High Performance Steel Plates for Bridge Construction —High Strength Steel Plates with Excellent Weldability Realizing Advanced Design for Rationalized Fabrication of Bridges—†

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Abstract:

A new YP500 MPa grade high strength steel plate was developed to meet the requirements of BHS500 (BHS: bridge high performance steel). Microstructure control of extremely-low carbon bainite steel by thermo-mechanical controlled rolling and controlled cooling by the Super-OLAC were applied to realize production of an as-rolled (non-heat-treated) high yield point steel with low P_{CM} *by an on-line process. The developed steel satisfied the required mechanical properties and showed satisfactory toughness after cold working and no deterioration in mechanical properties after the line-heating process. The maximum hardness of the heat affected zone (HAZ) was less than 280 points in Vickers hardness (HV) under small heat input conditions such as arc-strike, showing excellent welding hardening resistance, and no cracking occurred in the y-groove weld cracking test, indicating that preheating is not required for welding. Evaluation of butt welded joints produced by electro gas welding (EGW) and submerged arc welding (SAW) also revealed that the developed steel plate has good weldability.*

1. Introduction

Several hundred thousand tons of steel products are used in bridge construction every year. Recently, however, further rationalization of steel bridge fabrication in both the design and execution aspects has been strongly demanded from the viewpoint of energy saving and reduced initial construction costs. In the design aspect, rationalized steel bridges have been applied practically, and application of high strength steels with excellent weldability also tends to increase. As a high strength steel for bridges, SM570 (YP ≧ 450 MPa (YP: yield point)), as specified in the Japanese Industrial Standards (JIS), is generally used as the highest strength grade. However, it has been reported that HPS70W (YP ≧ 485 MPa) was already used practically as a high performance steel in 1997 in the United States, and contributed to cost reduction in steel bridge fabrication[1)].

Taking account of this background, BHS500 (YP ≧ 500 MPa) and BHS700 (YP ≧ 700 MPa) were proposed in Japan as bridge high performance steels (BHS) with appropriate performance in bridge applications[2)]. Adoption of high strength steel also contributes to reduction of the weight of steel bridges. However, considering the problems of buckling and fatigue strength, using higher yield point steel do not always lead to reduction of steel weight and in general bridges, approximately 500 MPa is considered to be the rational upper limit on the strength grade. On the other hand, in bridge types where it is possible to utilize the tensile strength of the steel to the fullest extent, as in truss structures, YP700 MPa grade steel, which has an even higher strength level, can be used effectively.

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As a steel corresponding to BHS700, JFE Steel has already developed an preheat-insensitive HT780 steel[3,4]. On the other hand, BHS500 is an advanced high performance steel which achieves higher strength than the conventional SM570, while also eliminating the need of preheating for welding by applying thermo-mechanical control process (TMCP) technology. Fabrication performance is also equal or superior to that of conventional steels.

In order to meet to these requirements, JFE Steel applied microstructure control of an extremely-low carbon bainitic steel and controlled cooling using the *Super*-OLAC, making it possible to manufacture an as-rolled high yield point steel with a low P_{CM} (weld cracking coefficient). This paper describes the metallurgical features of property control of the base material and the mechanical properties, workability, weldability, and welded joint performance of the steel plates.

2. Performance Targets

Table 1 shows the property targets for BHS500 in comparison with the JIS SM570 standard. The yield point and Charpy absorbed energy values are higher than those of JIS SM570. To reduce preheating work for welding, $P_{CM} \leqq 0.20$ is stipulated. In general, the P_{CM} value increases as the strength of steel is increased. Thus, it can be said that the new steel is an extremely high performance product, as it satisfies the mutually-contradictory requirements of improving weldability by maintaining a low P_{CM} while achieving a higher strength level than the conventional steel.

Where weldability is concerned, large heat input welding up to 10 kJ/mm is allowable. This supposes application of electro gas welding (EGW) of web joints in field welding.

Considering the bridge fabrication process, excellent cold workability enabling bending to a radius of 7*t* (*t*: plate thickness) is required. It is also a performance requirement that straightening by the gas flame heating method after welding is possible under the same conditions as with conventional steels.

