HIGH PERFORMANCE ABRASION RESISTANT STEEL PLATES USING MICROALLOYING TECHNOLOGY FOR GRAIN REFINEMENT

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Keywords: Abrasion Resistance, Wear Resistance, Low Temperature Toughness, Niobium, Microalloying, Grain Refinement, Hydrogen Embrittlement, Weldability

Abstract

In recent years, many additional material properties, such as weldability, low temperature toughness and resistance to delayed fracture, are required for abrasion resistant steel plates. However, all of these material properties usually show a trade-off relationship with strength and hardness. In response to these requirements, JFE steel has developed a series of high performance abrasion resistant steel plates known as the EVERHARD^{TM} LE series. The improved properties of these steels are discussed within this paper.

The effects of prior austenite grain size on the microstructure and properties of abrasion resistant steel plates were investigated and the results are presented and discussed in this paper. Microalloying technology, including the use of Nb, promotes austenite grain refinement during processing which produces a finer martensitic microstructure in the final product. As a consequence the low temperature toughness and resistance to hydrogen embrittlement are improved in the newly developed steel plates. The EVERHARD^{TM} LE series can be supplied with a guaranteed Charpy impact toughness at -40 °C. Crack-free welding of the EVERHARD^{TM} LE steels can be readily achieved by careful control of the consumable and the preheat temperatures.

Introduction

The requirements of steel plates for the mining and processing industry include excellent wear resistance against the abrasion effects caused by ore, rock or sand. Abrasion of steel plates is affected by surface hardness [1-5] and abrasion conditions such as the abrasive materials being handled and the local environment. Even though the abrasion resistance of the steel is improved by a dispersion of hard particles [6], such as carbides and retained austenite [7], surface hardness is the most important factor affecting the abrasion resistance of the steel. In order to increase the hardness of the steel plates, quenching is often used to produce a martensitic microstructure [8]. However, to obtain sufficient hardenability in thick plates, it is necessary to add alloying elements, depending on the plate thickness, and the increasing hardenability potentially leads to a deterioration of low temperature toughness and weldability. Additionally, requirements for the steel plates for use in construction and industrial machinery have diversified, for example, securing low temperature toughness to enable use in cold climates and improved weldability by lowering the required preheating temperature are the major aspects for expanding the application of abrasion resistant steels. Furthermore, hydrogen delayed fracture can be a possible failure mode when high strength steel with a tensile strength level of over 1000 MPa is used in wet or corrosive environmental conditions. Therefore, low temperature toughness, weldability and resistance to hydrogen embrittlement should be the primary issues to be addressed in developing abrasion resistant steel plate.

Considering an application of the abrasion resistant steels in the mining and processing industry, higher hardness is the essential material property. Therefore, a martensitic microstructure, which is obtained by a quenching treatment, is the starting point for material design. However, only increasing the hardness may result in reducing the toughness and resistance to hydrogen cracking of the steel. One of the key technologies to improve the properties is grain refinement with microalloying elements. Chemical compositions and plate manufacturing conditions are precisely controlled to avoid grain coarsening.

The authors reported [9] that grain refinement using NbC precipitation improved low temperature toughness and resistance to hydrogen embrittlement in HB 500 class abrasion resistant steel plates. Based on those results, JFE steel has developed a series of high performance abrasion resistant steel plates, EVERHARD^{TM} LE series, with a good balance of hardness, toughness and weldability. In this paper, the effects of prior austenite grain size on these properties in abrasion resistant steel plates are presented [9,10] and the features of the EVERHARD^{TM} LE series are introduced [11].

