DEVELOPMENT AND APPLICATION OF ADVANCED HIGH-STRENGTH STEELS IN LIGHTWEIGHT CARS FOR HEAVY-DUTY MINING DUMP TRUCKS

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Abstract

With the rapid development of the automobile industry in China, energy consumption and environmental pollution problems have become increasingly serious issues, and therefore, lightweight vehicles have received more and more attention. Shougang Group has developed advanced high strength steels (AHSS) of NM450 and Q690CF (crack-free) grades by using a Nb-Mo-B microalloyed design and two-stage rolling with quenching and tempering processing. Whilst maintaining the high strength, the toughness and weldability of the AHSS were improved by reducing the carbon equivalent. For the high strength wear-resistant NM450 grade, the yield strength is higher than 1100 MPa, the tensile strength is higher than 1350 MPa, the elongation is greater than 15%, and the low temperature (-40 °C) Charpy impact energy value is not less than 60 J. The abrasion resistance of NM450 is five times that of the typical Q235 grade. For the high-strength structural steel (Q690CF), the yield strength is greater than 750 MPa, the tensile strength is above 800 MPa, the elongation is higher than 20%, and the low temperature (-40 °C) Charpy impact energy value is more than 200 J. These AHSS grades are successfully applied in Shougang's SGE150® heavy dump body tub, resulting in a reduction of body weight, an improvement of the lifespan of the mine car and a reduction of the transportation costs.

Introduction

With the rapid development of the Chinese economy, China's automobile production and sales have ranked number one in the world for many years, leading to an increase in energy consumption and increasingly serious environmental pollution. Currently, reducing energy consumption and environmental pollution and saving resources are very important and urgent issues in China. The lightweight design of the vehicle car body is a key solution in improving the vehicle fuel efficiency, thus reducing the energy consumption, and reducing the environmental pollution [1-3]. According to the European Aluminum Association, reducing the vehicle weight by 10% can decrease the fuel consumption by 6-8% [4]. Since body mass accounts for about 40% of the total mass of the car, lightweight vehicle bodies play an important role.

Heavy dump trucks are widely used to transport soil, rocks, ore and other materials in mining and various other industries. In recent years, with the improvement of mechanization in the Chinese mining industry, the carrying capacity is gradually increasing, creating a high demand for heavy-duty mining dump trucks. In order to improve the transport efficiency and reduce costs, many large mines tend to use big tonnage mining dump trucks, which promote development of larger vehicles to meet the needs of the mining user. The statistics for the Chinese market for mine dump trucks show that there was a demand for nearly 7000 vehicles during the period 2010-2015. It is predicted that the needs will become even bigger in the next few years [5]. In developed countries, the S355 steel and/or higher strength structural steel grades are commonly used to manufacture heavy dump mine car bodies. However, in China the main material is still the conventional structural steel Q235, together with a small amount of low-alloy structural steel Q345 being used for special parts. There are obvious opportunities for the use of other steels to manufacture heavy-duty dump trucks in China compared with international practice.

This paper describes the development and application of AHSS in a heavy dump tub lightweight car body. It is of practical significance for the light-weighting process of Chinese heavy-duty mining dump trucks.

Lightweight Car Design of the Heavy-duty Mining Dump Truck

Figure 1 shows the heavy-duty mining dump truck of type SGE150® produced by the Shougang Heavy Duty Truck Manufacturing Company. The mine car with a weight of 105 t has a rated loading capacity of 136 t, and is mainly used for mining transportation. Shougang Heavy Duty Truck Manufacturing Company and CBMM (Companhia Brasileira de Metalurgia e Mineração) have made a lightweight car design together, see Figure 2. Instead of the original Q235 grade, the NM450 and Q690CF AHSS are used to reduce the weight of the car and hence energy consumption, increase the transportation load and the lifespan of the mine car, and decrease the maintenance costs.

Figure 1. Heavy-duty mining dump truck SGE150®.

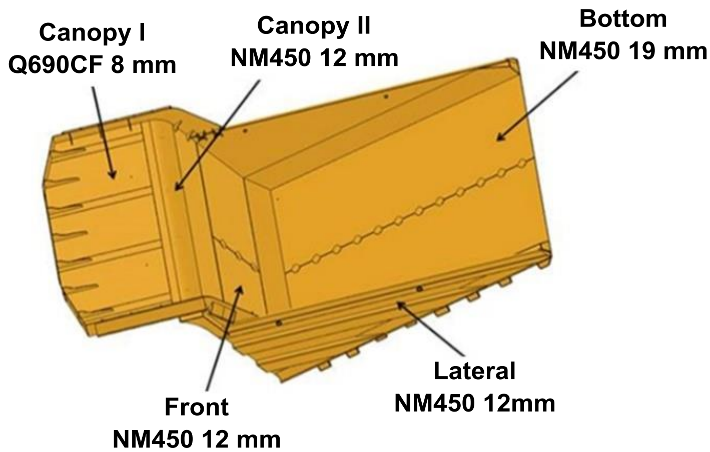

Figure 2. Lightweight car design.

Q235 plate is the main constituent material of the dump truck compartment. The yield strength of this material is about 250 MPa. The basic principle of the new lightweight design is that Q235 is replaced by the AHSS without changing the original structural strength and structural integrity. In the lightweight design process, the following formula is commonly used [6]:

$$\frac{t_2}{t_1} = \sqrt{\frac{R_{eL1}}{R_{eL2}}} \tag{1}$$

where:
t_2 - thickness of high strength steel
t_1 - thickness of low strength steel
R_{eL1} - yield strength of low strength steel
R_{eL2} - yield strength of high strength steel

Based on the above formula and considering the stress under different conditions, the lightweight design procedure is conducted for the various parts of the body.

Table I. Changes in the Thickness from Original Materials to New Materials

		Original Material (Q235)	**New Material (NM450)**	**New Material (Q690CF)**
Yield Strength, MPa		250	1100	700
Canopy I	Thickness (mm)	10		8
Canopy II		16	12	
Front Plate		16	12	
Lateral Plate		16	12	
Bottom Plate		25	19	
Stiffener		10		8

Table I shows the changes in the thickness from the original material to the new materials. The new canopy I was made of Q690CF steel with a thickness reduction from 10 mm (Q235) to 8 mm (Q690CF). Both the canopy II and the front plate are now made of NM450 with a thickness reduction from 16 mm (Q235) to 12 mm (NM450). The lateral plates are made of NM450 with a thickness reduction from 16 mm (Q235) to 12 mm (NM450). The bottom plates are made of NM450 with a thickness reduction from 25 mm (Q235) to 19 mm (NM450). Also, all the stiffener plates are made of Q690CF with a thickness reduction from 10 mm (Q235) to 8 mm (Q690CF). Due to the lightweight design, the total weight of the car can be reduced from 23.5 t down to 19.7 t (a reduction of 3800 kg (16%)).

