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Research and Development of the Advanced High Strength Steel for the Mining Machinery

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Abstract. Shougang has developed the advanced high strength steel(AHSS) of SQ690D for the lightweight heavy mining machinery by utilizing low carbon and microalloyed design and two-stage rolling coupled with purposeful heat treatment through quenching and tempering(Q&T). The quenched and tempered steel of 800MPa offers high strength, good formability, excellent low temperature toughness, and good weldability. For the high strength structural steel of SQ690D, the yield strength is more than 750MPa, the tensile strength is not less than 800MPa, the elongation is more than 20%, and the low temperature(-40 ºC) impact energy value is more than 200J. The steel plate is successfully applied in Shougang 150 ton haul truck buckets, and it has better satisfied the requirements of the performance of the steel plate for the heavy mining machinery.

1. Introduction

In recent years, with the improvement of Chinese mining industry mechanization, the carrying capacity is gradually increasing, bringing a lot of demand for heavy-duty dump mining trucks. In order to improve the transport efficiency, reduce cost, many large mines tend to use the big tonnage mining dump truck, which promotes development of many large-tonnage mine dump truck to meet the needs of the mining user.In the developed country the S355 steel and/or the higher grade structural steel and wear-resistant steel are commonly used to manufacture heavy dump mine buckets. However, in China the main material is still the ordinary structural steel Q235, and a small amount of the low-alloy structural steel Q345 is used in the special parts. There are obvious gaps in the use of materials to manufacture heavy-duty dump truck in China compared with international levels. This paper describes the research and development of AHSS in heavy dump tub lightweight bucket.

2. Chemical Composition Design

According to the requirements of lightweight truck bucket design, the AHSS of SQ690D with good mechanical properties is developed by utilizing Nb-Mo-Cr-B microalloying, two-stage rolling and Q&T process.Under the condition that the sufficient strength is obtained, the formability and weldability of the AHSS are improved by adding Nb, to an extent reducing the contents of C and other alloying elements.

C is an essential element for improving the hardenability, which has a direct effect on the strength, low temperature impact toughness and welding property of steel. However, when the carbon content is less than 0.06%, the high strength and toughness cannot be obtained. While the welding performance deteriorates beyond 0.12%, and the toughness of the steel plate also deteriorates. Therefore, the C content is preferably in the range of 0.06%-0.12%.

Mn is also an alloy element for improving the hardenability, which can increase the toughness, strength and hardness, and strongly stabilize austenite, but less than 0.5% can not get the effect of quenching, while more than 1.5% damage weldability, so the Mn content in the range of 0.5% to 1.5% is preferably.

Nb is a typical microalloying element, which plays an important role in the microstructure evolution at all stages during hot working and the final mechanical properties. Beneficial effects of Nb are used in many kinds of heat treatment. During the off-line heat treatment (RQ-T), the combination of Nb with Mo and B can improve hardenability, refine microstructure and improve toughness of high strength steel. Nb can serve two roles in QT steels by controlling the austenite grain size evolution during hot rolling in the mill and then adding a contribution of NbC precipitation strengthening upon final plate cooling.

B is a very powerful hardenability element that is added into steel in small amount, usually less than 50 ppm. Boron is at very powerful at shifting the microstructural phase transformation kinetics during quenching to allow the formation of significant volume fractions of martensite/bainite. Since boron is a strong nitride and oxide former, the goal should be to keep nitrogen and total oxygen as low as possible and use titanium in 3.4:1 stoichiometric relationship to tie up as much nitrogen as possible. Moreover, the synergic addition of Mo and Nb into the alloy can improve the effectiveness of B [1-4].

Considering the effect of the different elements in the steel, complete the chemical composition design of AHSS SQ690D (see Table 1).

Table 1. Chemical composition of SQ690D steel (Max，wt. %)

Steel	C	Mn	P	S	Nb	Cr+Mo+Ti	B	Ceq[a]
SQ690D	0.12	1.60	0.015	0.01	0.05	0.5	0.0020	0.45

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

3. Production process of smelting, rolling and heat treatment

3.1. Smelting
The contents of H, P, S, O and N are kept as low as possible, and the microalloying elements is required to be accurately controlled during smelting.Through the optimization of smelting and continuous casting process, the central segregation of the slab can be reduced and the internal quality of the slab can be acquired.

