DEVELOPMENT OF Nb-BEARING HEAVY STEEL PLATES WITH ULTRA HIGH STRENGTH AND EXCELLENT TOUGHNESS

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Abstract

Large engineering machinery is widely used all over the world and the market is still growing. Therefore, the demand for high strength and ultra-high strength steel plates with good toughness is increasing. To satisfy this need, Baosteel has developed Nb-bearing high strength heavy plates with high toughness and good weldability by direct quenching (DQ) or direct quenching and tempering (DQ+T) processes. With Nb/Nb+Mo microalloying, heavy plates with yield strengths from 690 to 1150 MPa were developed. The microstructures of these steel plates were composed of bainitic ferrite plates with 0.1~1.5 μm thickness and martensite-austenite constituent decorating the boundaries of the bainitic ferrite plates. Spherical cementite precipitates were observed at the bainitic ferrite boundaries after the tempering process. It was found by instrumented impact experiments that the steel plates exhibited good crack arrest properties at -40 °C. Steel plates with yield strengths of 690/890/1150 MPa, for which the C contents are less than 0.11% and carbon equivalents are less than 0.59%, have excellent weldability. These steels are commercially produced and already widely used in the mining industry.

Background

Construction and machinery equipment used in the engineering sector, such as truck cranes, concrete mixers and hydraulic supports for coal mining are growing in size and being used in increasingly severe working conditions. Therefore, the demands for high strength steel plates with excellent toughness are growing accordingly. Heavy steel plates with good weldability, good ability to arrest cracks and high resistance to delayed fracture, are expected by the market. Steel plates with improved performance were developed to meet the market demand [1-3].

In recent years, coal has accounted for about 70% of China's primary energy production and consumption. In order to improve productivity and decrease accidents, mining machinery, such as hydraulic supports, has been an area of rapid development. For coal mine machinery, steel accounts for 95% of total equipment weight. According to the available statistics, every 100 million tons of coal produced would consume about 60,000 to 80,000 tons of steel plates.

Baosteel has developed Nb bearing Q690CF, Q890CF and Q1150 steels to meet these needs. Heavy plates of Q690, Q890 and Q1150 have minimum yield strengths of 690 MPa, 890 MPa and 1150 MPa respectively. By refinement of bainitic ferrite plates and a uniform dispersion of martensite-austenite constituent or cementite, heavy plates show high -40 °C toughness, and good resistance to delayed fracture. Furthermore, the developed steel plates show excellent weldability due to the low C content (<0.11%) and low carbon equivalent.

This paper aims to introduce the development of these Nb-bearing heavy plates and then describes the applications of these plates in the coal mining industry.

Nb-bearing High Strength Heavy Plate

Concepts of Nb-bearing Materials Design

To obtain high strength and good weldability, steel plates with Nb/Nb-Mo and low C content were developed. The austenite grains of continuously cast slabs are refined by Ti and Al addition. Therefore, the complex interaction of Nb, Ti, Al, Mo and C, N, O should be considered before designing new steel plate compositions. Figure 1 shows that oxides of Al, Ti and Mg are formed at higher temperatures. Consequently, carbides and nitrides of Ti are formed in the temperature range 1000-1350 K followed by precipitation of NbC and NbN. To maximize the effects of Nb, an optimized Ti amount should be added to form carbides and nitrides whilst avoiding formation of coarse TiN precipitates which are detrimental to fatigue and fracture properties.

Figure 2 shows Nb contents in austenite and precipitates for different total Nb and C contents under thermodynamic equilibrium conditions. It is obvious that the contents of Nb in austenite and precipitates increase with total Nb content. Complex precipitates consume more Nb at high C contents. It is well known that Nb in austenite increases the recrystallization temperature. Sufficient Nb in austenite is beneficial to obtain fine austenite grains through dynamic recrystallization. Furthermore, a fine final microstructure can be produced from a fine austenite microstructure which can support more bainitic ferrite nucleation sites.

From the above discussion, Nb, C and Ti contents need to be optimized for producing heavy plates with a fine microstructure. Ti was added to form TiN and Ti_xO_y for consuming N and O. To obtain the optimum amount of Nb in austenite, Nb and C contents were optimized. At the same time, the C content was determined from consideration of the thermodynamics of bainite transformation and bainitic ferrite growth kinetics. Coupling the above theoretical analyses, high strength steel plates with good toughness and weldability were developed.