3. Features of Extremely-Low Carbon Bainite-type YP500 MPa Grade Steel Plate

When the carbon content of a steel is reduced to 0.02 mass% or less, which is the maximum solid-soluble limit to ferrite, and a bainitic single phase microstructure is formed by adjusting the chemical composition, the steel displays the distinctive transformation behavior of showing virtually no change in its microstructure over a wide range of cooling rates. Utilizing this feature, JFE Steel has already developed steel plates commercially which satisfy the JIS SM570TMC standard with air-cooling after plate rolling[5–7]. Because the cooling rate dependence of the microstructure is small in extremely-low carbon bainitic steel, strength deviations in the plate thickness direction are slight, and the plate also possesses excellent weldability.

In order to expand these features of extremely-low carbon bainitic steel to as-rolled (non-heat-treated) YP500 MPa grade steel, techniques for strengthening in yield point were examined. The extremely-low carbon bainite microstructure can be classified depending on the shape as quasi-polygonal ferrite, granular bainitic ferrite, and bainitic ferrite[8]. With the former two structures, transformation occurs at progressively higher temperatures and strength is somewhat low, these differences being greatest with quasi-polygonal ferrite. In extremely-low carbon bainitic steel corresponding to the aforementioned SM570TMC standard (YP ≧ 450 MPa), the microstructure comprises mainly granular bainitic ferrite, but this steel has a mixed microstructure which also contains some quasi-polygonal ferrite. Quasi-polygonal ferrite is a soft phase which transforms at a high temperature, and is a cause of reducing YP. Thus, to meet the requirements of YP500 MPa, it is necessary to avoid the formation of this soft phase and secure granular bainitic ferrite or a mixed microstructure with bainitic ferrite. **Photo 1** shows an example of the microstructures of steels which have the same chemical composition but different yield points. Although both have extremely-low carbon bainite microstructure, in

Table 1 Property targets of steel plates and their welded joints

Grade	Steel plate							Welded joint	
	Tensile test					Charpy impact value, $_vE_{-5}$ (J)	P_{CM} (%)	Heat input (kJ/mm)	$_vE_{-5}$ (J)
	Yield strength and tensile strength			Elongation					
	Thickness (mm)	YP (MPa)	TS (MPa)	Thickness (mm)	El (%)				
BHS500	$6 \leqq t \leqq 100$	≧ 500	≧ 570			≧ 100	≦ 0.20	≦ 10	≧ 47
JIS G 3160 SM570	$t \leqq 16$	≧ 460	570–720	$t \leqq 16$	≧ 19	≧ 47	≦ 0.28 ($t \leqq 50$)	≦ 7[9]	≧ 47
	$16 < t \leqq 40$	≧ 450		$16 < t \leqq 20$	≧ 26		≦ 0.30 ($50 < t$)		
	$40 < t \leqq 75$	≧ 430		$20 < t \leqq 100$	≧ 20				
	$75 < t \leqq 100$	≧ 420							

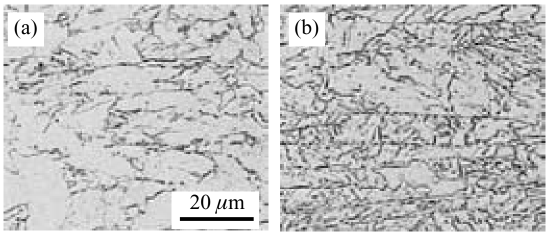

Photo 1 Examples of microstructure of extremely-low carbon bainitic steel (a) YS = 485 MPa (b) YS = 535 MPa

the microstructure in Photo 1 (b), which corresponds to the YP500 MPa grade, prior austenite grain boundaries can be clearly observed, and the generation of quasi-polygonal ferrite from the grain boundaries has been suppressed.

To achieve the above-mentioned microstructure control, accelerated cooling was applied after rolling. With general low carbon steels, it is impossible to achieve the optimum microstructure from the surface to the center of plate thickness due to the cooling rate dependency of the microstructure, and for this reason, manufacture of as-rolled thick plates is difficult. However, this problem was overcome by utilizing the extremely-low carbon bainite microstructure and uniform cooling using the *Super*-OLAC technology, enabling production of as-rolled thick steel plates exceeding YP500 MPa.