Experimental Procedures

Materials with Fine Prior Austenite Grains

HB 500 class abrasion resistant steel plates were used for the development program. Table I shows the chemical compositions of the steels. Two types of chemistries were used for obtaining different microstructures. Both steels contain approximately 0.3 wt.% carbon and several alloying elements to obtain sufficient hardenability, but additions of the microalloying elements such as Nb and Ti are different in the two steels. 25 mm thick steel plates were produced with application of a heat treatment. The concepts used for obtaining a fine microstructure are shown in Figure 1. Microalloying elements, such as Nb, Ti and V, contribute to the refinement of the austenite grains through a solute drag effect and a pinning effect by carbide precipitates. Furthermore, the dissolution of these elements in austenite also affects hardenability. Based on an alloy design that is capable of obtaining these effects, plate manufacturing parameters such as slab reheating temperature, controlled rolling and heat treatment were optimized to achieve a fine microstructure.

Table I. Chemical Compositions of Steels (wt.%)

	C	**Si**	**Mn**	**P**	**S**	**Nb**	**Others**	**Ceq**
Conventional steel	0.30	0.29	1.08	0.009	0.002	-	V, Ti, etc.	0.55
Developed steel	0.29	0.28	1.25	0.009	0.003	0.02	V, Ti, etc.	0.54

Ceq=C+Mn/6+(Cu+Ni)/15+(Cr+Mo+V)/5

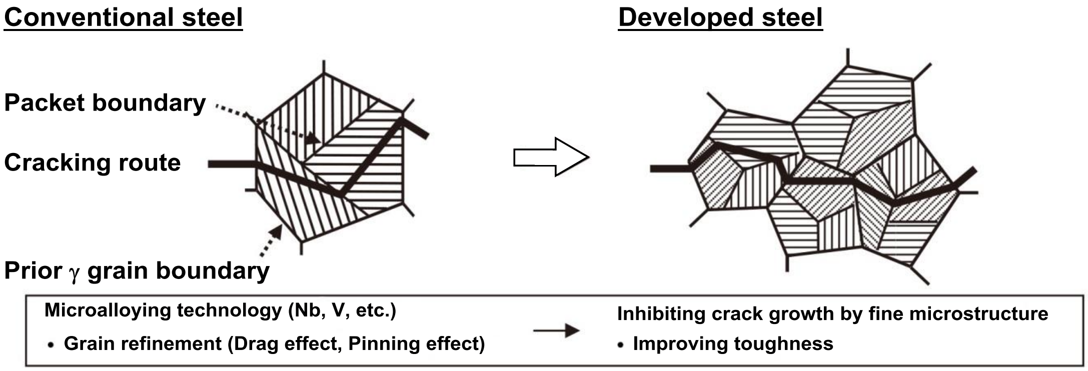


Figure 1. Schematic illustration of austenite grain refinement with microalloying technology.

Figure 2 shows photomicrographs of the prior austenite grains for the conventional abrasion resistant and the developed steels. By applying the above-mentioned austenite grain refining technologies, prior austenite grains, which were conventionally coarse, with a size of the order of 40–50 µm, were successfully refined to approximately 20 µm or less.

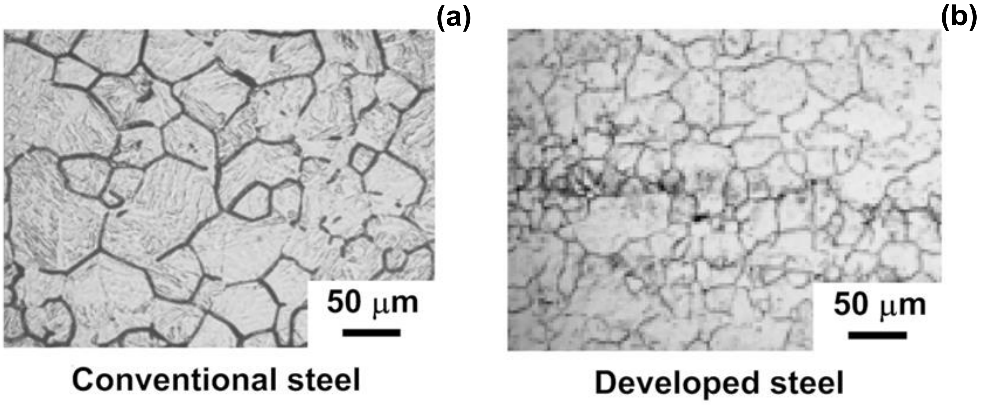


Figure 2. Prior austenite grains of; (a) conventional and (b) developed steel.