After the lightweight car design, a force analysis by computer aided engineering (CAE) was carried out under different conditions, such as full-load motionless, full-load moving on uneven road, or braking and cornering. The stress state of the whole car changed little, and the maximum stress was 570 MPa, which is much lower than the yield strength of the new materials. The new materials, therefore, meet the production requirements of the new mine car.

Production Design of the AHSS

According to the requirements of lightweight car design, the AHSS (NM450 and Q690CF) with good mechanical properties were developed using Nb-Mo-B microalloying, two-stage rolling and quench and tempering processing. Under the condition that sufficient strength was obtained, the formability and weldability of the AHSS were improved by adding Nb, while reducing C and certain other alloying element contents.

B is a very powerful hardenability element that is added to steel in small amounts, usually less than 50 ppm. Since B is a strong nitride former, Ti is usually added at around the stoichiometric ratio for TiN precipitates (wt.%Ti = 3.4 × wt.%N) to protect B, and thus maximize its effectiveness. Moreover, the combined addition of Mo and Nb can improve the effectiveness of B [7-9].

Nb is often added to structural steels as a typical microalloying element, usually less than 0.05%. Nb plays an important role in the microstructure evolution at all stages during hot working and hence in determining 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 the hardenability, refine the microstructure and improve the toughness of the high-strength steel. Nb precipitates form Nb(C,N) in austenite and the amount of precipitate depends on the temperature and the contents of C and N. When the steel is heated above Ac3, the fine Nb(C,N) particles precipitate in the matrix. With the increase of the heating temperature, the precipitates first form and then gradually dissolve into γ. The complete dissolution temperature depends on the contents of Nb, C and N. Figure 3 shows the solubility of Nb(C,N) in austenite. It can be seen that a large amount of Nb will precipitate to form Nb(C,N) from austenite in the 900-950 °C temperature range. Due to the relatively low temperature, the particle size of these Nb(C,N) precipitates is very small, which is beneficial for the control of the austenite grain size during the reheating process.

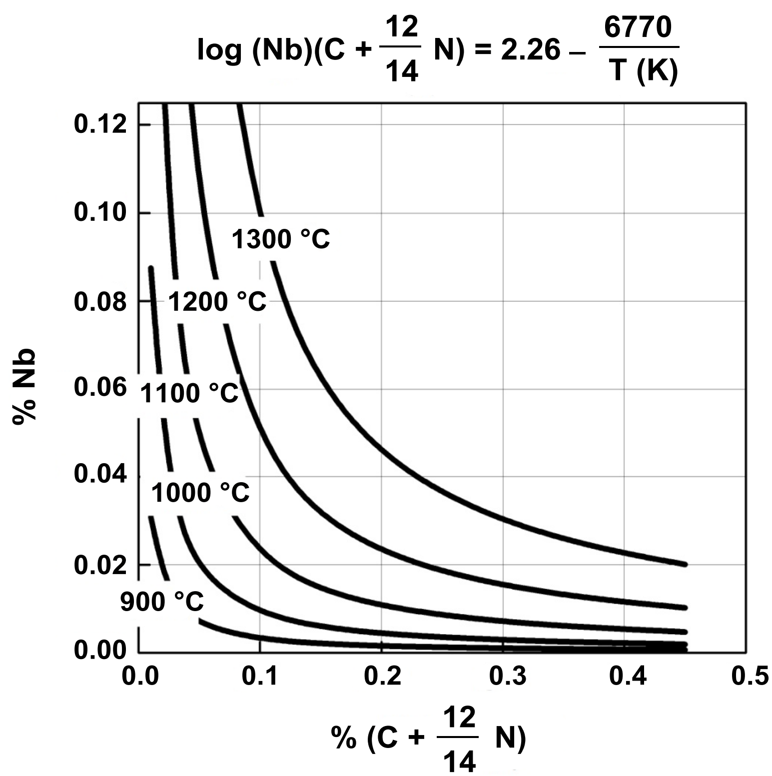

Figure 3. Solubility of Nb carbonitride.

Laboratory Investigation

In order to obtain the optimum addition of Nb, NM450 and Q690CF plates with different additions of Nb were evaluated in the laboratory. The appropriate production processing conditions were obtained through studying the effects of different routes. Theoretical studies showed that to achieve the best results, the addition of Nb in the quenched and tempered steel should not be more than 0.05%. This level of Nb addition could be fully dissolved during slab reheating. Niobium additions of 0%, 0.03% and 0.05% were compared in the experiments, Table II.

Table II. Chemical Composition of the Trial Steel (wt.%)

Steel	**C**	**Si**	**Mn**	**P**	**S**	**Alt**	**Nb**	**Other**	**Mo**	**B**	**CET***
NM450	0.18	0.30	1.20	0.008	0.003	0.025	0/0.03/0.05	Ti, Cr	0.25	0.0020	0.33
Q690CF	0.09	0.20	1.40	0.010	0.003	0.025	0/0.03/0.05	Ti, Cr	0.20	0.0020	0.27

*CET=C+(Mn+Mo)/10+(Cr+Cu)/20+Ni/40

Mechanical Properties

Wear-resistant steel is widely used in the production of machines and equipment which require wear resistance in industry, agriculture and construction. Typical fields of application are machines to excavate or transport raw materials, such as coal, ores, and stone. These steels contain characteristic alloying elements, Mn, Cr, Mo, Ni, B and are based on a C content up to 0.40%. Consequently, they attain high hardness values of 400 to 600 HB by quenching the steel to a martensitic microstructure [10]. The wear-resistant steel, NM450, with a chemical composition of 0.18%C-0.25%Mo-20 ppm B and Brinell hardness of 425-475 HB is produced by the Shouqin company. A significant increase of the toughness could be achieved by the addition of Nb, whilst still guaranteeing the strength and hardness, as shown in Figure 4. Enough strength and hardness could be obtained by C, Mn, Mo, Cr and B interactions and the martensite transformation during the water-quenching heat treatment. Refinement of the martensitic microstructure by the addition of Nb leads to the observed increase in toughness.