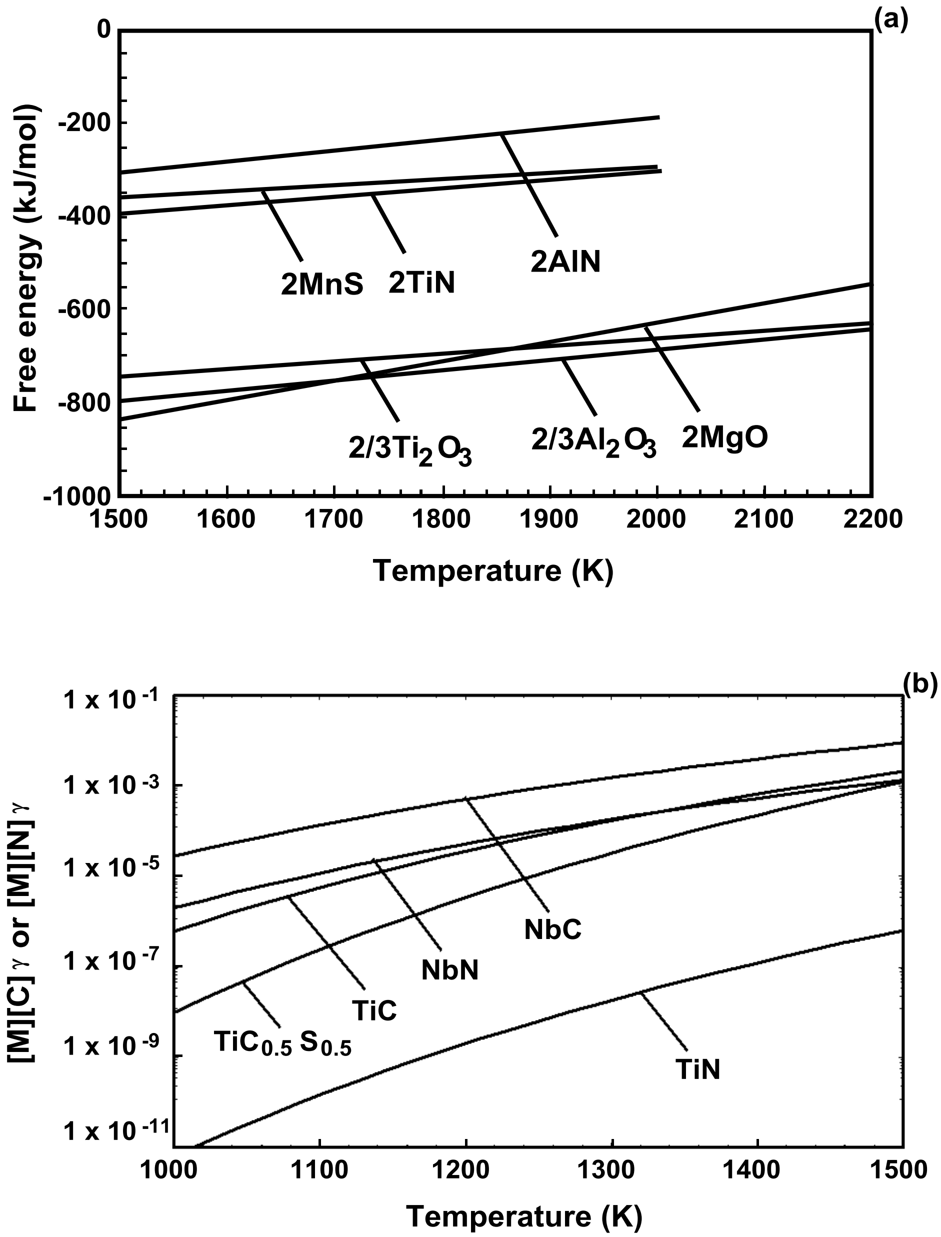


Figure 1. Oxides, carbides and nitrides formed at different temperatures; (a) Chemical driving force of compounds at high temperature, (b) Solubility of carbides and nitrides of Nb, Ti in austenite (S: 0.003wt.%) [4].

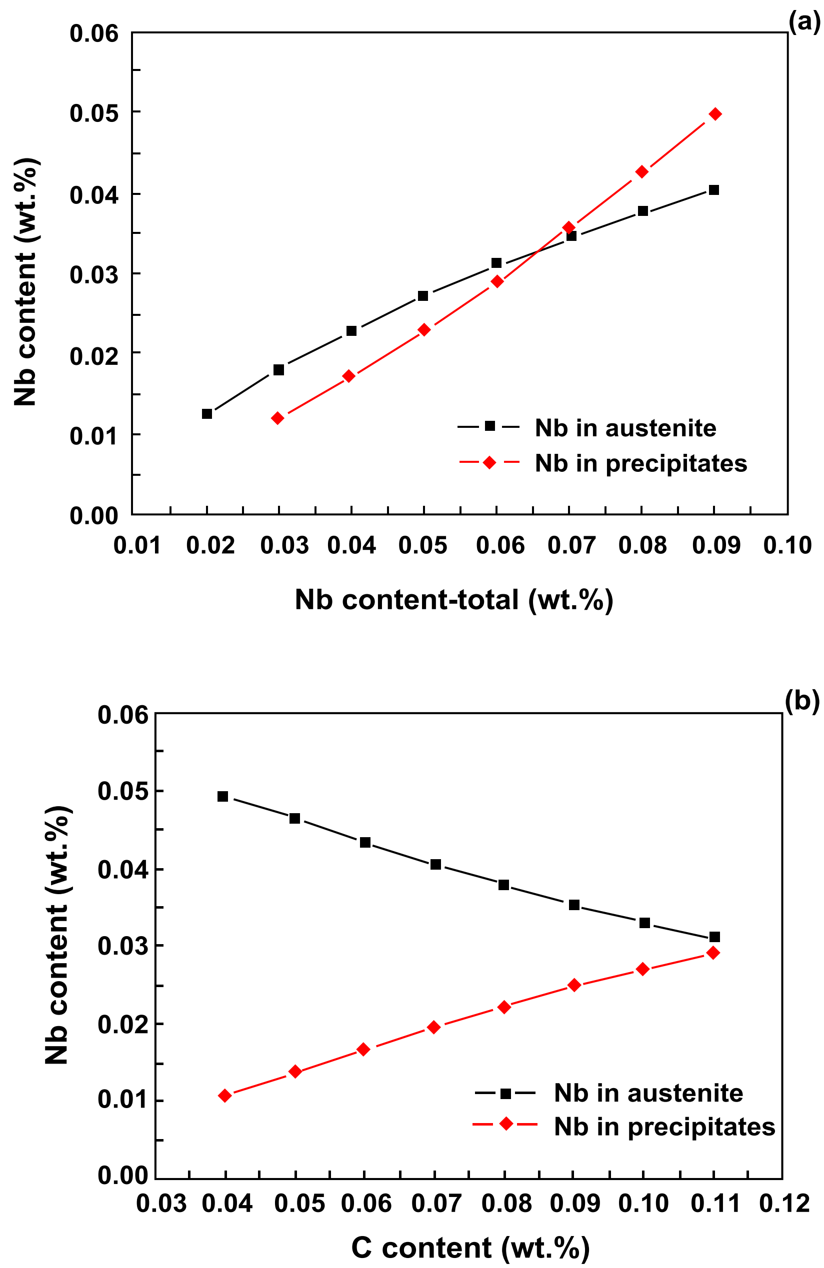


Figure 2. Nb contents in austenite and precipitates at different Nb total contents and C contents (austenized at 1200 °C); (a) Nb in austenite and precipitates at different Nb total content (0.11%C-0.03%V-0.02%Ti-0.0040%N-x%Nb), (b) Nb in austenite and precipitates at different carbon contents (0.06%Nb-0.03%V-0.02%Ti-0.0040%N-x%C) [5].

Chemical Composition

Chemical compositions and carbon equivalents of the developed heavy plates are shown in Table I. Using the calculation method mentioned above, the Nb content in austenite should be 0.035%, 0.040%, 0.036% and 0.037% in Grade Q690CF, Q690HP, Q890CF and Q1150 heavy plates respectively. For studying the effects of Nb on the high strength heavy plates' mechanical properties, steel plates without Nb were also studied. Mo provides 20-30 kJ/mol solute drag energy to diffusional transformation boundaries, whereas Ni and Mn provide 8 kJ/mol [6-8]. This means that the effect of Mo on diffusional phase boundary mobility is 3-4 times as large as that of Mn and Ni according to the thermodynamics. Thus, fine microstructures can be obtained by optimizing the content of Mo which can restrain the diffusional growth mechanism.