4. Properties of Developed Steel

4.1 Mechanical Properties of Base Material

Table 2 shows the chemical compositions of the developed steel. The carbon content is adjusted to 0.02 mass%, and alloy components are added corresponding to the plate thickness to obtain a bainitic single-phase microstructure. The value of P_{CM} is extremely low, being 0.13 mass% and 0.16 mass% with plate thicknesses of 25 mm and 60 mm, respectively.

Photo 2 shows the microstructures of the respective plates at the 1/4 and 1/2 thickness positions. In all cases, the microstructure is controlled to granular bainitic ferrite or a mixed microstructure with bainitic ferrite, and virtually no differences in the microstructure depending on the plate thickness or the thickness position can be observed. **Figure 1** shows the hardness distribution in the thickness direction in the 60 mm plate. A flat hardness distribution around HV = 200 points has been obtained in the thickness direction, with no increase in hardness at the surface. Thus, it can be understood that material properties are extremely uniform in the thickness direction.

Table 3 shows the results of a tensile test and Charpy

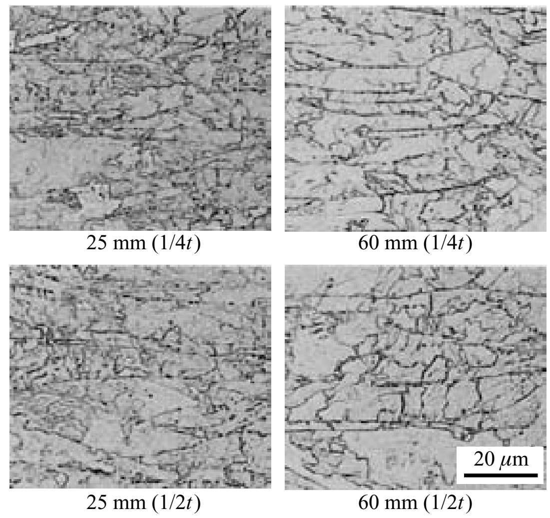

Photo 2 Microstructure of YS500 MPa grade extremely-low carbon bainitic steel

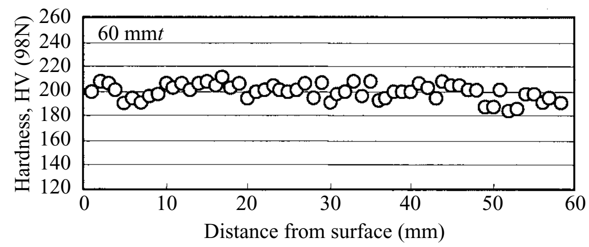

Fig. 1 Hardness distribution over the thickness of the steel plate

Table 3 Mechanical properties of steel plates

Thickness (mm)	Position	Direction	YP (MPa)	TS (MPa)	El (%)	$_{V}E_{-5}$ (J)
25	1/4*t*	L	587	684	27	361
		C	611	709	26	276
	1/2*t*	L	582	681	27	355
		C	611	703	25	278
60	1/4*t*	L	513	595	29	311
		C	529	613	27	256
	1/2*t*	L	508	589	28	340
		C	527	610	28	252

Table 2 Chemical compositions of steel plates

(mass%)

Thickness (mm)	C	Si	Mn	P	S	Others	C_{eq}	P_{CM}
25	0.02	0.30	1.57	0.008	0.003	Cu, Ni, Cr, Nb, Mo, B	0.31	0.13
60	0.02	0.25	1.54	0.014	0.003		0.39	0.16

P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + 5B
C_{eq} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14

impact test of the steel plates. With both plates, YP satisfies the target value of 500 MPa. Furthermore, Absorbed energy at −5°C is 250 J or higher, amply satisfying the target value of 100 J, and confirming that the plates possess excellent toughness.

4.2 Workability Test

When cold working is performed in a steel plate, there is possibility of deterioration in the toughness of base materials. Therefore, a strain-aged test was performed to confirm that a Charpy absorbed energy of 47 J can be secured even after bending working. Specifically, a Charpy impact test was performed with test pieces which had been given aging treatment at 250°C for 1 h after 5% or 10% plastic strain. The 10% prestrain applied here is equivalent to working at a bending radius of 5 times the plate thickness, and thus is a more severe evaluation than working at a bending radius of 7*t*, as mentioned above. The test results are shown in **Table 4**. The Charpy absorbed energy exceeded 47 J at the test temperature of −5°C, showing satisfactory bending workability.

