Analysis of Inclusions with Unqualified Z-direction Performance of Heavy Bridge Plates

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Abstract—By using the analysis tools of scanning electron microscope (SEM) and energy dispersive X-ray (EDX), the reason for the disqualified Z-direction performance of a 60mm Q370qEZ35 heavy steel plate was investigated. The results showed that the disqualified Z-direction performance of Q370qEZ35 was due to the presence of a large number of inclusions, the types of which were mainly massive and strip-like (Nb, Ti)C and metal Nb inclusions as well as spherical oxide (MgO, Al_2O_3, etc.) and sulfide inclusions (CaS, MnS). The cause of various types of inclusions and the impact on the Z-direction property was analyzed, and the corresponding improvement measures were put forward from smelting, casting and rolling and cooling process, such as controlling the amount and adding time of Nb and Ti, extending the refining time, controlling the superheat temperature, optimizing the process of heating, rolling and cooling, etc., and finally, we achieved good results.

Keywords-Q370qEZ35; Heavy plate; Z-direction performance; Fracture morphology; Cause analysis

I. INTRODUCTION

With the increase in the level of design and construction of the bridges, the numbers of large-span bridges are gradually increasing; the connection types are developed from riveting and bolting to the whole welding [1-3]. Large-span steel bridges require not only high strength, high toughness, good weldability and seismic performance, but also good resistance to lamellar tearing performance, which is also named the thickness direction performance or the Z-direction performance [4-5]. The Z-direction steels are generally obtained by smelting, rolling and after heat treatment, which are based on some kind of structural steel (called the mother grade steel).They have lower sulfur content than ordinary steel, and the grade level of which can be divided into Z15, Z25 and Z35[6].

In this study, the Q370qEZ35 heavy steel plates were produced to meet the needs of bridge engineering. However, in the actual production process, we found the Z-direction performances of some batches of steel were lower, and they could not meet the technical delivery conditions. Therefore, in this paper, we intend to use scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) to analyze the microstructures and inclusion types of the plate, find out the reasons for unqualified Z-direction performance, and thus suggest improvement measure to increase the passing rate of Z-direction performance, and finally meet the supply needs.

II. EXPERIMENTAL PROCEDURE

A. Experimental Materials

According to GB/T 5313-2010 "Steel plates with through-thickness characteristics" and GB/T 228.1-2010 "Metallic materials-Tensile testing-Part 1: method of test at room temperature", the experimental materials were cut from the Q370qEZ35 defect plate, the thickness of which was 60mm, and its chemical compositions were listed in Table 1.

TABLE I.   THE CHEMICAL COMPOSITIONS OF THE TESTED MATERIALS (WT.%)

C	Si	Mn	P	S	Nb	Als
≤0.18	≤0.55	1.0~1.70	≤0.020	≤0.010	≤0.060	≥0.015

The actual rolling process and Z-direction performance of the heavy plate was shown in Table 2 and Table 3.

TABLE II.   ROLLING PROCESSES OF THE PLATE

Stage Ⅰ		Stage Ⅱ			Finishing cooling Temp. /°C
Open rolling Temp. /°C	Finishing rolling Temp. /°C	Open rolling Temp. /°C	Finishing rolling Temp. /°C	Intermediate slab thichness /mm	
≥1150	≥1000	≤950	≥850	100~120	650~750

TABLE III.   Z-DIRECTION PERFORMANCE OF THE PLATE

Thickness /mm	Z-direction performance			
	Z1	Z2	Z3	Average
60	21.5	18.5	17.0	19.0

B. Characterization

The fracture morphologies and the inclusion types of the tested specimens were investigated by using SEM (FEI Quanta 400) and EDX.

III. RESULTS AND DISCUSSION

A. Tensile Fracture Morphologies Analysis

According to the SEM analysis, the fracture morphologies of Z1, Z2 and Z3 were similar. Therefore, we chose the Z3 as a representative specimen for analysis. The tensile fracture morphologies were shown in Figure 1.
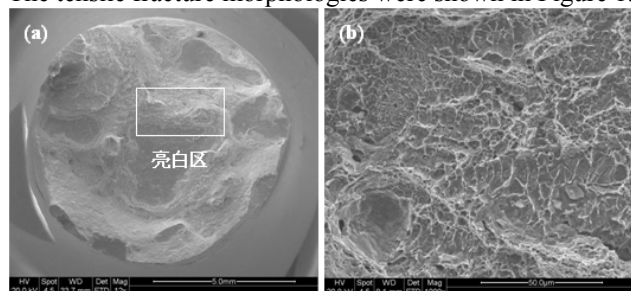

Figure 1.   Tensile fracture morphologies of the tested specimens

From Figure 1, it can be seen that the tensile fracture had typical ductile fracture morphology, the surface was irregularities (fibrous) and distributed different sizes of dimples (Figure 1b), and there existed of inclined sections at the edge of the fracture (shear lip morphology). Most areas of the fracture were showing dark gray, but there were bright white regions in some areas, the fracture of these regions were relatively smooth, and there were presence of significant particulate matters.