The Carbon Equivalents (CEVs) of the developed steels are no more than 0.43%, 0.56% and 0.58% for Q690CF, Q890CF and Q1150 steel plates, respectively. Moreover, heavy plates with yield strengths exceeding 690 MPa can be welded without preheat if the carbon equivalent is no more than 0.39%, as for the Q690HP variant in Table I. The plate thickness range is 12.0-40.0 mm for yield strengths of 690 MPa/890 MPa heavy plates and is 15.0-40.0 mm for a yield strength of 1150 MPa heavy plates.

Table I. Chemical Composition and Carbon Equivalent of Developed Steels (wt.%)

Grade	C	Si	Mn	P	S	Nb	Mo	Others	CEV max.	Nb in austenite (austenitized at 1200 °C)
Q690CF	0.060	0.30	1.83	0.010	0.002	0.045	---	B,Ni,Al,Ti	0.43	0.035
Q690HP*	0.055	0.20	1.78	0.010	0.001	0.050	---	B,Ni,Al,Ti	0.39	0.040
Q890CF	0.085	0.30	1.90	0.008	0.001	0.055	0.26	Cr,B,Ni,Al,Ti	0.56	0.036
Q1150	0.095	0.30	1.95	0.008	0.001	0.060	0.34	Cr,B,Ni,Al,Ti	0.58	0.037

CEV=C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15
* Q690HP with 12.0-40.0 mm thickness can be welded without preheat.

Manufacturing Process and Fine Microstructure

Heavy plates with high tensile strength are generally manufactured by DQ/DQ+T or reheat quenching and tempering (RQT) processes. In the case of DQ, heavy plates are quenched directly after controlled rolling. As far as the DQ process is concerned, austenite grain refining by dynamic recrystallization and a high dislocation density were introduced during hot rolling. Thus, the density of nucleation sites for new phases is increased. The growth of plate-like bainitic ferrite, controlled by a diffusional process, is restrained by the use of higher cooling rates and lower finish cooling temperatures. Fine bainitic ferrite plates are formed because the nucleation site density is higher and growth rate is lower. The C concentration of residual austenite (RA) increases during RA transformation to martensite-austenite (MA) constituent. Thus, comparing with reheat quenching, we can produce heavy plates with the same carbon equivalent and higher tensile strength, or the same tensile strength and lower carbon equivalent, by using the controlled rolling and DQ process.

Microstructures of steel plates with minimum yield strength 690 MPa, produced by the DQ process with average cooling rates of 20 °C/s and 30 °C/s are shown in Figure 3 [9]. The microstructure of the 690 MPa heavy plates is composed of bainitic ferrite with MA constituents decorating the boundaries of the bainitic ferrite plates after DQ processing. Bainitic ferrite plates become finer at higher cooling rates. TEM micrographs of 690 MPa steel plates produced by direct quenching (cooling rate 20 °C/s) followed by tempering at different temperatures are shown in Figure 4 [9]. MA constituents decomposed during the tempering process.

FESEM of 890 MPa plates after DQ and DQ+T are shown in Figure 5. TEM micrographs of 1150 MPa steel plates after DQ, DQ+T are shown in Figure 6. For 1150 MPa grade steel plates, the thickness of sub-units of bainitic ferrite plates is nearly 0.1-0.5 μm. Spherical cementite precipitates at the bainitic ferrite boundaries are found after the tempering process.

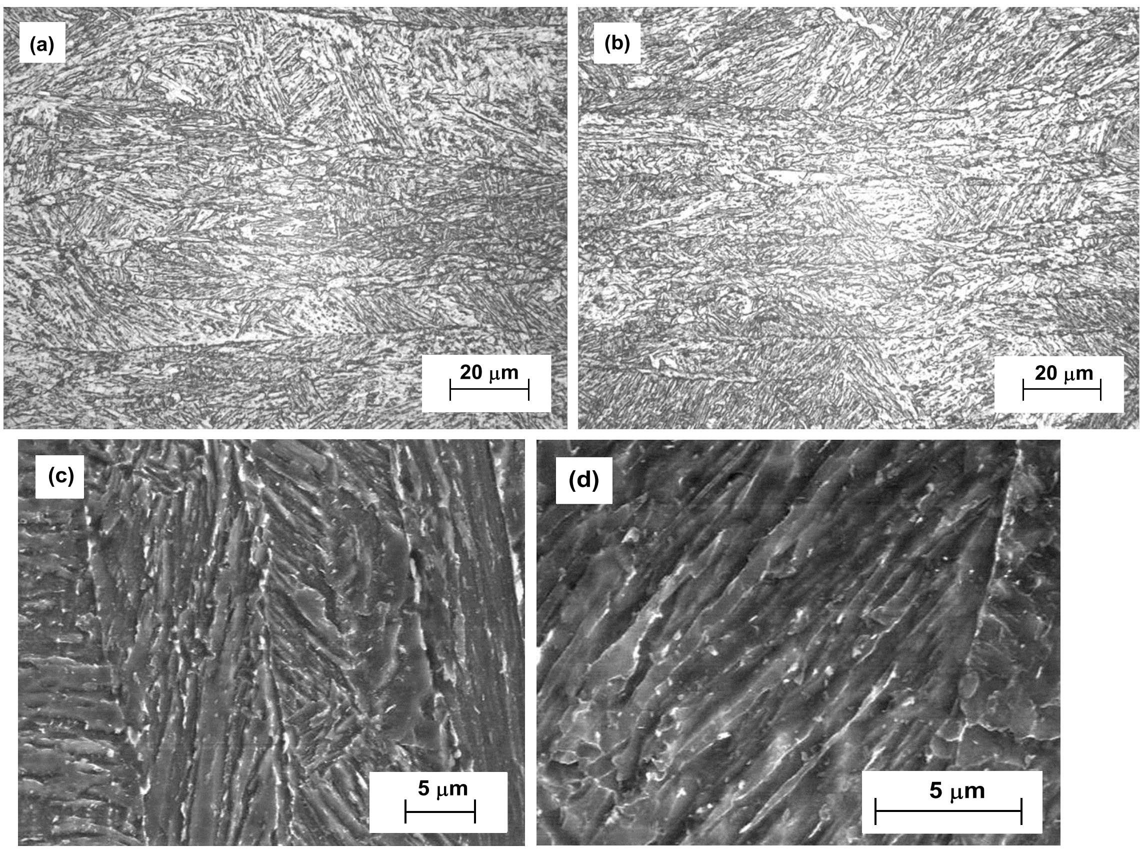


Figure 3. Microstructure of steel plates with minimum yield strength of 690 MPa produced by DQ with;
(a) average cooling rate 20 °C/s (optical micrography), (b) average cooling rate 30 °C/s (optical micrography), (c) average cooling rate 20 °C/s (FESEM), (d) average cooling rate 30 °C/s (FESEM) [9].