Table 4 Results of strain aging test

Thickness (mm)	Position	Direction	$_{v}E_{-5}$ (J)	
			5% strain	10% strain
25	1/4*t*	L	285	130
60	1/4*t*	L	173	142

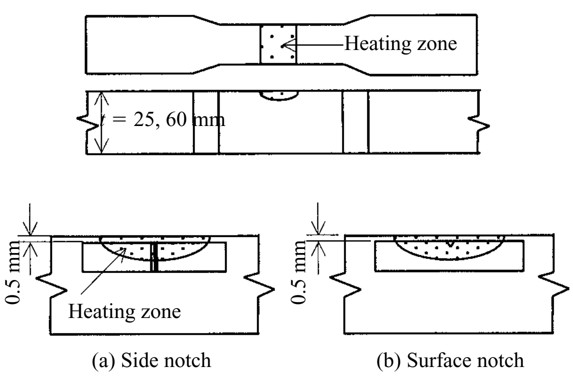

Fig. 2 Preparation of tensile test specimen and location of V-notch Charpy impact specimen

To secure dimensional accuracy after welding in steel bridge fabrication, straightening work by the gas flame heating method is unavoidable. The specified line-heating conditions for TMCP steels with a carbon equivalent (C_{eq}) exceeding 0.38 mass% are air cooling after heating to a maximum plate surface temperature of 900°C or water quenching at a maximum temperature of 500°C after air cooling. With C_{eq} of 0.38 mass% or less, the specification is immediate water quenching or air cooling after heating to a maximum plate surface temperature of 900°C[9]. It is also necessary to confirm that there is no deterioration in the material properties of the steel after the line-heating in these conditions. Here, a line-heating test was performed under a stricter condition of a maximum heating temperature of 1 000°C, and a full-thickness tensile test at the positions shown in **Fig. 2** and Charpy impact test of the surface layer were performed. The hardness of the heated zone was also tested.

Table 5 shows the results. Under all conditions, the strength satisfied a yield point value of 500 MPa or higher. Likewise, absolutely no deterioration in toughness could be observed, and the maximum hardness of the heated zone was HV = 277 points. These results confirmed that this steel maintains satisfactory base material properties even after line-heating to a plate surface temperature of 1 000°C, demonstrating that straightening work can be performed by the gas flame heating method with no problems.

4.3 Weldability Tests

A maximum hardness test was performed as specified in JIS Z 3101. The test piece was a 20 mm reduced thickness test piece, with the bead length varied from 125 mm to 10 mm. A test was also performed under arc-strike condition. For comparison, a conventional quench and tempered steel (SM570Q, P_{CM} = 0.22 mass%) was also tested. **Figure 3** shows the relationship between the bead length and the maximum hardness of the heat affected zone (HAZ). Developed steel showed extremely

Table 5 Mechanical properties of the steel plates after line-heating treatment

Thickness (mm)	Maximum heating temperature (°C)	Cooling conditions	YP (MPa)	TS (MPa)	El (%)	$_{v}E_{-5}$ (J)		Maximum hardness, HV
						Side notch	Surface notch	
25	900	Immediate WQ	599	697	33	300	396	277
		WQ from 600°C	607	675	34	358	416	246
	1 000	Immediate WQ	566	676	38	357	379	275
		WQ from 600°C	575	667	34	396	394	238
60	900	Immediate WQ	521	610	52	301	247	267
		WQ from 600°C	518	602	52	254	392	239
	1 000	Immediate WQ	516	605	48	315	199	265
		WQ from 600°C	509	589	51	264	372	223

Table 6 Welding condition for y-groove weld cracking test and results

Thickness (mm)	Atmosphere		Preheat temperature (°C)	Welding conditions				Crack ratio		
	Temperature (°C)	Humidity (%)		Rod	Current (A)	Voltage (V)	Speed (mm/s)	Surface (%)	Root (%)	Section (%)
60	20	60	20	LB-62UL (4 mmϕ)	170	25	2.5	0.0	0.0	0.0
								0.0	0.0	0.0
								0.0	0.0	0.0