High-strength structural steel, with good toughness and weldability, is mainly used in the structural parts of engineering machinery. The AHSS grade Q690CF with the chemical composition of 0.09%C-0.20%Mo-20 ppm B, with a yield strength of 690 MPa and low welding crack susceptibility is produced by the Shouqin Company. The results in Figure 5 demonstrate that the strength was obviously increased by the addition of Nb, but this effect saturated when the content of Nb reached 0.03%.

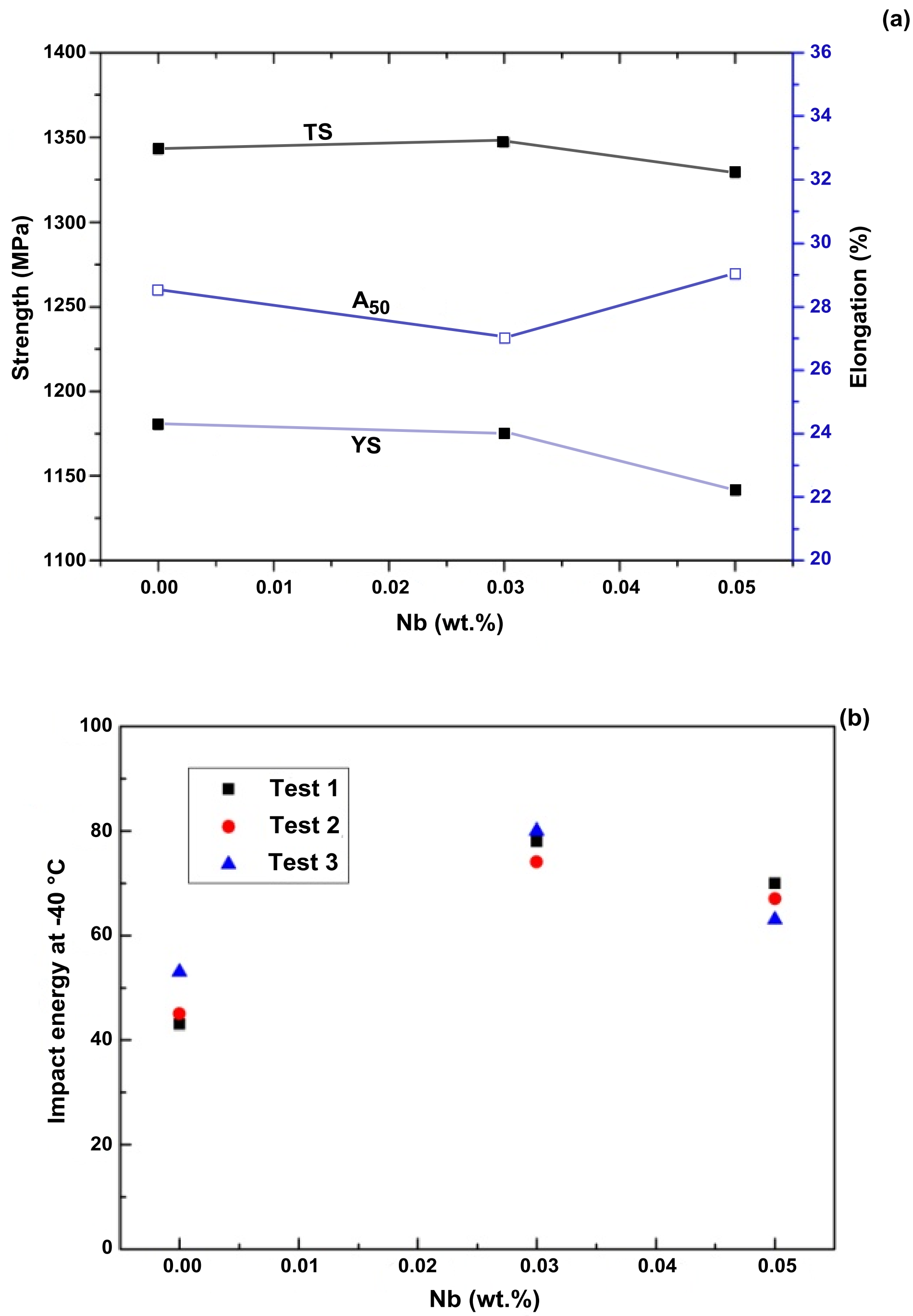

Figure 4. Variation of mechanical properties of NM450 wear resistant steel with Nb content; (a) tensile properties and (b) Charpy impact energy at -40 °C.

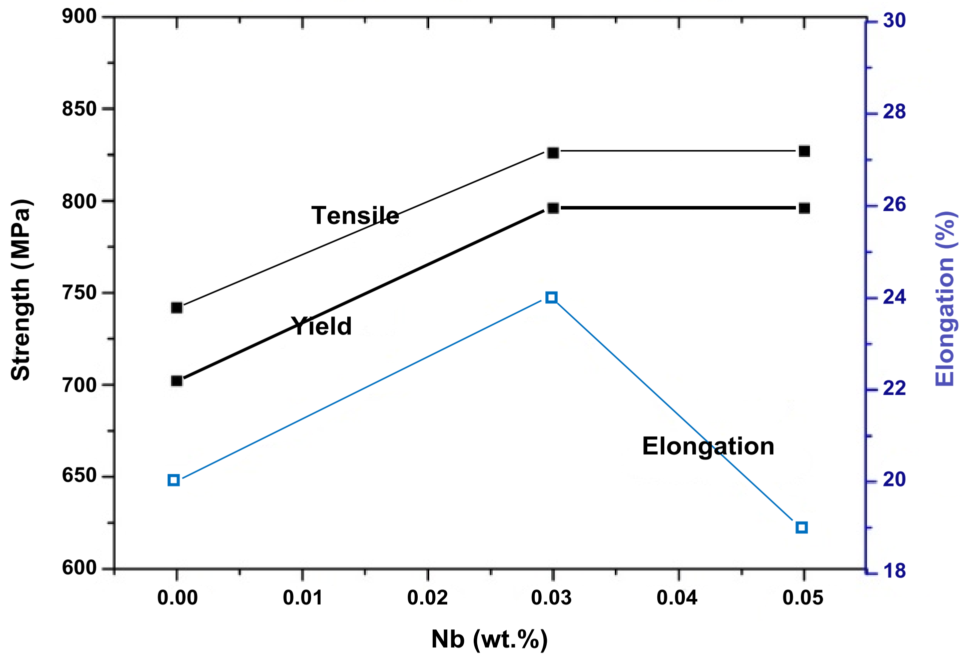

Figure 5. Variation of tensile properties of Q690CF high strength steel with Nb content.