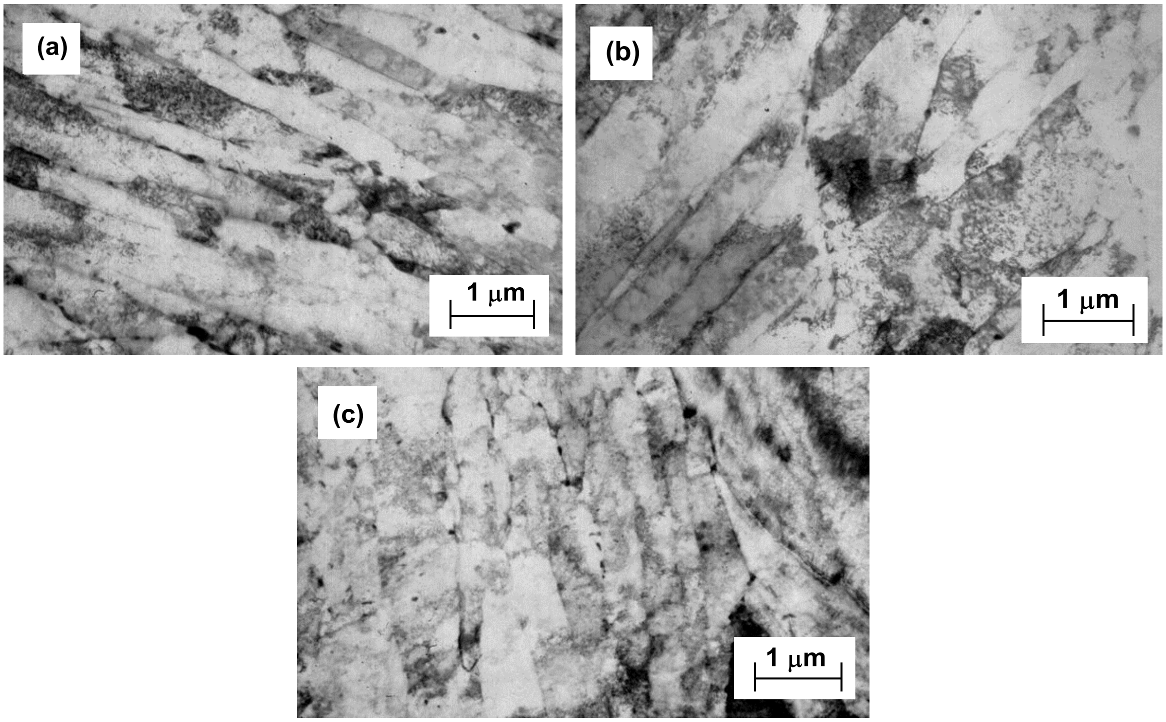
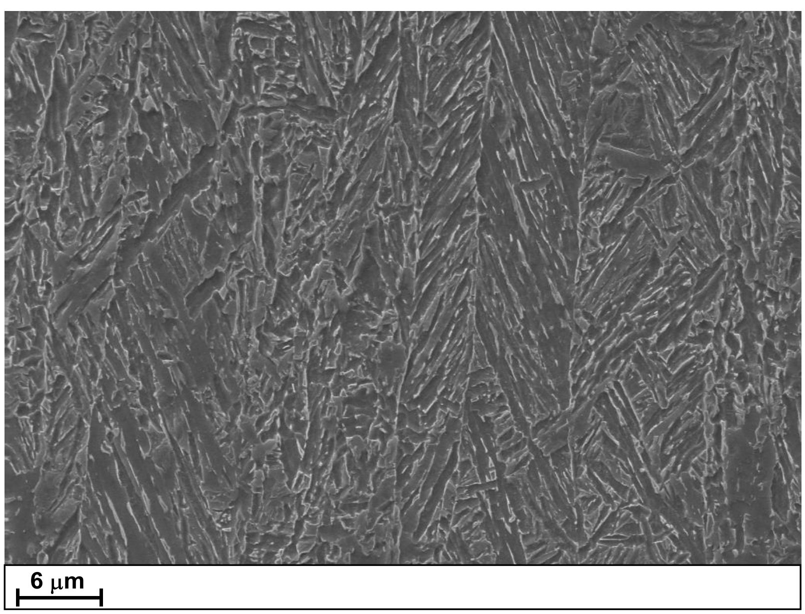


Figure 4. TEM micrographs of steel plates with yield strength 690 MPa produced by direct quenching (cooling rate 20 °C/s) followed by tempering at different temperatures; (a) 610 °C, (b) 630 °C, (c) 650 °C [9].

(a)



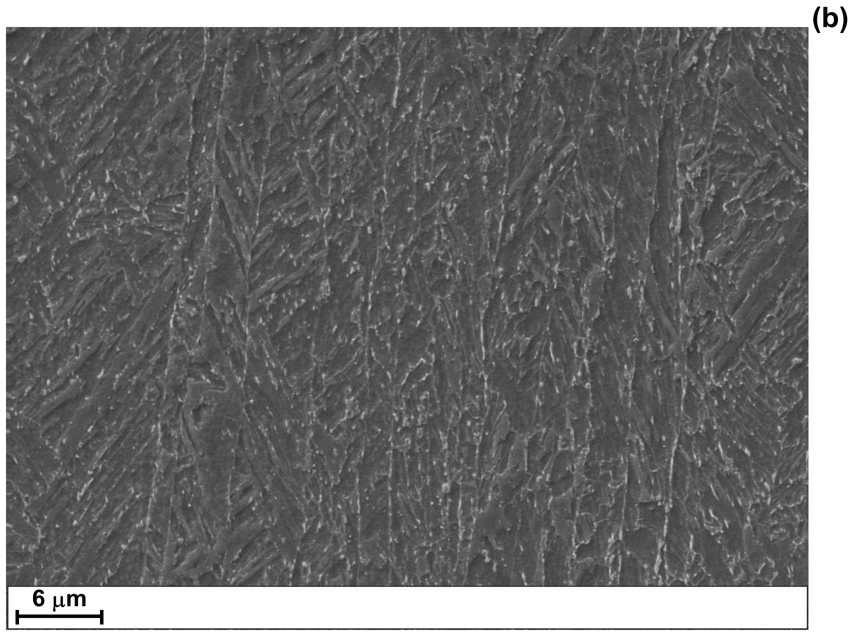


Figure 5. FESEM micrograph of 890 MPa yield strength steel plates; (a) DQ, (b) DQ+T.