Procedures for Material Evaluation

Low temperature toughness was evaluated by Charpy impact tests conducted at -40 °C. Standard V notch specimens were used. Longitudinal Charpy specimens were machined from the quarter thickness position and parallel to the rolling direction of the steel plate.

Resistance to hydrogen embrittlement was evaluated by testing hydrogen charged tensile specimens. Round bar tensile specimens with a gauge length of 6.0 mm in diameter and 70 mm in length were machined from the mid-thickness location of the steel plates. Hydrogen charging was conducted by immersing the specimen into an aqueous 5% ammonium thiocyanate solution with different immersion times of 0.5 to 2 hours at 50 °C. Immediately after hydrogen charging, the specimens were immersed in liquid nitrogen at -196 °C for an hour. Subsequently, a tensile test was conducted at a constant crosshead speed at 5 mm/min to fracture at ambient temperature. Additionally, another specimen prepared under the same hydrogen charging conditions was subjected to hydrogen analysis. Diffusible hydrogen in the specimen was measured by hydrogen thermal desorption analysis using a gas chromatograph at a heating rate of 200 °C/hour.

Results and Discussion

Improvement of Low Temperature Toughness

For the use of abrasion resistant steels in cold climate regions, steels need to have sufficient toughness to prevent brittle fracture of the machine parts. Therefore, for the development of the improved HB 500 steel we set the target material Charpy impact toughness at a low temperature of -40 °C. Table II shows the surface hardness of the developed and conventional steels using the Brinell Hardness Test. Surface hardness of the steels was decisively controlled by C content for fully martensitic microstructures.

Table II. Surface Hardness of Developed Steel and Conventional Steel
from Brinell Hardness Test

	HBW 10/3000					
	Individual value					**Ave.**
Conventional steel	499	507	518	514	503	508
Developed steel	501	495	501	507	504	502

Reducing prior austenite grain size, resulting in a fine packet size, is quite effective [7] in improving the Charpy impact toughness. Figure 3 shows the Charpy energy values at -40 °C of the developed and conventional steels. Even with very high surface hardness levels, the Charpy toughness of HB 500 was improved significantly by refinement of the prior austenite grains.

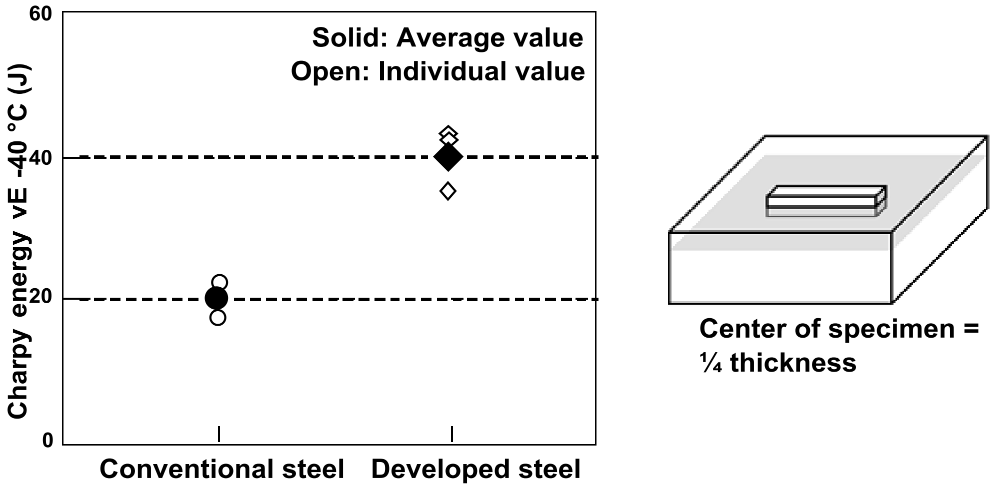


Figure 3. Charpy energy at -40 °C of developed and conventional steel.