B. Inclusions Analysis

In order to investigate the type of the particulate matters in the bright white region, one region was enlarged and the composition of the particles was analyzed, the results were shown in Figure 2.
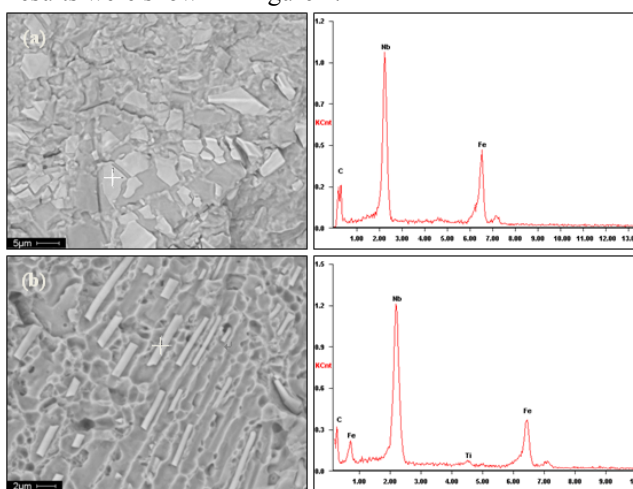

Figure 2.   EDX analysis of the inclusions

As shown in Figure 2, it can be found that there were many massive and strip-like inclusions, which distributed densely together, the main chemical compositions, were Nb, Ti and C. The dimensions of the inclusions were from less than 1 micron to more than ten microns, the total length was up to hundreds of microns.

In addition to the above inclusions, some spherical inclusions were also be found in tough nest, whose sizes were generally about several microns, the chemical compositions of which were mainly O, Mg, Al, S, Ca, Mn, Fe, and also a small number of Na and Si (see Figure.3a), They might be formed the simple compounds MgO, Al_2O_3, CaO, SiO_2, CaS, MnS, FeS, etc., or some complex compounds. In addition, there were large pieces of MnS inclusions, as shown in Figure 3b.
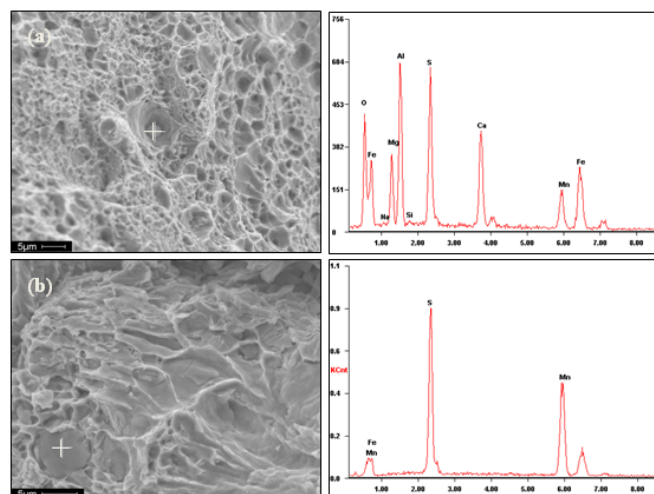

Figure 3.   EDX analysis of the inclusions

C. Discussion

From the EDX anlysis results in Figure 2, it can be obseved that the main elements of the inclusions were C , Nb and Ti, and therefore it can be inferred that they mihgt be present in the form of (Nb, Ti) C. According to some researches [7-8], in the solidification process, at the beginning, the C, Nb and Ti contents of some liquid steel were less than the average content, and in the solidification front, these three elements progressively enriched, when the sodificaiton reached to a certain stage, due to the increased C, Nb and Ti contents, the concentration of the compound C-Nb and C-Ti was reached, so the C-Nb and C-Ti inclusions will be formed in the solidification microstructure. The presence of a large number of C-Nb and C-Ti inclusions, undermined the strength and toughness of the Z-direction, resulted in the cracking along the Nb-Ti particle distribution layers when the heavy plate subjected to a large tensile stress. In addition, from Figure 2, it also found that the inclusions mostly presented in the form of blocky and rod, which had large sizes, quantities, and the relatively higher content of Nb, that indicated metal Nb will be presented. In the design of the steel's composition, Nb was an important component elements, whcih was mainly obtained through adding niobium alloy, the niobium alloy had a high melting point (1580~1630 °C) and density (8.1g/ cm^3), it was insoluble in the liquid steel, mainly dissolved by [Nb] diffusion[9]. If the niobium alloy was too small, it will be lost in the form of dust or be captured in the slag; but if that was too large, niobium, it will be quickly sinking and