<u>Microstructure</u>

Figure 6 shows the effect of Nb on the prior austenite grain size of the NM450 steel. The average prior austenite grain size (PAGS) of the steel without Nb is 17.9 μm, while the average PAGS of the steel with 0.03%Nb is only 12.3 μm. The major role played by Nb in steel is the austenite grain refinement via the delay of austenite recrystallization during hot rolling. Nb(C,N) first dissolves in austenite during the slab reheating process, and then precipitates during finish rolling. These fine Nb(C,N) precipitates can effectively pin the austenite grain boundaries or dislocation substructure, which is beneficial for the refinement of the as-rolled phase-transformed product. Moreover, the remaining Nb can continue to precipitate during the reheating process, which favors the refinement of the austenite grain size before quenching. Figures 7 and 8 show the refinement effects of Nb additions in NM450 and Q690CF, respectively. Obvious refinement was observed by comparing the steels with and without Nb addition.

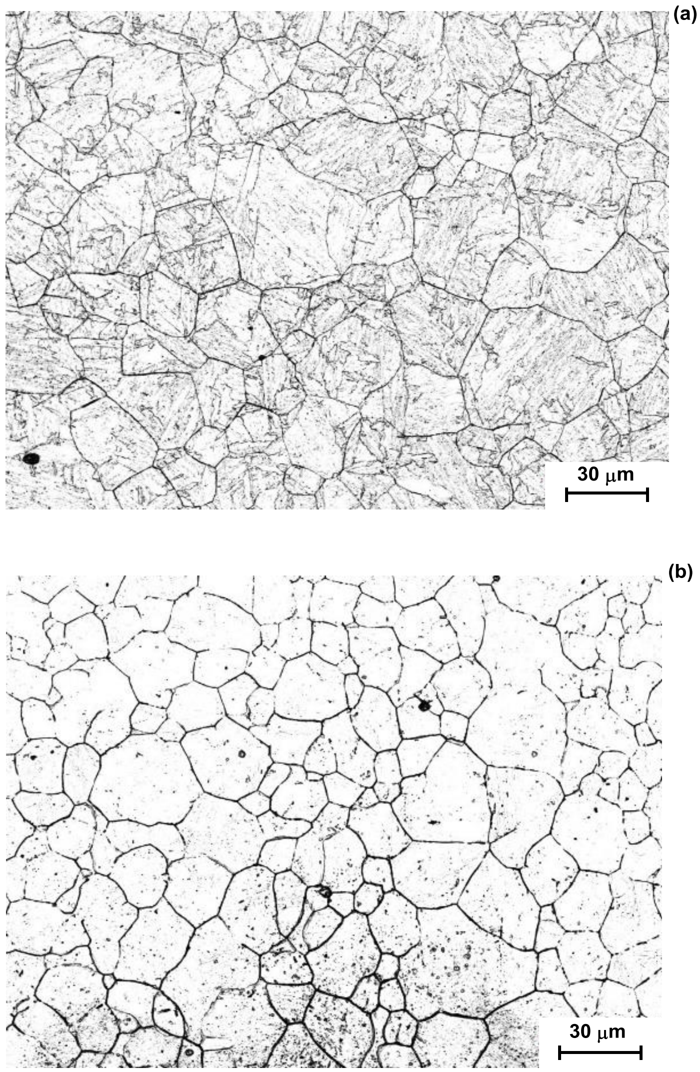

Figure 6. Light optical micrographs of prior austenite grain size; (a) without Nb in steel and (b) with 0.3%Nb steel.