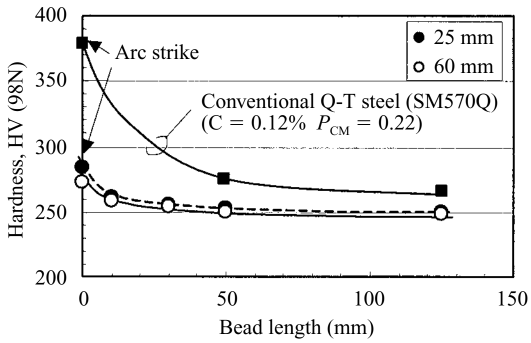

Fig. 3 Result of maximum hardness test

small hardening due to the increased cooling rate accompanying reduced bead length, and Vickers hardness was 280 points or less, even under arc-strike welding condition. This is a sufficiently low value in comparison with the 350 point value, which is generally the upper limit on the maximum hardness of the HAZ for preventing weld cracking. At present, Specifications for Highway-bridges specify that the leg length of fillet welds must be $\sqrt{2t}$ (t: plate thickness) or more from the viewpoint of preventing cold cracking, but there is a possibility that this can be relaxed.

Table 6 shows the results of a y-groove weld cracking test performed in accordance with JIS Z 3158 using 60 mm thick steel plate. The test was carried out under test environment conditions of temperature: 20°C and humidity: 60%. Cracking was not observed, even without preheating. Accordingly, it can be said that this steel sufficiently meets requirements for omission of preheating in general welding condition.

4.4 Performance of Welded Joints

Welded joints were prepared by single-layered EGW and multi-layered submerged arc welding (SAW) using steel plates with thicknesses of 25 mm and 60 mm to investigate the mechanical properties of welded joints. **Table 7** shows the conditions used in fabricating the welded joints. With the steel plate of 25 mm thick, a large heat input of 12 kJ/mm was applied, which exceeds the proposed allowable heat input of 10 kJ/mm. The welding wires were products suitable to the conventional JIS Z 3319 YFEG-32C with EGW and a JIS Z 3183 S624-H3 equivalent with SAW.

Figure 4 shows the hardness distribution of the

Table 7 Welding conditions

Welding method	Thickness (mm)	Welding wire	Welding flux	Shielding gas	Preheating temperature (°C)	Current (A)	Voltage (V)	Speed (mm/s)	Heat input (kJ/mm)	Groove shape
EGW	25	DWS-60G 1.6 mmϕ	–	CO_2 100%	Room temperature	380	38	1.17	12.3	V
SAW	60	KW101B 4.8 mmϕ	KB110	–	Room temperature	750–850	34–38	4.6–5.5	5.1–6.9	X

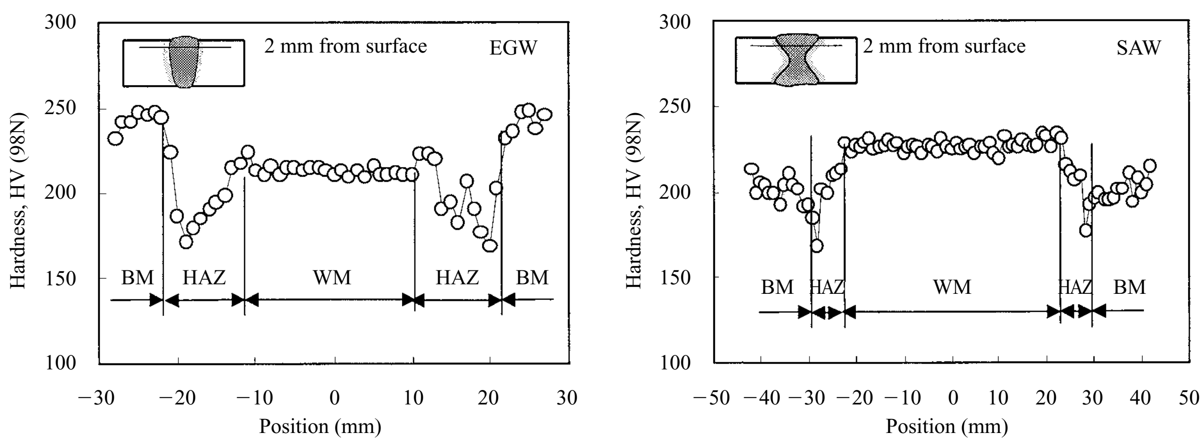

Fig. 4 Hardness distribution of the welded joints

Table 8 Mechanical properties of butt welded joints

Welding method	Thickness (mm)	Tensile test		Bend test	Charpy impact value, ${}_VE_{-5}$ (J)				
		TS (MPa)	Position of failure	Side bend, $R = 2.0t$	Weld metal	Bond	HAZ 1 mm	HAZ 3 mm	HAZ 5 mm
EGW	25	619	HAZ	Good	109	86	187	213	331
SAW	60	620	BM	Good	154	178	250	282	333