Improvement of Resistance to Hydrogen Embrittlement

Figure 4 shows the relationship between diffusible hydrogen content and resistance to hydrogen embrittlement of the developed and conventional steels. The resistance to hydrogen embrittlement was evaluated by the safety index of the hydrogen embrittlement resistance given as R1/R0 x 100 (%), where R0 and R1 represent the reduction in area of the uncharged specimen and the charged specimen, respectively. As shown in Figure 4, the resistance to hydrogen embrittlement of the developed steel is good compared to the conventional steel.

Figure 5 shows scanning electron microscope (SEM) micrographs of fracture surfaces of the hydrogen charged specimens. The conventional steel shows intergranular fracture. On the other hand, the developed steel shows quasi-cleavage fracture. The resistance to hydrogen cracking of the developed steel is improved by suppression of intergranular fracture which results from the refinement of the prior austenite grains and the consequential refinement of the martensitic microstructure.

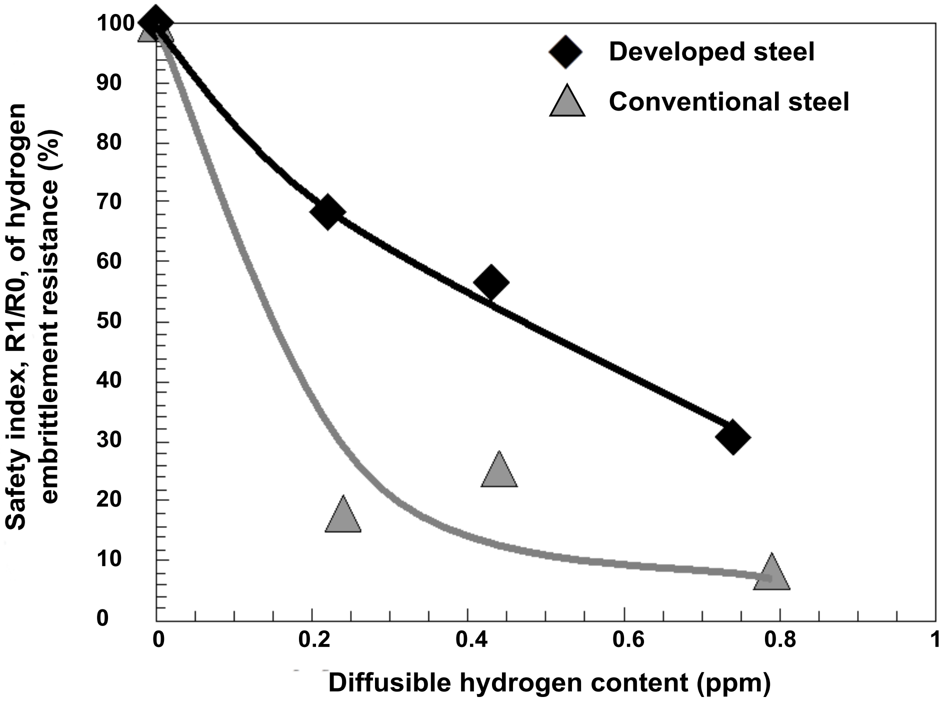
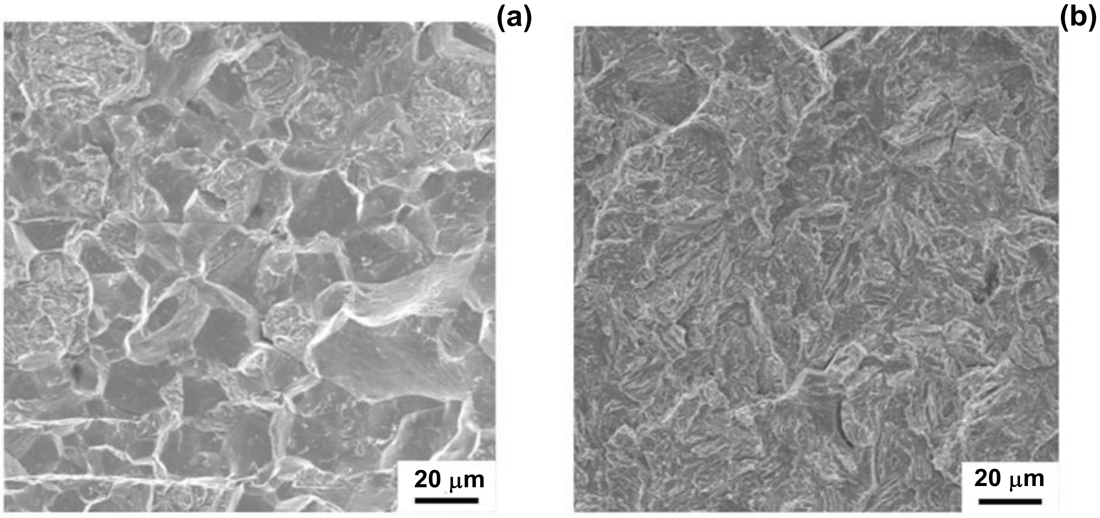