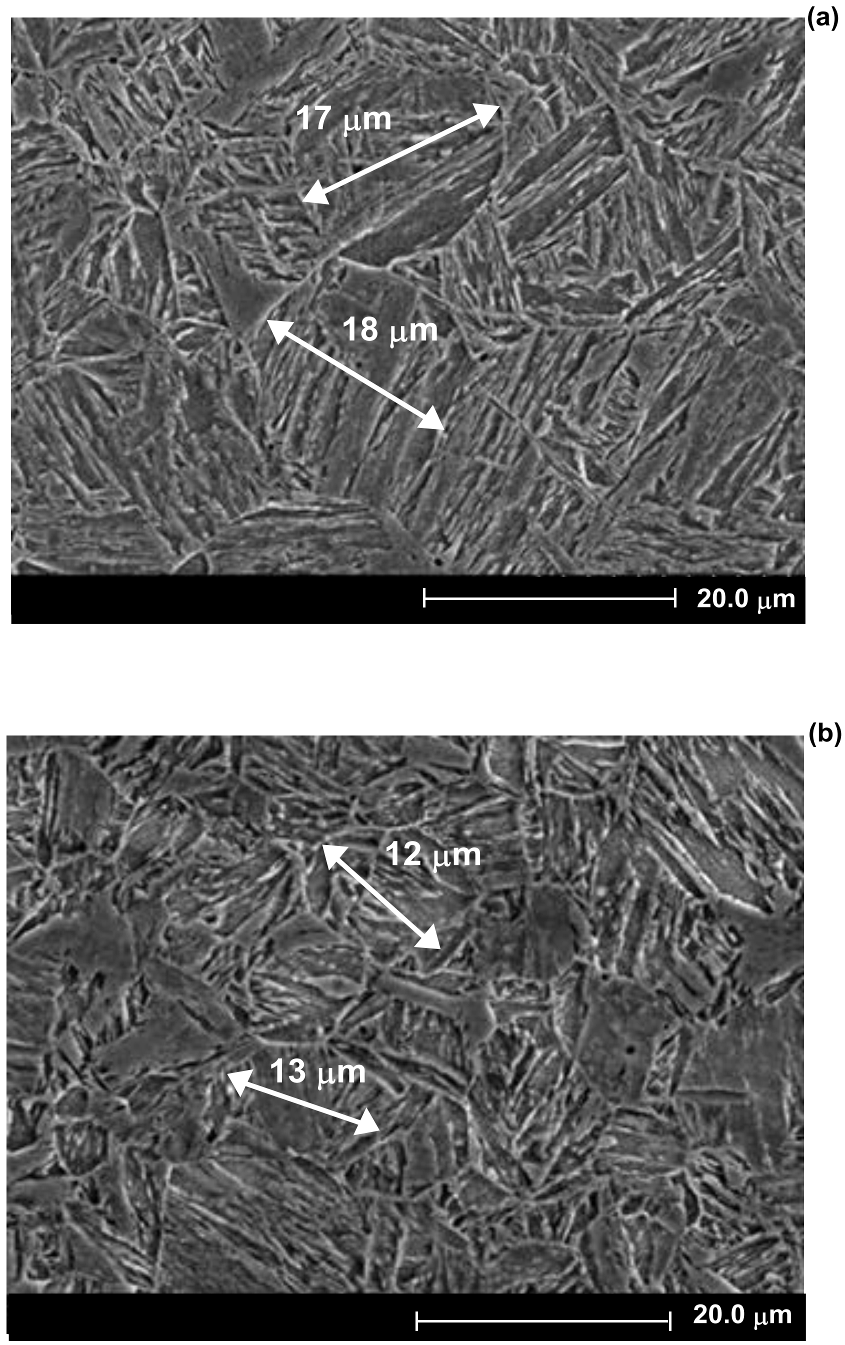

Figure 7. SEM micrograph of the microstructure of quenched and tempered NM450 steel; (a) without Nb and (b) with 0.03%Nb.

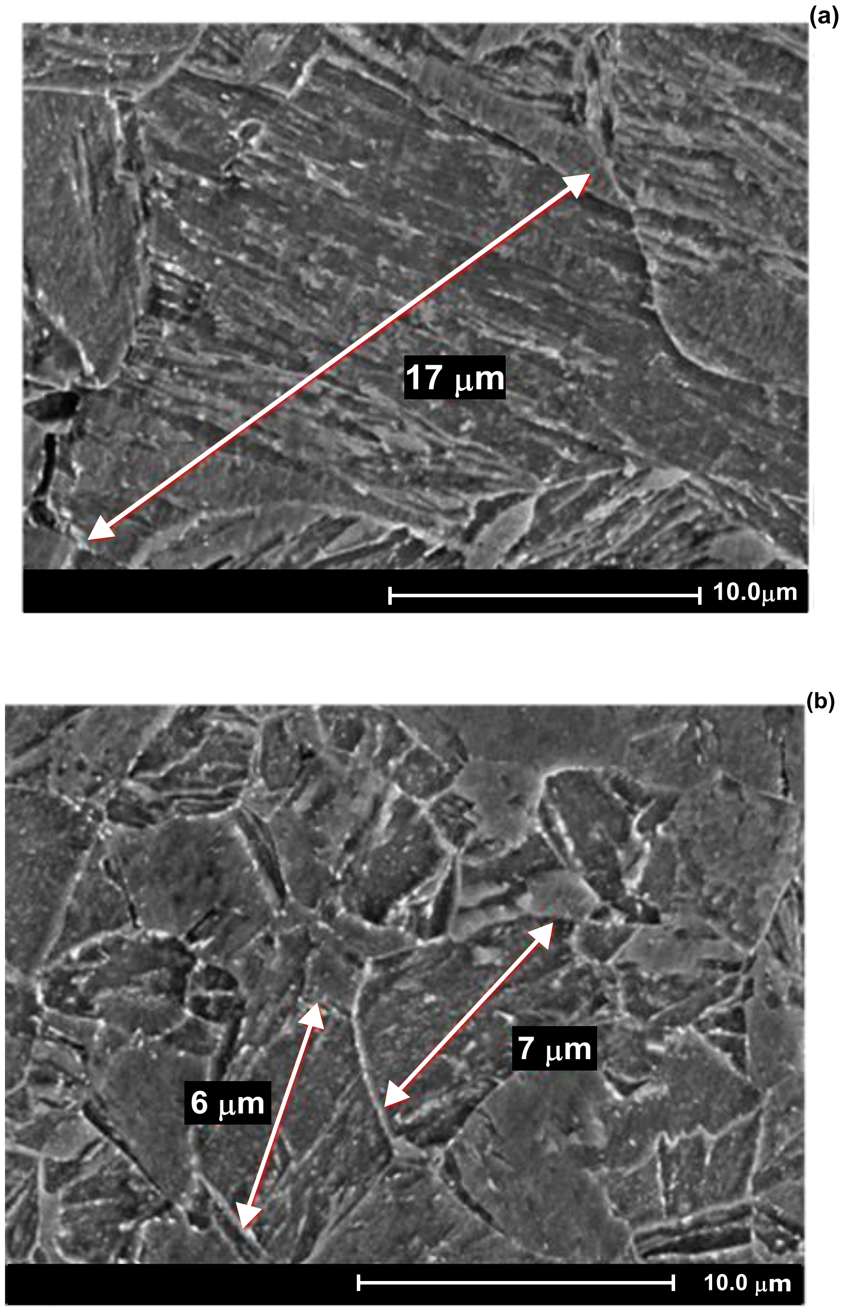

Figure 8. SEM micrograph of the microstructure of quenched and tempered Q690CF steel;
(a) without Nb and (b) with 0.03%Nb.

Both the finer microstructure and the finely dispersed precipitation of carbo-nitrides are obtained by Nb-Mo-B microalloying. The toughness of the steel is improved through refining the microstructure. Precipitates with the size ranging from 10-40 nm in the NM450 steel with 0.03%Nb are shown in Figure 9. The precipitates are dispersed and identified as Nb(C,N) by EDS analysis.