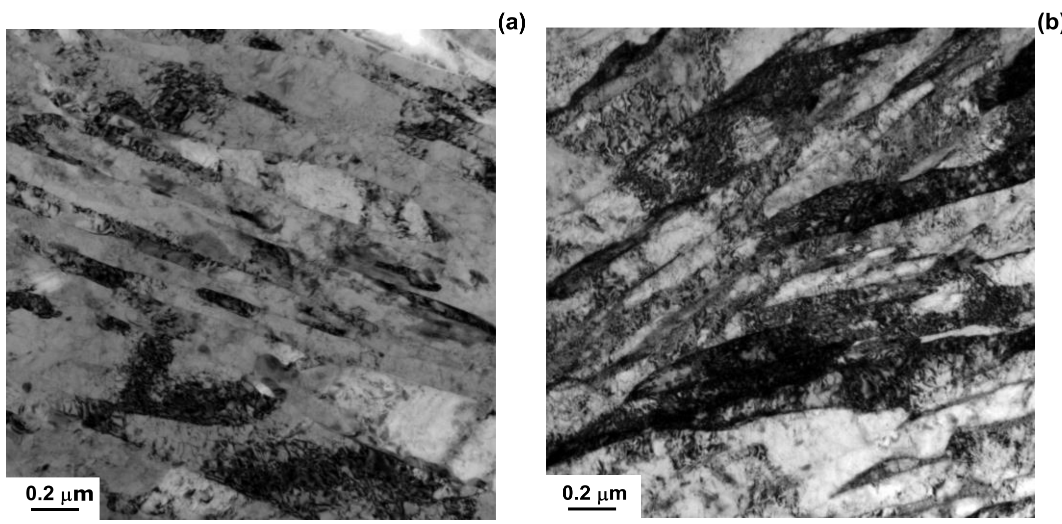


Figure 6. TEM micrographs of 1150 MPa yield strength steel plates; (a) DQ, (b) DQ+T.

Mechanical Properties

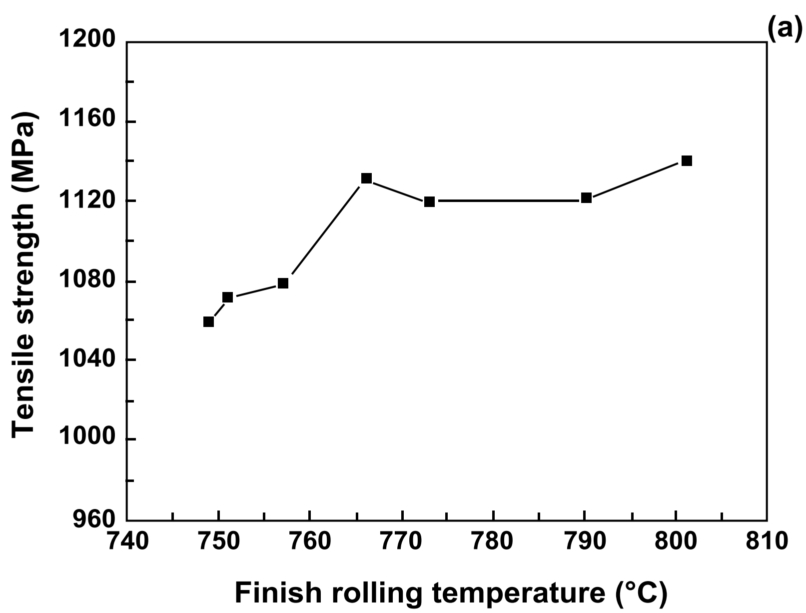
The mechanical properties of heavy plates with yield strengths 690/890/1150 MPa are shown in Table II. It can be seen that the developed steels have high yield strength, good low temperature toughness and elongation. Figure 7 shows the effects of finish rolling temperature on tensile strength and -40 °C Charpy V-notch impact energy. At higher finish rolling temperatures, aggregation of boron at grain boundaries restrains the austenite decomposition and increases the depth of hardenability. Moreover, surface ferrite may be formed at lower finish rolling temperatures which reduces the tensile strength. The dislocation density in austenite is increased by ausforming at lower temperatures. Thus, a fine microstructure can be formed which increases the low temperature impact toughness.

Figure 8 shows the results of instrumented impact energy tests and impact fracture morphology [9]. The formation and propagation work of cracking are the energy absorbed by the specimen before and after the maximum load. Heavy plate with a yield strength of 690 MPa has good crack arrest properties as propagation work of cracking values are 168 J, 190.5 J and 179 J at 0 °C, -20 °C and -40 °C respectively. Impact fracture exhibits the ductile mechanism as the fracture surface has many tiny and uniform dimples. Dynamic yield strengths are 879 MPa, 903 MPa, 927 MPa and dynamic tensile strengths are 1093 MPa, 1132 MPa, 1152 MPa at 0 °C, -20 °C and -40 °C, respectively, Table III. It seems that the work hardening effect is more significant at lower temperatures.

Effects of Nb on low temperature impact energy of the developed steels are shown in Figure 9. It is obvious that the low temperature impact energies of heavy plates are improved by the Nb addition.

Table II. Mechanical Properties of 690/890/1150 MPa Heavy Plates

Grade	Yield strength(YS) MPa	Tensile strength(TS) MPa	Elongation % $L_0=5.65\sqrt{S_0}$	Akv -40 °C J
Q690CF	750	845	21	260
Q890CF	985	1120	16	187
Q1150	1180	1280	12	115