Figure 4. Resistance to hydrogen cracking of developed and conventional steel.



Conventional steel

Developed steel

Figure 5. SEM micrographs of tensile test fracture surfaces after hydrogen charging by immersing in aqueous 5% ammonium thiocyanate solution for half an hour.

Application of EVERHARD^{TM} LE Series

Grade Variants and Features

The microalloying technology for microstructural refinement described above was applied in the development of JFE steel's high performance abrasion resistant steel plates, named EVERHARD^{TM} LE series. The product grades and features of the LE series are shown in Table III together with data for the conventional steels. In the conventional "Standard Series", surface hardness is guaranteed by the alloy design and special heat treatment. In the "LE Series", low temperature toughness at -40 °C is also guaranteed by grain refinement through the use of microalloying technology including Nb. The guaranteed toughness enables the use of the LE series in arctic climates and also improves safety against external impact and forming by cold bending. In Table III, the numbers showing hardnesses of (400, 450, 500) represent the median values of the surface hardness range.

Because low temperature toughness tends to decrease as plate thickness increases, there was a limit to plate thickness with the conventional technology. However, in response to requests for heavier gauges for larger scale buckets or vessels, the maximum thickness of EVERHARD C400LE was increased from the conventional 32 to 60 mm, and a new product EVERHARD C450LE (maximum thickness: 50.8 mm) was developed. An increase in maximum thickness of EVERHARD C500LE from 32 to 50 mm is also under consideration.

Table III. JFE Steel's Abrasion Resistant Steel Plates EVERHARD^{TM} Series

Series	Features	EVERHARD Products	Grade	Surface hardness (HB)	Thickness (mm)	Charpy absorbed energy at -40 °C vE-40 (J)
Standard	Basic EVERHARD ^{TM} Basic alloy-design for economical and easy-welding fabrication	EVERHARD C340 EVERHARD C400 EVERHARD C450 EVERHARD C500 EVERHARD C550	HB 340 HB 400 HB 450 HB 500 HB 550	340±30 400±30 450±30 500±40 550±40	38-160 6-101.6 6-101.6 6-101.6 6-32	-
LE	Low temperature service Sufficient toughness at -40 °C	EVERHARD C400LE EVERHARD C450LE EVERHARD C500LE	HB 400 HB 450 HB 500	400±30 450±25 500±40	6-60 6-50.8 6-32	≥27 J (t≥12) ≥27 J (t≥12) ≥21 J (t≥12)

The relationship between the surface hardness and abrasion resistance of the EVERHARD^{TM} series is shown in Figure 6. Abrasion resistance is expressed by the weight loss ratio comparing the EVERHARD grade with a standard 400 MPa class mild steel in the rubber wheel abrasion test carried out in accordance with ASTM G65. The abrasion resistance of "Standard" and "LE series" shows a comparable dependence on hardness. The abrasion resistance of the HB 400 grade is approximately three times that of mild steel, and HB 450 and HB 500 class steels have outstanding abrasion resistance, approximately four and five times higher than mild steel respectively.