respective welded joints 2 mm below the surface. In the multi-layered SAW joint, slight softening of the HAZ was observed. With the single-layered EGW joint, the minimum value of hardness in the HAZ exhibited some softening (HV = 170), but as shown in **Table 8**, welded joint tensile strength of 619 MPa was secured. The tensile strength of the multi-layered SAW joint showed values equivalent to the base material, and the results of the side bend test of the welded joint were also satisfactory. The notch positions in the Charpy impact test of the welded joints were the 1/4 thickness position at the weld metal, bond, and HAZ 1 mm, 3 mm, and 5 mm from the fusion line. The impact values of both joints satisfied specifications at all notch positions, showing good welded joint toughness.

5. Conclusion

An as-rolled YP500 MPa grade steel plate with excellent weldability, corresponding to bridge high performance steel (BHS500), was developed. The features and results obtained with this plate are summarized below.

(1) By applying controlled cooling to extremely-low carbon bainitic steel, it is possible to manufacture high strength steel plates of 50 mm thick or thicker which satisfy YP ≧ 500 MPa.

(2) The maximum hardness of the heat affected zone (HAZ) is 280 points or less in Vickers hardness, even under small heat input welding conditions such as arc-strike, showing excellent resistance to welding hardening. Furthermore, no cracks were generated in the y-groove weld cracking test, indicating excellent resistance against cold cracking.

(3) In a strain-aged test, the developed steel had sufficient Charpy absorbed energy after 10% prestrain, confirming that bending forming at a radius of 7*t* (*t*: plate thickness) can be performed without problems.

(4) In a line-heating test, the developed steel showed virtually no deterioration in the properties of the base material at a maximum heating temperature of 1 000°C, confirming that efficient execution of straightening work by the gas flame heating method

Table 9 List of JFE Steel's steel plates for bridge construction

Use, Class			JFE Standard	JIS Standard
Structual steel	Low yield stress steel plate		JFE-LY100 JFE-LY160 JFE-LY225	
	Ordinaly steel plate			JIS G 3101 SS400 JIS G 3101 SM400
	High strength steel plate	Preheat-insensitive	SM490Y-EX SM520-H-EX SM570(-H)-EX JFE-HITEN780EX	JIS G 3106 SM490Y JIS G 3106 SM520 JIS G 3106 SM570 JIS G 3128 SHY685
		Large heat input welding	SM490Y-EG SM570-EG	JIS G 3106 SM490Y JIS G 3106 SM570
		High weldability	SM570TMC(-H)(-LB)	JIS G 3106 SM570
Weathering steel plate	Ordinaly steel plate			JIS G 3114 SMA400W
	High strength steel plate	Preheat-insensitive	SMA490W(-H)-EX SMA570W(-H)-EX	JIS G 3114 SMA490W JIS G 3114 SMA570W
		Large heat input welding	SMA490W-EG SMA570W-EG	JIS G 3114 SMA490W JIS G 3114 SMA570W
		High weldability	SMA570TMC(-H)(-LB)	JIS G 3114 SMA570W
	Ni added weathering steel plate for coastal use		JEF-ACL400Type 1, 2 (SMA400W-MOD) JEF-ACL490Type 1, 2 (SMA490W-MOD) JEF-ACL570Type 1, 2 (SMA570W-MOD)	
Longitudinally profiled steel plate			Tensile strength grade 400, 490, 570 N/mm^2	

is possible.

(5) The properties of single-layered EGW and multi-layered SAW welded joints satisfied the required values for both welded joint strength and welded joint Charpy impact properties.

Based on this excellent performance, further rationalization in bridge fabrication is considered possible by applying the developed steel and a design which makes the maximum use of this performance.

Finally, **Table 9** summarizes the standards of representative steel plates for bridge construction which can be manufactured by JFE Steel.

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