3.2. Rolling
In order to fully exert the refined crystalline strengthening role of Nb, thermo-mechnical control process (TMCP) is employed. The number of rolling passes, rolling temperature and cooling schedule should to be strictly controlled. The plate is rolled by using 4300mm double stand mill. In order to ensure proper pass reduction, adopting low speed and high reduction rolling in the rough rolling.Especially adopting low speed and high reduction rolling in the region of high temperature austenite recrystallization, so that the deformation can fully penetrate into the core of plate, and the austenite grain is uniformly refined by repeated deformation and recrystallization[5].The finish rolling temperature is controlled during finishing rolling, and the accelerated cooling (ACC) system is used to cool the plate.

3.3. Heat Treatment

Generally the quenching temperature of hypereutectoid steel lies on higher 30-50 ºC than the temperature of Ac1/Ac3. Considering the effect of alloying elements, the quenching temperature lies on a much higher level in order to accelerate austenitization, generally which is quenched at 50-100 ºC higher than the temperature of AC1/AC3. According to the chemical composition of SQ690D, the temperature of Ac3 is 864 ºC, the temperature of Ac1 is 719 ºC. Depending on the alloying elements content and production experience, the quenching temperature of SQ690D lies at 900-910 ºC, and the tempering temperature lies at 550-600 ºC.

4. Results and Discussion

4.1. Mechanical properties

The mechanical properties of SQ690D can be seen in Table 3, which are rolled and coupled with Q&T. The steel has superior mechanical properties. The yield (YS) strength are more than 750MPa and tensile (TS) strength are not less than 800MPa. The elongation is greater than 20%, and the impact energy at -40 ºC is more than 200J.

Table 2. Mechanical properties of SQ690D

Steel grade	Thickness mm	YS MPa	TS MPa	A %	-40ºCAkv J		
SQ690D	8	829	847	24	224	236	230
SQ690D	10	799	828	24.5	253	216	237

4.2. Microstructure

Figure 1 shows the refinement effects of Nb addition in SQ690D. Nb also plays an positive role in the Q&T steel, the most important role is refinement strengthening and precipitation strengthening during phase transformation[6].0.03% aim is an optimum level of Nb to assure the ability to produce a fine as-rolled austenite/ferrite grain during TMCP rolling and have enough Nb precipitates to help pin austenite grain during austenization for quenching[7].Obvious refinement is observed in microstructures by comparing the steels with 0.03% and without Nb addition.