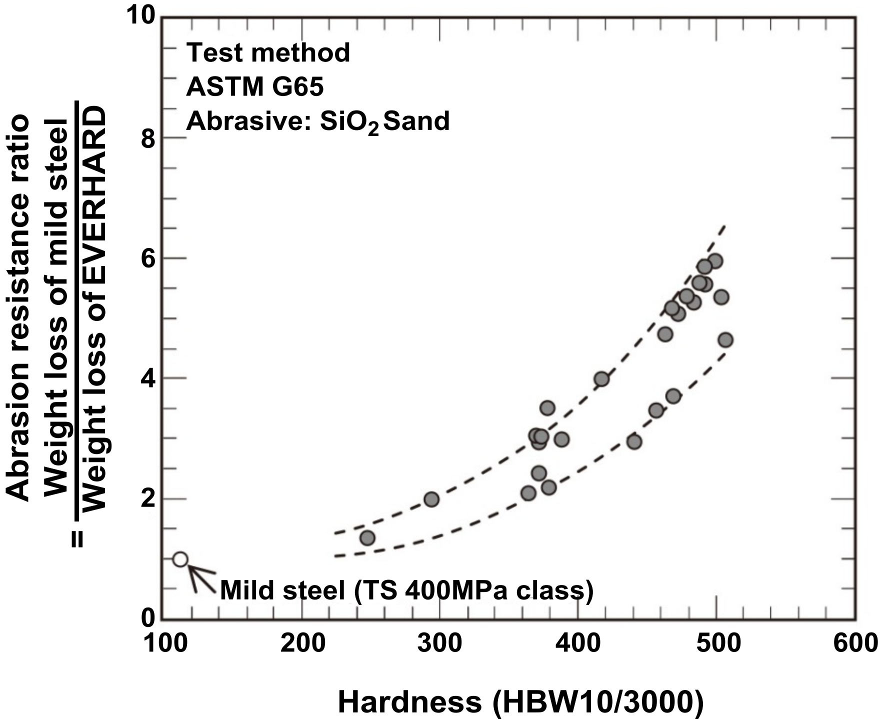
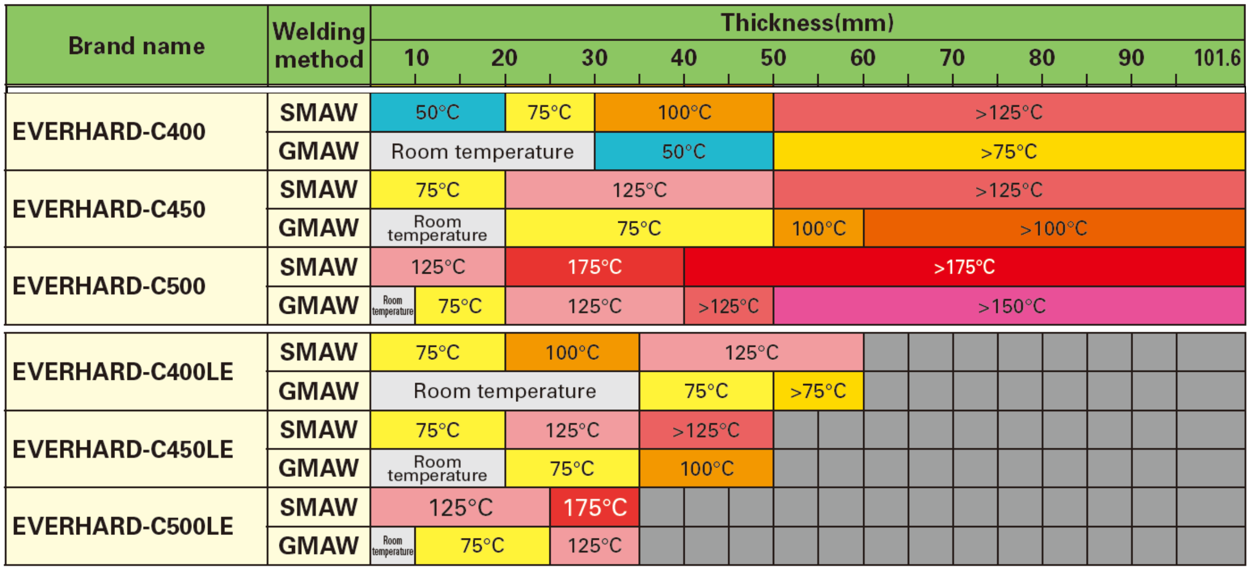