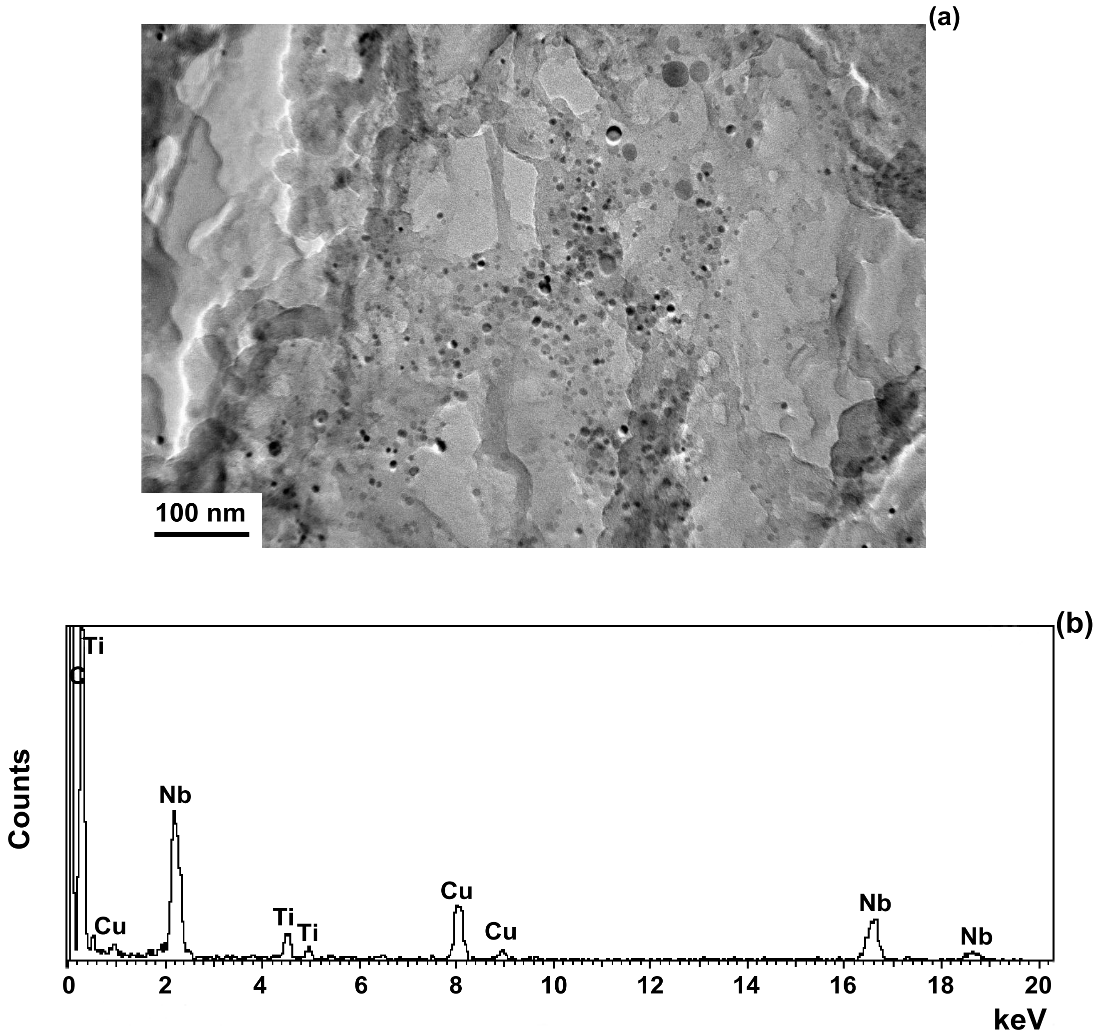

Figure 9. (a) TEM micrographs of the precipitate in quenched and tempered NM450 steel with 0.03%Nb. Dispersed carbide size ranges from 10-40 nm, (b) energy dispersive spectroscopy (EDS) analysis of Nb(C,N) precipitate. (The peaks of Cu are from the Cu-grid which supports the carbon replica.)

Toughness

Toughness is an important property for the applications of wear resistant steel. Tempering of the quenched plate is a commonly used process; higher tempering temperature leads to the reduction of strength and hardness. For wear-resistant steel, NM450, the tempering temperature ranged from 200-250 °C. In this case, the toughness has not been improved compared with the as-quenched steel, but the internal residual stress can be reduced and consequently cracking susceptibility is reduced to an extent. By the addition of microalloying elements such as Nb, Mo and B, with a lower C content, the strength and hardness of the steel can be maintained, and meanwhile the toughness of the steel can be improved. In particular, a significant improvement of toughness was obtained through adding the element Nb. Figure 10 shows the beneficial effect on toughness in the NM450 steel of Nb microalloying. Over the entire range of testing temperatures, the impact energy is significantly improved with a Nb addition.

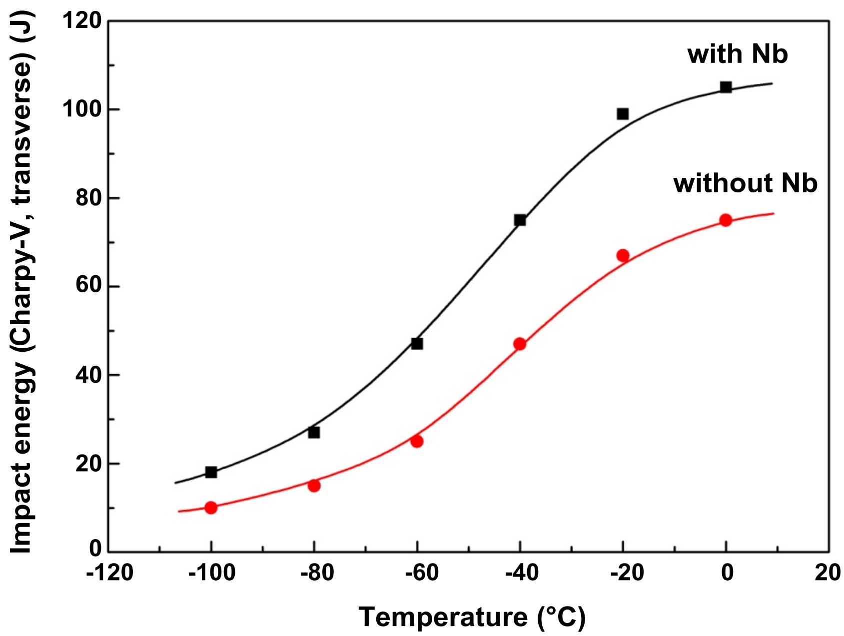

Figure 10. Charpy-V impact energy variation with temperature for NM450 without and with Nb microalloying.

Abrasion Resistance

Abrasion resistance is an important indicator of the potential performance of wear-resistant steel. The internationally recognized method for relative abrasion resistance measurement is a pin on disc abrasion technique. The wear resistance tests on the NM450 trial plate were carried out using a two-body abrasive wear test, on the ML-10 abrasive wear tester. Details of the pin on disc testing used for the relative abrasion resistance comparison are as follows:

- Sample size - 6.0 mm diameter × 25 mm length;
- Disc rotation - 60 rpm, Load – 42 N;
- Abrasive Paper - 80 Grit, SiC wet sand paper;
- Sample radial feed rate - 4 mm/revolution;
- Starting radius - 13 mm;
- Termination radius - 103 mm;
- Wear tip - 8.2 mm.