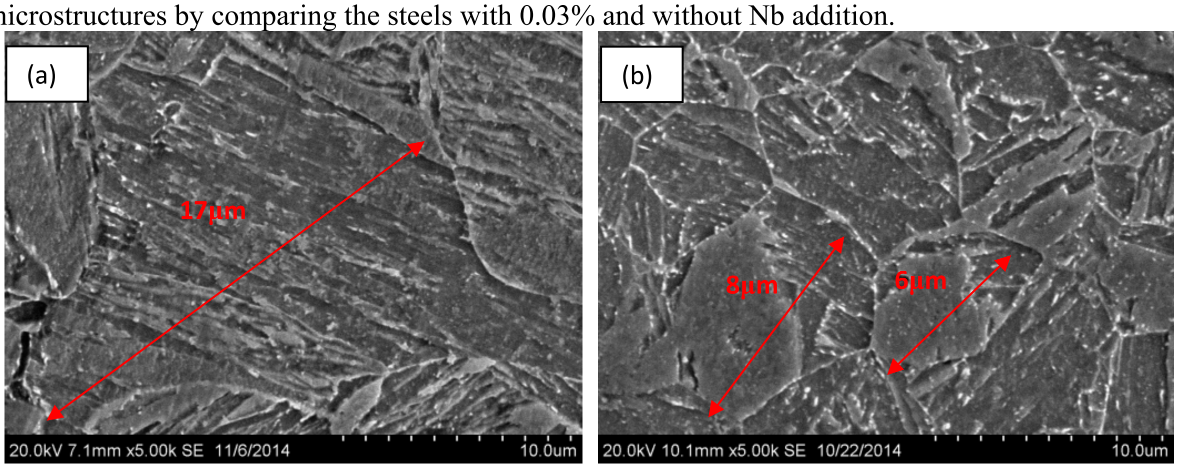

Figure 1. SEM micrograph of the microstructures of quenched and tempered SQ690D steel: (a) without Nb and (b) with 0.03% Nb.

Both the finer microstructure and the dispersed precipitation carbonitrides are obtained by Nb-Mo-Cr-B micro-alloying.The size of fine NbC precipitates is mostly in the range of 10-50 nm. The toughness of steel is improved through refining microstructure. The fine NbC precipitates is can be seen in Fig. 2.

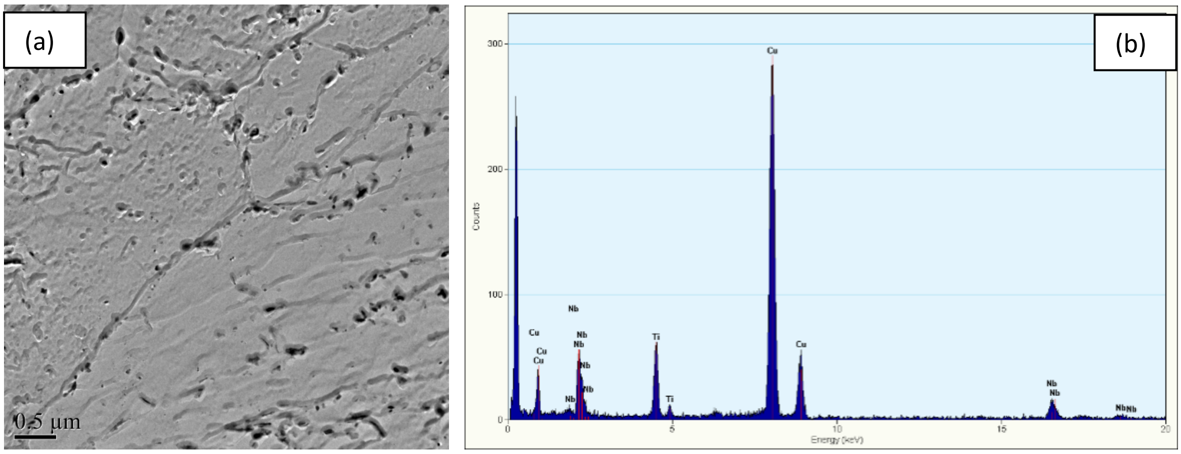

Figure 2. (a) TEM micrographs of the precipitate in quenched and tempered SQ690D steel with 0.03%Nb: Dispersed carbide size ranges from 10-50nm, (b) energy dispersive spectroscopy (EDS) analysis of Nb(C, N) precipitate. The peaks of Cu are from Cu-grid which supports carbon replica.

4.3. Cold bending

A series of cold bending tests with different radius and the constant angles of 90º and 180º are carried out. According to the Chinese National Standards(CNS), when the plate thickness is not more than 20mm, the thickness of the cold-formed sample is the same as plate thickness, and the width of that is 40mm. In order to simulate the production of heavy dump truck, a wide range cold bending performance test of non-standard samples is carried out in the laboratory. The size of the cold-formed specimen is processed to 10mm (thickness) × 200mm (width) × 500mm (length). when the bending radius(r) equal to 10mm(1.0t), 15mm (1.5t), 20 mm(2.0t) and 25 mm(2.5t), different cold bending radius tests are bend to 90º.Table 3 shows the results of a series of cold bending test. It can be seen that when the radius is 1.0t of thickness, cracks appear on the surface after cold bending to 90º, and two cracks of 30-35mm length are also found in cold-formed specimen(Fig.4-a). As the radius equals 1.5t of thickness, tiny cracks appear, then the crack is slighter(Fig.4-b). In the case of the radius ≥2t, no cracks on the surface are observed(Fig.4-c,d). For SQ690D, as the radius is not less than 2.0t, no cracks appear on the surface. These results indicate that the cold bending properties of plates are good enough to meet the requirement of high-grade engineering machine production.