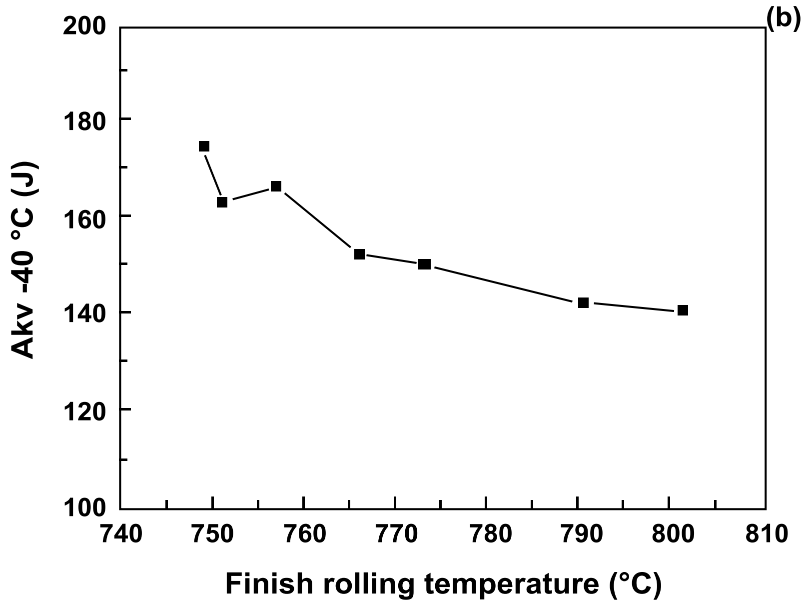
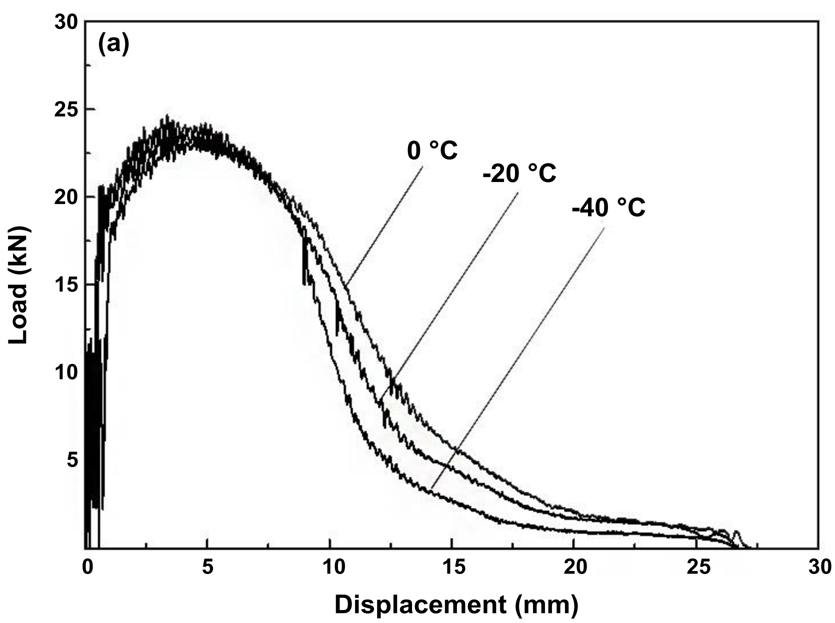


Figure 7. Effect of finish rolling temperature on; (a) tensile strength, (b) -40 °C Charpy V-notch impact energy of Q890CF.



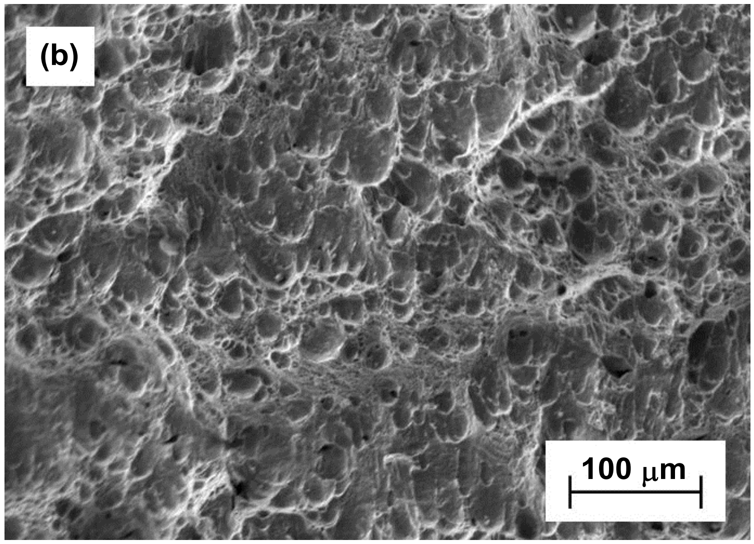


Figure 8. Instrumented impact results of steel plate (690 MPa) produced by DQ with cooling rate of 20 °C/s and tempered at 630 °C; (a) displacement - load curves, (b) fracture morphology [9].

Table III. Formation and Propagation Work of Micro-cracking and Dynamic Strength of Steel Plates Produced by DQ with Average Cooling Rate of 20 °C/s and Tempered at 630 °C [9]

Temperature °C	Formation work of crack J	Propagation work of crack J	A_{kv} J	F_{yd} kN	σ_{yd} MPa	F_{max} kN	σ_{bd} MPa
0	93	168	261	18.82	879	23.40	1093
-20	62.5	190.5	253	19.32	903	24.24	1132
-40	62	179	241	19.85	927	24.65	1152

F_{yd}: yield load; σ_{yd}: dynamic yield strength; F_{max}: maximum load ; σ_{bd}: dynamic tensile strength

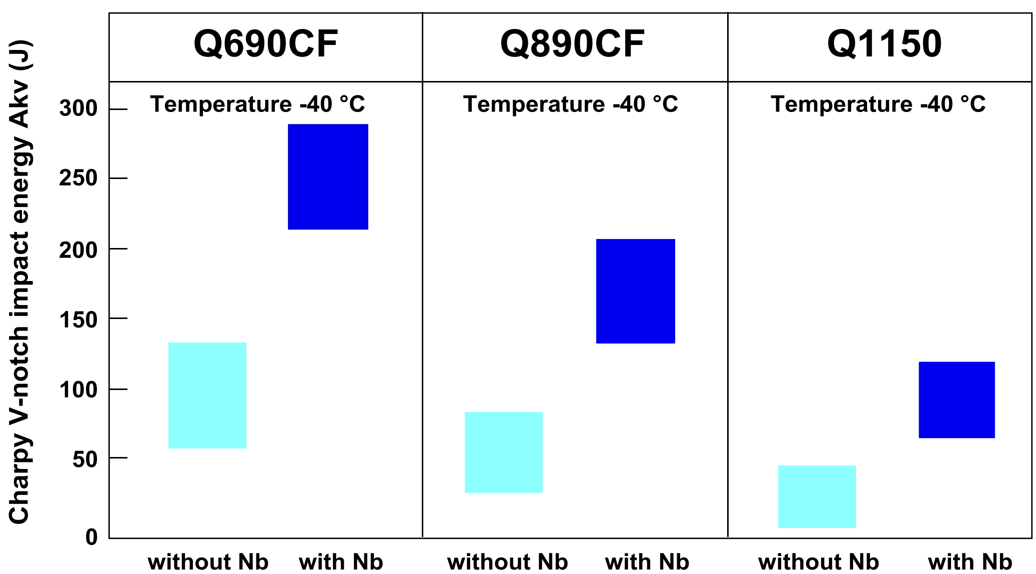


Figure 9. Effects of Nb on toughness of DQ+T high strength heavy plates.