Figure 6. Relationship between hardness and abrasion resistance. The two lines represent the scattter band of results.

Weldability

High hardness, high strength steel plates generally display high sensitivity to low temperature cracking due to welding. In contrast, crack-free welding is possible with EVERHARD^{TM} grades with the use of controlled welding conditions. Low temperature cracks occur in weld metal or heat affected zone (HAZ) when these regions are embrittled by the penetration of hydrogen into the steel as a result of the welding process. However, this type of crack can be prevented by selection and control of welding consumables, etc. together with a correct application of preheating. For example, the recommended preheating temperatures for the "LE series" are shown in Table IV. These preheat values are based on the results of y-groove weld cracking tests (JIS Z 3158, JIS: Japanese Industrial Standards) and on evaluation of the steel chemical compositions for SMAW (shielded metal arc welding) using an ultra-low hydrogen welding electrode, and GMAW (gas metal arc welding) using a solid wire. Whereas these are examples in which restraint is comparatively large, it is also possible to simplify welding work by relaxing the preheating temperature corresponding to the restraint intensity in practical welding situations.

Table IV. Preheating Temperature Guideline for EVERHARD^{TM} Series



Brand name	Welding method	Thickness(mm)																		
		10		20		30		40		50		60		70		80		90		101.6
EVERHARD-C400	SMAW	50°C			75°C		100°C				>125°C									
	GMAW	Room temperature					50°C				>75°C									
EVERHARD-C450	SMAW	75°C			125°C						>125°C									
	GMAW	Room temperature			75°C						100°C		>100°C							
EVERHARD-C500	SMAW	125°C			175°C				>175°C											
	GMAW	Room temperature	75°C		125°C				>125°C		>150°C									
EVERHARD-C400LE	SMAW	75°C			100°C			125°C												
	GMAW	Room temperature						75°C			>75°C									
EVERHARD-C450LE	SMAW	75°C			125°C			>125°C												
	GMAW	Room temperature			75°C			100°C												
EVERHARD-C500LE	SMAW	125°C				175°C														
	GMAW	Room temperature	75°C			125°C														

⬜ Room Temperature
🟦 50°C
🟨 75°C
🟨 >75°C

🟧 100°C
🟧 >100°C
🟥 125°C
🟥 >125°C

🟪 >150°C
🟥 175°C
🟥 >175°C

Conclusions

Conventional abrasion resistant steels are usually designed to have a high surface hardness with minimal attention being paid to the toughness of the steel. However, as the applications for such steels become more severe, eg. use in colder climates, it has become necessary for steels to be developed with a guaranteed toughness requirement and improved resistance to hydrogen embrittlement.

The effects of prior austenite grain size control on the properties of quenched abrasion resistant steel plates were investigated with the aim of improving the steel toughness and resistance to hydrogen embrittlement by refinement of the final martensitic microstructure. The results are summarized as follows:

1. The inclusion of Nb in the alloy design resulted in a refined austenite grain size prior to quenching and a refined martensitic microstructure in the final quenched product.

2. Fine martensitic microstructures resulted in improved low temperature toughness and resistance to hydrogen embrittlement even for the higher hardness grades typically used as abrasion resistant steels.

3. Abrasion resistant steel plates of HB 400-500 class with fine microstructures, named the EVERHARD^{TM} LE series, were developed utilizing Nb microalloying for microstructure control. They exhibit excellent low temperature toughness, resistance to hydrogen embrittlement and improved weldability while maintaining a high surface hardness for good abrasion resistance.

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