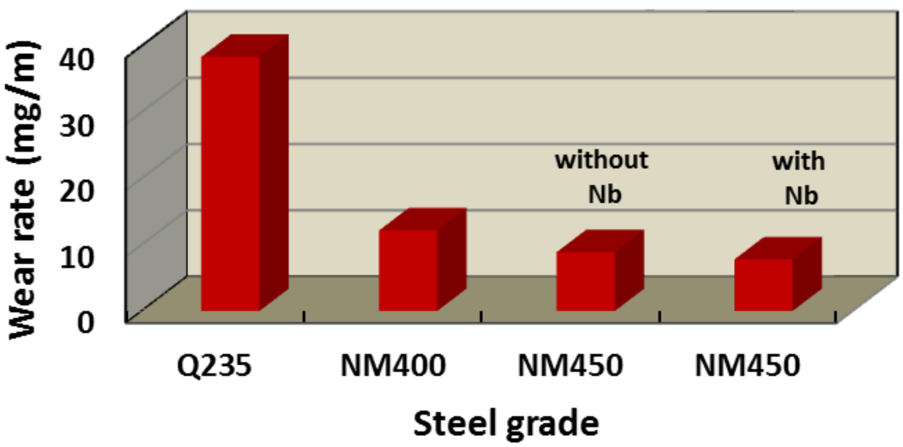

Figure 11. Increase of wear resistance in NM450 through addition of Nb.

The characteristic wear type is ploughing leading to abrasion. Thereby, the plate surface gets scratched when exposed to an abrasive and hard material, such as sand or typical minerals, and is then removed. A high hardness of the material is, therefore, one important factor for promoting good wear resistance. Furthermore, higher material toughness improves the wear resistance and thus reduces the material loss, because it changes the wear mechanism from micro-ploughing into micro-machining [10,11]. Figure 11 shows the results from this study on the wear properties of the various steels. The service life of NM450 with 0.03 %Nb is five times that of Q235, 1.56 times that of NM400, and is increased by around 14% compared with that of NM450 without Nb. As a result of the addition of Nb, the martensitic microstructure is refined and the toughness is improved. Nb microalloying not only improves the wear resistance of NM450, but also can reduce the probability of the appearance of cracks in a low temperature environment, thus increasing the material's service life [12]. Figure 12 shows the scratch morphology of NM450 without Nb and with Nb after wear testing. The NM450 with a Nb addition exhibits more uniformly distributed and shallow furrows on the worn surface, compared with NM450 without the Nb addition, indicating that the former has better wear resistance.

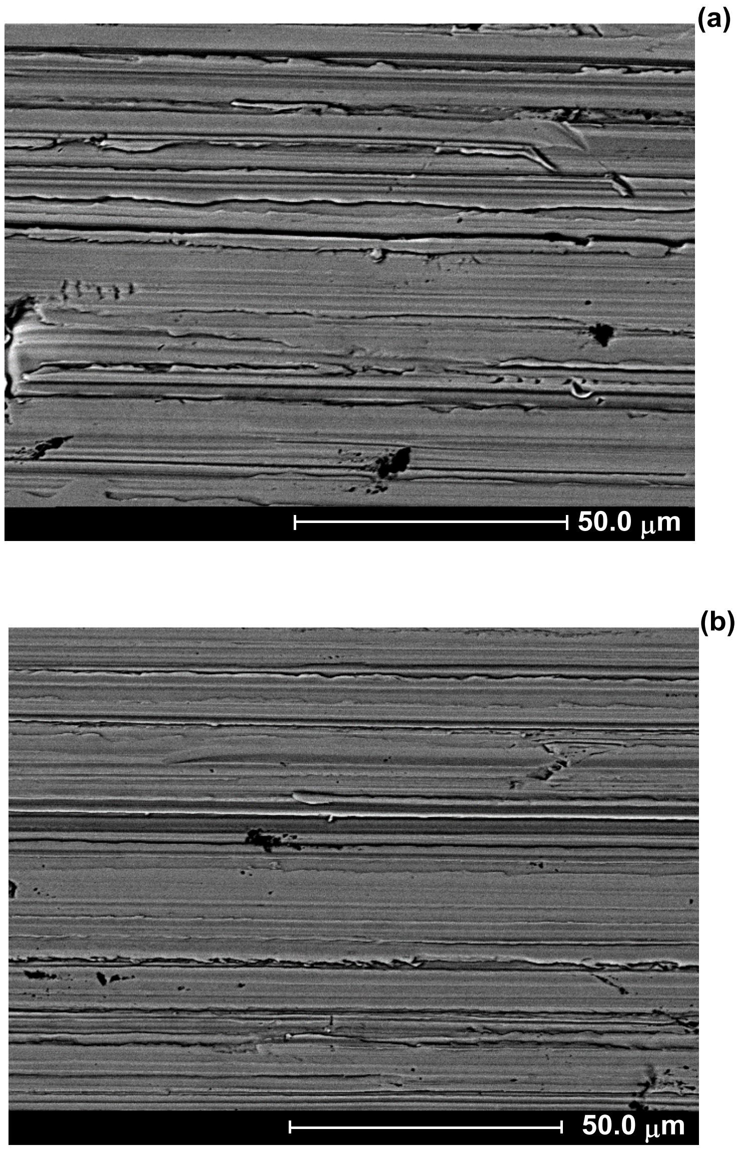

Figure 12. Scratch morphology for NM450; (a) without Nb and (b) with Nb after wear testing.

Industrial Production

The industrial production of AHSS was conducted on the 4300 mm rolling line of Shouqin.

The smelting process was as follows: blast furnace molten iron - hot metal desulfurization - converter smelting - LF+RH refining - slab continuous casting. The contents of P, S, O and N were reduced as much as possible, and the contents of microalloying elements were required to be accurately controlled during smelting.

In order to fully utilize the grain refinement role of Nb, thermomechanical controlled processing (TMCP) was employed. The number of rolling passes, rolling temperatures and cooling schedule need to be strictly controlled. Two-stand rolling was conducted on the 4300 mm rolling line. A relatively large force was applied to ensure that there was enough rolling reduction during roughing. The finish rolling temperature was controlled and the accelerated cooling (ACC) system was used to cool the plate.

