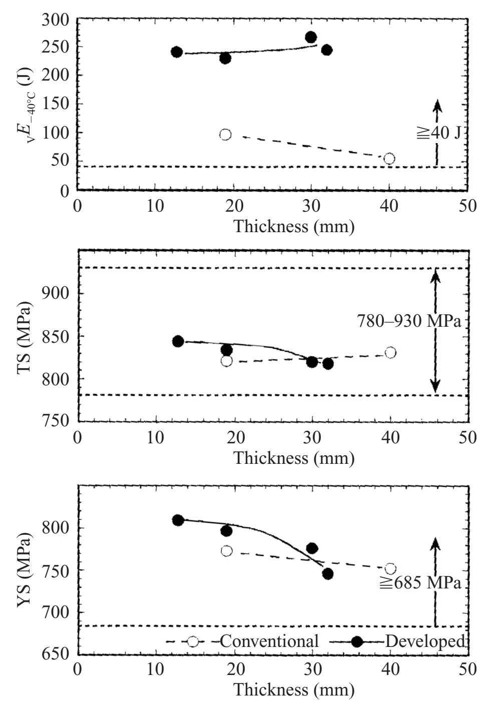


Fig. 7 Mechanical properties of JFE-HITEN780LE

Table 6 Bending test results of JFE-HITEN780LE (Bending radius: 1.5*t*)

Thickness (mm)	Specimen size Thickness × Width (mm)	Direction	Result
12.8	Full thickness × 38	L C	Good Good
	Full thickness × 200	C	Good
32.0	Full thickness × 38	L C	Good Good
	Full thickness × 200	C	Good

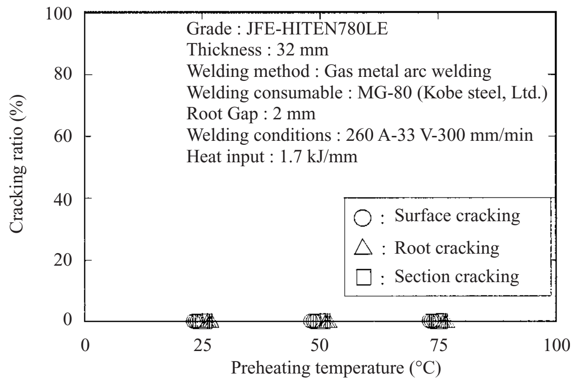


Fig. 8 y-groove cold cracking test result

in terms of impact resistance and safety. Because C_{eq} is reduced to secure weldability, the developed steel plate has good weldability, with no cracking at a preheating temperature of 25°C, making it an excellent product in terms of weldability as well. Moreover, because the new plate also has excellent bending formability, it can be used in a wide range of parts applications.

4. Conclusion

The developed steels, "JFE-EH360LE/EH500LE" and "JFE-HITEN780LE" (LE Series) are the world's first abrasion resistant steel plates/high tensile strength steel plates for construction and industrial machinery use to guarantee toughness at −40°C. These are outstanding products in many respects. In addition to enabling use in cold districts, they also offer excellent impact resistance and safety, and as a result of a reduced carbon equivalent (C_{eq}), they also provide superior weldability.

Since the start of sales of the developed steel in the "LE Series" in May 2001, these products have won an excellent reputation with many manufacturers of construction and industrial machinery, processing manufacturers, and transportation contractors around the world, and particularly in the Americas, Europe, and Australia. The cumulative total of orders received to date exceeds 30 000 t.

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