accumulating in the bottom of the ladle when added to the molten steel, part of the [Nb] wil be diffused and dissolved, and the others will be enriched into the central portion of the slab in the continuous casting process, and finally be presented in the continuous casting in the form of metal niobiums[10]. In the subsequent rolling process, due to the limited rolling force and compression ratio, the large pieces of metal niobiums were difficult to be broken, an then existed obtain in the form of large-sized inclusions in the heavy plate. As can be seen from Figure 3, there were a small amount of oxide and sulfide inclusions dispersed in the tensile fracture, such as MgO, Al_2O_3, CaO, SiO_2 and CaS, MnS, FeS and so on. The oxide inclusions were generally brittle inclusios, which will be broken at a sufficient rolling force, but the inclusions as shown in Figure 3 (a) embedded in the dimples of the tensile fracture, it is difficult to get broken. However, the sulfide inclusions wer generally plastic inclusions, which were the product of precipitates when the sulfur in the molten steel solidificated, they were not be broken or deformed in the rolling process. Therefore, the above composite inclusions also impacted the Z-direction performance of the heavy plate.

In summary, the presence of inclusions was the main cause of the unqualified Z-direction performance of the Q370qEZ35 heavey plate. A large number of (Nb, Ti)C and metal Nb inclusions were accumulatively distributed in steel core, formed the inclusion bands with dozens or even hundreds of microns, destroyed the continuity of the steel substrate, resulted in the uniformity of the microstructure. Due to presenting a large number of hard and brittle microstructure, and thus in the Z-direction tensile stress, the cracking will be formed on the contact surface of the steel substrate and the inclusions, and then continue to expand along the extension direction of the inclusions, and eventually connected to each other through, caused the Z-direction performances of the steel plate dramaticly being destroyed. In addition, although the sulfide inclusions were the plastic inclusions, but when the steel subjected to Z-direction stress, they will have a greater concentration of stress at the end of the inclusions, and thus induced the microcracks and finally reulted in the the destruction of the Z-direction tensile property of the steel plate.

IV. IMPROVEMENT

A. Smelting Process Control

In the smelting process, in order to improve the slab quality and reduce the formation of large particles of Nb and Ti compounds, some measures were implemented, such as reducing appropriately the internal target of Nb, optimizing the slagging process, and strictly controlling the added time, tapping temperature and the tapping time of Nb alloys and Ti alloys. In addition, strengthening the control of the refining process, extending the refining time for 5~10mim, to make the white slags fully maintained. Moreover, optimizing the process of argon blowing, the argon blowing time will be prolonged for 5~8min, to make the inclusions fully floating up.

B. Casting Process control

Applying the low-temperature fast pouring process, meanwhile, reducing the superheat of the molten steel, and controlling the superheat of which in less than 25°C. Furthermore, improving the solidification rate of the slab, supported by a stable casting speed, in order to effectively reduce the excessive growth of Nb and Ti carbonitride precipitates and the generation of the large-size inclusions

C. Rolling and Cooling Process Control

Optimizing the slab heating process, the temperature of the soaking zone was increased 20~30 °C, the heating time was prolonged for 20min. In the controlled rolling stage, applying the high-temperature high-reduction process, rolling pass reduction of the two roll was greater than 20mm, the cumulative reduction ratio was greater than 60%, of which the cumulative reduction ratio of the last three passes was greater than 30%, so that the grains in the slab core were fully broken. The finishing temperature will be controlled between 820°C and 840°C, and then by optimizing the upper and lower water ratio of the ACC system, the final cooling temperature was controlled below 650 °C, and then cooling slowly on the cooling bed, in order to fully refine the grains, meanwhile reduce the microstructural defects and improve the comprehensive performances of the plate.

V. IMPROVED RESULTS

After the above improved processes had been completed, four heavy plates were produced, of which there were two 60mm and two 64mm, their mechanical properties were shown in Table 4.

TABLE IV. THE MECHANNICAL PROPERTIES OF THE PLATE

Thk. /mm	R_{eL} /MPa	R_m /MPa	A /%	-40°CCA_{kv2} /J			Z-direction Performances /%			
							Z1	Z2	Z3	Avg.
60	420	565	30	216	209	223	54.5	52.3	55.8	54.2
60	430	570	29	190	187	196	49.6	47.5	50.7	49.3
64	415	580	32	220	195	214	57.9	56.1	58.5	57.5
64	410	575	30	197	184	196	53.8	52.0	55.2	53.7

From the above table, it can be seen that through a series of processes improvement, the conventional mechanical properties of these two thicknesses plates met the requirements of Q370qE plate; moreover, the single values and the average values of the Z-direction performances were all above 45%, fully met the requirements of Q370qEZ35, and thus achieved a very significant effect.

VI. CONCLUSIONS

1) The disqualified Z-direction performance of the Q370qEZ35 heavy steel plate was mainly due to the presence of a large number of massive and strip-like (Nb, Ti)C and metal Nb inclusions as well as spherical oxide and sulfide inclusions, which destroyed the continuity of the steel substrate, caused the internal microstructures inhomogeneity, and finally resulted in the reduce of the Z-direction performance.

2) Through the rational optimization of the smelting, casting, rolling and colling processes, the Z-direction performances of the heavy plates were efficiently improved, and all the performance parameters met the requirements of technical delivery conditions.

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