The mechanical properties of as-produced AHSS plates are given in Table III. The NM450 and Q690CF plates have superior mechanical properties to the previous grades. The yield (YS) and tensile (TS) strength of NM450 are more than 1100 MPa and 1350 MPa respectively. The elongation (A_{50}) is greater than 15% and the average Charpy impact energy at -40 °C exceeds 60 J. The Brinell hardness (HB) is not lower than 430 HB. For Q690CF plate, the YS is greater than 750 MPa, the TS is larger than 800 MPa, the A_{50} is greater than 20%, and all the Charpy impact values at -40 °C are not less than 200 J.

Table III. Mechanical Properties of As-produced AHSS Plates

Steel Grade	Plate Thickness mm	YS MPa	TS MPa	A_{50} %	Charpy Impact Value -40 °C J			AVE	Hardness HB			AVE
NM450	12	1186	1383	18	70	92	91	84	438	435	432	435
NM450	19	1124	1375	21.5	57	59	78	65	436	431	434	434
Q690CF	8	829	847	24	224	236	230	230				
Q690CF	10	799	828	24.5	253	216	237	236				
Q690CF	30	786	818	32	253	241	246	247				

Cold Bending

A series of cold bending tests with various radii and a constant angle of 180^{o} were carried out. When the plate thickness was not more than 20 mm, the thickness of the cold-formed sample was the same as the plate thickness, and the width of that was 40 mm. When the plate thickness was greater than 20 mm, the thickness of the cold-formed sample was thinned to 20 mm, and the width of that was again 40 mm.

Table IV. Results from Cold Bending Tests

Steel Grade	Plate Thickness (mm)	Bending Sample Size (mm)		Bending Radius (t=plate thickness)				
		Width	Thickness	5.0 t	4.0 t	3.0 t	2.0 t	1.5 t
NM450	12	40	12	○	○	△	×	×
Q690CF	10	40	10	○	○	○	△	×
Q690CF	30	40	20	○	○	○	○	○

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

Table IV gives the results of a series of cold bending tests. It can be seen that when the radius is only 1.5 or 2.0 times the thickness, big cracks appear on the surface of NM450 after cold bending. When the radius equals 3.0 times thickness only micro-cracks appear. In the case of a bending radius of 4 t, no cracks on the surface of NM450 were observed. For Q690CF, when the radius is not less than 3.0 t, no cracks appear on the surface. These results indicate that the cold bending properties of NM450 and Q690CF plates are good enough to meet the requirements of high-grade engineering machine production.

Welding

The weldability of the AHSS grades, NM450 and Q690CF, was evaluated against the criteria used in the production of dump trucks. The butt joint welding test between NM450 plates and lap joint welding CTS test were carried out.

The butt joint, rigid restraint welding cold crack test refers to GB/T13817-1992. The dimensions of the NM450 test piece were 19 x 450 x 220 mm. The rigid base plate was Q345B steel with the dimensions of 50 x 600 x 440 mm. Before welding, the oxide skin, oil and rust on the touching surfaces of the two plates and around the weld joint were cleared. The processing parameters of welding are given in Table V.

Table V. Processing Parameters for Welding

Method	**Type of welding wires**	**Size of welding material (mm)**	**Current (A)**	**Arc voltage (V)**	**Welding rate (mms^{-1})**	**Interpass temperature (°C)**	**Post-welding heat treatment**
manual electric-arc welding	ER50-6	Φ1.6	160-280	28-30	6-7	≤250	No

The specimen is fixed on the rigid base plate by spot welding, and then the restrained joint is welded. The height of the weld joint is the same as the thickness of plate. Three experiments were performed. For the first experiment, only one joint was welded with no preheating. For the second and third experiments, again only one welding joint was welded, but with preheating. After cooling and 48 h holding, the specimens were cut equally into six parts along the length direction. The presence of cracks was checked by the naked eye or a magnifying glass after grinding and polishing.

The lap joint welding CTS test refers to GB/T4675.2-1984. The base plate was NM450 with the dimensions of 19 × 175 × 100 mm. The tested Q690CF steel had the dimensions of 8 × 100 × 75 mm. Before welding, the oxide skin, oil and rust on the touching surfaces of the two plates and 50 mm around the weld joint were cleared. The welding processing parameters are given in Table VI. The Q690CF specimen was fixed on the base plate by screw bolts. The restrained joints were welded, and two-side passes were performed. After the specimen was fully cooled down to room temperature, the other joint was welded. This operation was repeated two times. After 48 h holding, every welding joint was cut into three parts. The specimens were examined on a macroscopic scale and checked for the presence of cracking.

The butt joint, rigid restraint welding cold crack test and lap joint welding CTS test results show that during the production of the tested steel, the low carbon and Nb-Mo-B microalloying were correctly designed, the elements that influence the C equivalent were appropriately controlled and the contents of P, S and gases (eg. N, O, H) were also properly controlled. This resulted in a low sensitivity to weld cracking in the tested steel. Optical observation showed that a good joint was obtained between the welding materials and parent materials. No cracks were observed in the welded joint and heat affected zone (HAZ). The microstructure of the welded joint was homogeneous. The parent materials mainly consisted of tempered martensite (M). The HAZ was composed of granular bainite (GB) and a small amount of M. The results of hardness testing showed that the HAZ had no softened zone. The occurrence of GB in the HAZ indicates that the HAZ of wear resistant steel has a low hardenability and a low sensitivity to cracking.

Conclusions and Prospects

The Shougang Heavy Duty Truck Manufacturing Company and CBMM (Companhia Brasileira de Metalurgia e Mineração) have collaborated to design, produce, and put into service an improved dump truck car tub of 136 t load capacity. Instead of the original Q235 grade, the NM450 and Q690CF AHSS grades were developed and used to reduce the weight of the car and hence energy consumption, increase the transportation load and the lifespan of the mine car, and decrease the maintenance costs. The developed steels employed Nb-Mo-B alloying methodology to achieve the required higher strength to allow thinner, lighter sections to be employed in the car construction whilst maintaining or exceeding all the other requirements such as weldability, toughness and wear resistance.

The NM450 Charpy impact energy is significantly improved and the service life under abrasive wear is increased by around 14% compared to the standard grade, and the Q690CF strength is obviously improved, and the weldability and cold bending of the AHSS comfortably meet requirements. The development of the AHSS fully met the requirements for the new dump truck tub.

The AHSS of NM450 and Q690CF were applied in the SGE150 heavy dump body tub, reducing the weight of the truck by 3800 kg, decreasing the energy consumption by 10-13%, and reducing the transportation costs by over 3%. The development of these AHSS, therefore, provides further opportunities for lightweight materials for the development of other cars and components in the mining dump truck industry.

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