Table 3. Results of a series of cold bending test

Steel grade	Thickness/ mm	Bending sample size/mm			Bending radius(t = plate thickness)					
		Width	Thickness	Bending angle/°	4.0t	3.0t	2.5t	2.0t	1.5t	1.0t
SQ690D	10	40	10	90	○	○	○	○	○	○
SQ690D	10	40	10	180	○	○	○	○	○	△
SQ690D	10	100	10	90	○	○	○	○	△	×

Note: ○-no crack, △-tiny crack, ×-crack.

4.4. Welding

According to the requirement of weldability of steel during the production of dump truck, the weldabilities of produced SQ690D are tested and evaluated. The welding cold crack test of butt joint and lap joint are carried out.

The butt joint rigid restraint welding cold crack test refers to GB/T13817-1992. The dimension of SQ690D is 10mm×450mm×220mm. The rigid base plate is Q345B steel with the dimension of 50mm×600mm×440mm. Before welding, oxide skin, oil and rust on the touching surfaces of the two plates and around weld joint were cleared. The processing parameters of welding are given in Table 4.

Table 4. Processing parameters of welding

Method	Mark of welding material	Size of welding material/mm	Current /A	Arc voltage /V	Welding rate/mms^{-1}	Interpass temperature /°C	Preheating temperature /°C
manual electric-arc welding	ER50-6	Φ1.6	260-280	28-30	6-7	≤250	No

The specimen is fixed on rigid base plate by spot welding, and then restraint weld joint is welded. The height of weld joint is the same as the thickness of plate. Three experiments are performed. For the first experiment, only one welding joint was welded under the condition of without preheating. For the second and third experiment, only one welding joint was also welded, but with reheating. After 48h holding, the specimens were equally cut into 6 parts along the length direction. The section cracks will be checked by naked eye or magnifying glass after grounding and polishing.

The lap joint welding test refers to GB/T4675.2-1984. The base plate is SQ690D with the dimension of 10mm×100mm×75mm. Before welding, oxide skin, oil and rust on the touching surfaces of the two plates and 50mm around weld joint were cleared. The processing parameters of welding are given in Table 4. The SQ690D specimen is fixed on the base plate by screw bolt. The restraint welding joints are welded, and two-side passes are performed. After the specimen is fully cooled down to room temperature, the other welding joint is welded. This operation is repeated two times. After 48h holding, every welding joint is cut into 3 parts. The specimen underwent macroscopic examination, and the cracks will be checked.

Optical observation shows that a good joint is obtained between welding materials and mother materials. No cracks are observed on the welding joint and heat affected zone (HAZ). The microstructure of welding joint is homogenous. The mother materials mainly consist of tempered martensite (M). The HAZ is composed of granular bainite (GB) and a small amount of M. The results of hardness shows that HAZ has no softening zone. The occurrence of GB on HAZ indicates that the HAZ of wear resistant steel is small in hardenability, and low in the sensitivity of cracking.The butt joint rigid restraint welding cold crack test and lap joint welding cold crack test results show that the plate steel is in a low sensibility of welding cracking of tested steel.

5. Conclusion

The SQ690D plate steels have optimum mechanical properties, formability and weldability through either controlled recrystallization hot rolling coupled with precipitation strengthening or the process with Nb-Mo-B microalloying metallurgy design. With the niobium addition in the steel, the austenite grains and the microstructure are refined to improve the ductility and toughness while ensuring the high strength and hardness of the plate. The welding performance is good, and meet the requirements of field operations, reduce the welding difficulty and workload of the welder. The SQ690D steel plates are successfully applied to manufacture the lightweight weight heavy duty 150 ton haul truck buckets, the development of the AHSS fully meet the needs of the lightweight of heavy-duty dump mining truck.

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