Delayed Fracture

Delayed fracture of ultra high strength steel plates is caused by aggregation of hydrogen at dislocations and micro-cracks. The dislocation density is usually higher in ultra-high strength steel plates because these tend to employ lower temperature deformations. Thus, delayed fracture may occur because of the hydrogen aggregation phenomenon. To ensure their safety of application, high strength steel plates, as are used to build large items of machinery, should have good resistance to delayed fracture.

Delayed fracture properties were evaluated by low strain-rate tension and four-point bending experiments. For the low strain-rate tension experiments, specimens were immersed in 3.5% NaCl+HCl solution which has a pH value of 3.5. Delayed fracture susceptibility can be indicated by comparing the fracture times of the specimens in air and in solution under a strain rate of 1.0×10^{-6}/s. These results are shown in Table IV. The ratios of fracture time in solution and air, Ts/Ta, are 0.977, 0.968 and 0.965 for Q690CF, Q890CF and Q1150, respectively. The four-point bending experiments were carried out by loading specimens which were immersed in 0.1 mol/L HCl solution to 80% yield stress. The final thicknesses of the specimens were measured after 360 hours. These results are shown in Figure 10 and Table V. The thickness reductions of Q690CF, Q890CF and Q1150 were 0.07 mm, 0.12 mm and 0.16 mm, respectively. It can be seen that the developed high strength heavy plates have high resistances to delayed fracture. The microstructure of the developed heavy plates (Figures 4-6) is composed of fine bainitic ferrite plates and MA/cementite decorating the bainitic ferrite plate boundaries. Therefore, this suggests that the resistance to delayed fracture is enhanced because hydrogen may be trapped harmlessly by fine cementite and MA.

Table IV. Fracture Time of Low Strain-rate Tension Specimens

Grade	**D (diameter) mm**	**T_a h**	**T_s h**	**T_s/T_a**
Q690CF	6.45	61.3	59.9	0.977
Q890CF	6.45	62.4	60.4	0.968
Q1150	5.63	48.9	47.2	0.965

T_a: Fracture time in air; T_s: Fracture time in solution

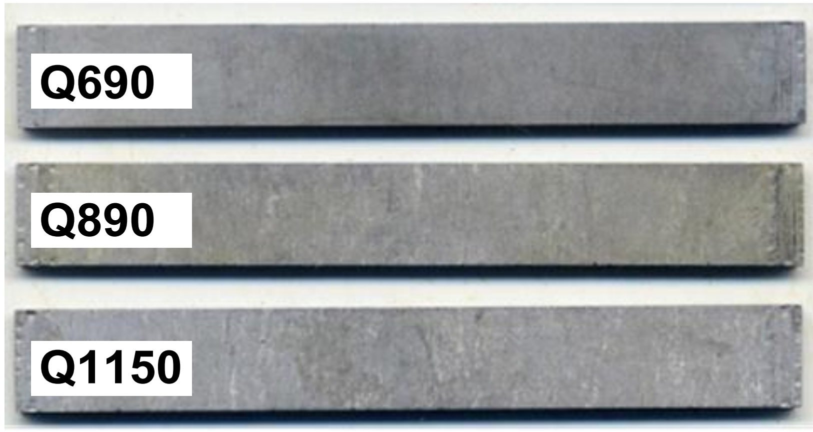


Figure 10. Specimens after four-point bending test 360 h.

Table V. Four-point Bending Test Results of Q690CF/Q890/Q1150

Specimen	Distance between internal bending points mm	Loading parameter % of yield strength	Original thickness mm	Final thickness mm	Thickness reduction mm
Q690CF	27.5	80%	3.53	3.46	0.07
Q890CF	27.5	80%	3.48	3.36	0.12
Q1150	27.5	80%	3.54	3.38	0.16

<u>Weldability</u>

Welding parameters and mechanical properties of welded joints are shown in Table VI. Welded joints of the developed heavy plates have good tensile strength and high Charpy V-notch energy at low temperature. Moreover, steel plates of Q690HP (yield strength 690 MPa) can be welded without preheating due to low carbon content and CEV.

Oblique Y type groove welding crack experiments were carried out on Q1150 plate. Experimental parameters and results are shown in Table VII and Table VIII. The surface or root crack ratios were calculated by (total length of surface (root) cracks/total length of welding line) x 100%. The crack ratio of the section is calculated by (total height of cracks at section/minimum thickness of welding line) x 100%. The crack ratios are average values of five specimens in one welding sample. The morphology of an oblique Y type groove welding crack sample section is shown in Figure 11. Although under severe welding conditions, heat affected zone cracking of Q1150 can be eliminated by preheating at ≥100 °C.

Table VI. Welding Parameters and Mechanical Properties of Welded Joint (GMAW)

Grade	**Thickness mm**	**Heat input kJ/mm**	**Preheat temperature °C**	**Interpass temperature °C**	**TS MPa**	**Fracture position**	**Charpy impact energy**	
							Location	**Akv -40 °C J**
Q690CF	40	1.7	75	≤200	840	Weld metal	HAZ	228
Q890CF	40	1.5	75-150	≤200	1010	Weld metal	HAZ	146
Q1150D	25	1.2	100-175	≤200	1069	Weld metal	HAZ	82

Table VII. Oblique Y Type Groove Welding Crack Experimental Parameters for Q1150 (25 mm thick)

Grade	**Welding current A**	**Welding voltage V**	**Preheating temperature ºC**	**Protective gas**	**Gas flow L/min**
Q1150	220-280	24-32	100, 125, 150	80%Ar+20% CO_2	14-22

Table VIII. Oblique Y Type Groove Welding Crack Results for Q1150

No.	**Preheating temperature °C**	**Gap mm**	**Crack ratio of surface %**	**Crack ratio of section %**	**Crack ratio of root %**
1-1	150	1.95-1.97	0	0	0
1-2	150	1.97-1.97	0	0	0
2-1	125	1.95-1.96	0	0	0
2-2	125	1.95-1.96	0	0	0
3-1	100	1.95-1.95	0	0	0
3-2	100	1.96-1.96	0	0	0
4-1	100	2.08-2.10	0	0	0
4-2	100	2.12-2.14	0	0	0

Figure 11. Section of Oblique Y type groove welding crack sample (preheating 150 °C).

Applications

<u>High Performance Heavy Plates for Coal Mine Equipment</u>

The developed heavy plates have improved performance and less alloying content, as shown above. Moreover, production time was reduced because there was no need for the reheat process. Steel heavy plates developed by Baosteel are widely used for coal mine equipment, such as hydraulic supports. Figure 12 shows a comparison of manufacturing cost for the developed steels and conventional heavy plates.

The coal mining supports are manufactured by an engineering company, then transported to a mine and installed at several hundred meters underground. To facilitate the transport and installation operations, developed higher strength steels with thinner gauge are used to decrease the weight of the supports. More recently, Nb-bearing heavy plates Q890CF and Q1150D, developed by Baosteel, have been used in the main structure of mine hydraulic supports. For support ZFY18000/28/53D, Table IX shows that total weight reduces by 10% and steel weight reduces by 15% through replacing conventional steel by the developed Nb-bearing heavy plates (Figure 13).

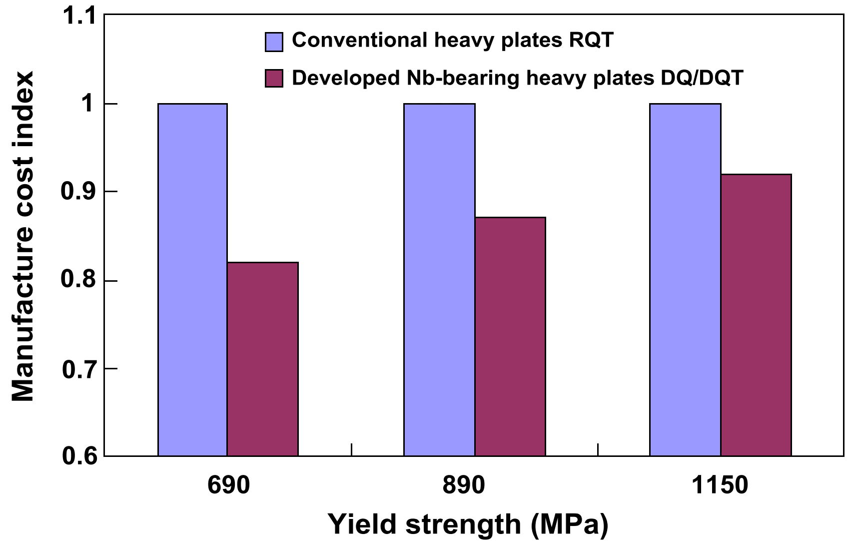


Figure 12. Comparison of manufacturing costs of conventional heavy plates (RQT) and developed Nb-bearing heavy plates (DQ/DQT).

Table IX. Lightweight Design of Mine Hydraulic Support ZFY18000/28/53D

Structure	Yield strength (Conventional heavy plate → Developed Nb-bearing heavy plate) MPa	Thickness (Conventional heavy plate → Developed Nb-bearing heavy plate) mm
Top beam	690→890	30→25
Pedestal	690→890	40→30
Shield beam	690→890	30→25
Push rod	890→1150	30→25

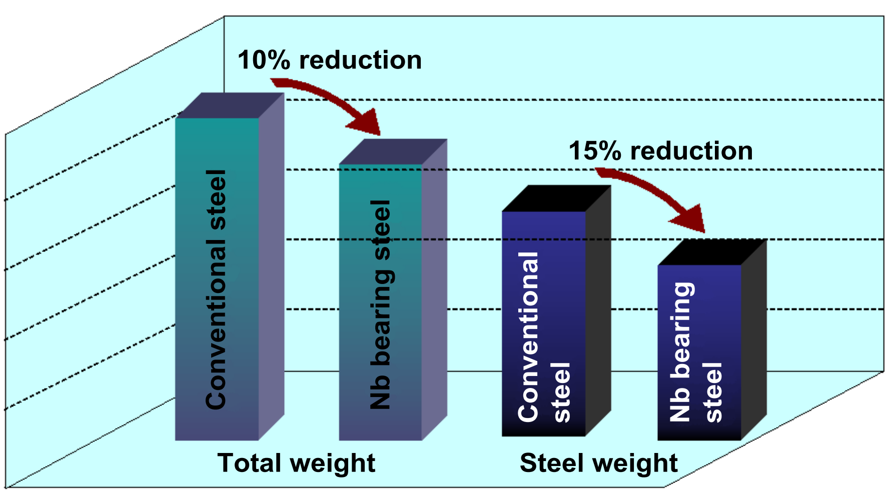


Figure 13. Total and steel weight reduction of mine hydraulic support ZFY18000/28/53D through replacing conventional steel by developed Nb-bearing steel heavy plates.

Welding of Q690HP Heavy Plates with No Preheat.

Conventional heavy plates with high yield strength such as 690 MPa generally should be preheated before welding to decrease the hardness of the Heat Affected Zone (HAZ) and avoid welding cracks. To reduce the labor intensity and welding cost, Nb-bearing heavy plate Q690HP with thickness 40 mm, which can be welded without preheating, was developed. Table X shows the welding parameters and welded joint mechanical properties of Q690HP. Shield beams of mine hydraulic supports are now manufactured with Q690HP. It is obvious that Q690HP has a good market potential due to its cost saving potential.

Table X. Welding Parameters and Welded Joint Mechanical Properties of Q690HP

Grade	**Heat input kJ/mm**	**Preheat temperature °C**	**Interpass temperature °C**	**TS MPa**	**Fracture position**	**Charpy impact energy**	
						Location	**Akv -40 °C J**
Q690HP	1.5-1.9	Room temperature (≥10)	130-180	835	Weld metal	HAZ	237

Conclusions

Baosteel has developed Nb bearing high strength heavy plates with high toughness and good weldability by direct quenching (DQ) or direct quenching and tempering (DQ+T) processes. The C content was varied from 0.055 to 0.095% according to the desired strength and Nb content from 0.045 to 0.060%. With Nb/Nb+Mo microalloying, heavy plates with yield strengths from 690 MPa to 1150 MPa were developed. The microstructures of these steel plates were composed of bainitic ferrite plates with 0.1~1.5 µm thickness and martensite-austenite constituent decorating the boundaries of the bainitic ferrite plates.

With this development of Nb/Nb+Mo-bearing Q690CF, Q690HP, Q890CF and Q1150D grades, Baosteel has expanded its heavy plate products series. These steels show high/ultra-high strength, good low temperature toughness, high crack arrestability, high resistance to delayed fracture and excellent weldability. Moreover, Q690HP with thicknesses ranging from 12.0-40.0 mm can be welded without preheat. In recent years, these products have become widely used in large machinery such as hydraulic supports in mines. In light of this, we expect the demand for these steels in large machinery, such as automobile cranes, crawling cranes, concrete mixers and mining trucks to expand.

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