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MICROSTRUCTURE EVOLUTION IN THE HEAT-AFFECTED ZONE OF Zr -Ti MICROALLOYED HIGH-STRENGTH HIGH-TOUGHNESS OFFSHORE STRUCTURAL STEELS

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Abstract

The microstructural evolution and mechanical properties of heat-affected zone of high-strength offshore structural steels was investigated. Micron and sub-micron complex Zr-Ti oxides were observed and evenly dispersed in the heat-affected zone. MnS was spheroidized and refined. The acicular ferrite grains formed on complex oxides in the heat-affected zone effectively partitioned austenite grains and thus refined microstructures. In the meantime, the low carbon content and suitable amount of Ni, Cr, Cu and Mo additions were adopted in the design of high-strength steels. Therefore, bainitic microstructure was obtained in the heat-affected zone within a large heat input welding range (25~100 kJ/cm). The V-notch impact absorbed energy (180 J) of the coarse-grained heat-affected zone for the steel plates welded by submerged arc welding at a heat input of 50 kJ/cm indicated that high-strength offshore structural steels had excellent impact toughness at -60 °C.

Introduction

With the development of infrastructures, bridges, ships, oil storage tank, pipelines, the demand of high performance steels is ever increasing, not only in the excellent mechanical properties, but also in the superior weldability [1]. The improvement of mechanical properties can be carried out by thermomechanical controlled process, microalloying, heat treatment and modification of inclusions. However, the increase in strength and toughness usually results in the decrease in weldability.

Large heat input welding is becoming an important technology because it can increase welding efficiency and reduce labor cost. However, compared with conventional welding, the toughness of heat-affected zone (HAZ) with large heat input welding is significantly deteriorated due to microstructure coarsening [2], especially in the coarse-grained heat-affected zone (CGHAZ) which is adjacent to the fusion line. Extensive studies have been carried out on the improvement of the toughness in the CGHAZ [3-7]. They include reducing austenite grain size, spheroidizing of MnS, modifying of inclusions, oxide metallurgy and the formation of acilaular ferrite in the CGHAZ. The fast cooling has also been used to improve the toughness of the X120 pipeline steels [7]. In the present work, Zr-Ti microalloying, low carbon design and suitable amount of addition of Ni, Cr, Cu and Mo were adopted to improve toughness of high-strength structural steels. Thermal simulation and submerged arc welding were utilized to investigate the microstructure evolution in the heat-affected zone of the Zr-Ti microalloyed high-strength high-toughness offshore structural steels.

Experimental

The experimental material was the Zr-Ti microalloyed high-strength offshore structural steel, which was produced by thermomechanical controlled process at Nanjing Iron & Steel Group Co., Ltd. The heat treatment of steel plates was quenching and tempering. The welding samples (600×200×60 mm) were cut from the vertical of rolling direction. The chemical composition of the investigated steel is shown in Table 1. It is seen that low carbon and high manganese was adopted in the design of the structural steel. Suitable amount of Ni, Cr, Cu and Mo additions was utilized to improve the strength and toughness.

Table 1 Chemical composition of the investigated steel (wt%)

C	Si	Mn	S	P	Cu+Cr+Nb+Ni+Mo
0.05-0.08	0.2-0.4	1.5	0.007	0.003	2.02

GLEEBLE 3500 simulator was used to measure the A_{c1} and A_{c3}. The dimension of the specimen was Φ6×85 mm. Specimens were heated at a rate of 0.5 °C/s and isothermally held at 950 °C for 600 s and then cooled at a rate of 2 °C/s. A_{c1} and A_{c3} were obtained from the temperature-dilation curves.

GLEEBLE 3500 simulator was also utilized to simulate the microstructure of the CGHAZ. Specimens were heated at a rate of 200 °C/s, held at the peak temperature of 1350 °C for 1 s, and then cooled to ambient temperature at the rate of 0.05, 0.1, 0.3, 0.5, 1, 5, 10, 20, 35, 60 °C/s, respectively. The specimens were cut from the central line of the isothermal zone, and the volume fraction of transformed phases was measured by the point-count method.

Based on the results of the thermal simulation, submerged arc welding was carried out at a heat input of 50 kJ/cm. The double vee groove was prepared with a bevel angle 30°. The selected welding wire was MCJ62CF with a diameter 4 mm, and the corresponding flux was SJ105G. The welding parameters are shown in Table 2. The preheating temperature was 100 °C, and the interpass temperature was also 100 °C. Heat treatment was used after the welding (holding for 2.5 h at 600 °C). Low temperature impact toughness was measured after tempering treatment. The standard specimens (55×10×10 mm) were prepared for the Charpy V-notch impact test. The testing temperature was -60 °C. The V-notch was located in the fusion line and the fusion line +2 mm.

Optical and scanning electron microscopes were utilized to observe microstructures and inclusions.

Table 2 Welding parameters of high-strength structural steel plates

Welding current I(A)	Arc voltage U(V)	Welding speed v(cm·min^{-1})	Heat input E(kJ·cm^{-1})
680~700	33~34	27	50

Results

Fig. 1 shows the optical microstructure of the base metal. It is seen that the microstructure is quenched-tempered martensitic microstructure. Fig. 2 shows the inclusion and its energy dispersive spectroscopy results. It is seen that the inclusion is a complex oxide which is composed of Zr, Ti, Al and some other elements.

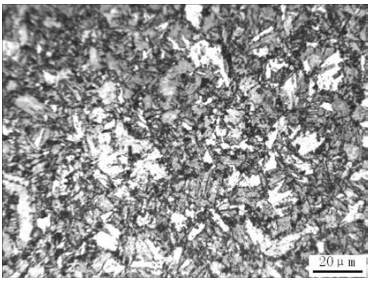
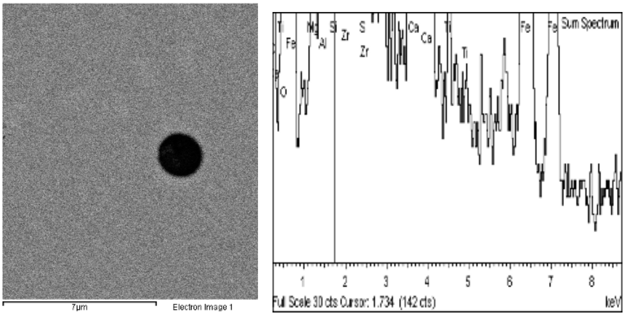


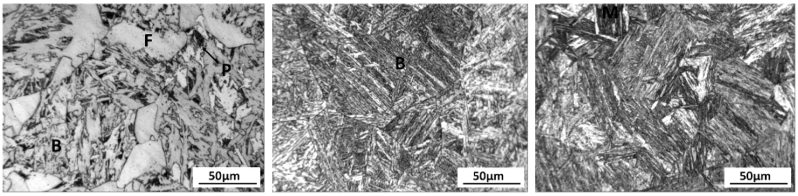
Fig. 1 Optical micrograph of the base metal



Element	Weight%	Atomic%
C K	6.77	17.24
O K	16.83	32.17
Mg K	0.81	1.02
Al K	3.66	4.15
Si K	2.14	2.33
S K	2.30	2.20
Ca K	19.70	15.03
Ti K	0.71	0.45
Fe K	45.31	24.81
Zr L	1.77	0.59
Totals	100.00	

Fig. 2 The inclusion in the base metal and its energy dispersive spectroscopy analysis

The typical microstructure of the simulated specimens is shown in Fig. 3. The microstructures in the simulated coarse-grained heat-affected zone vary from ferrite (F), bainite (B) to martensite (M). The measured proportion of constituents at different cooling rates is summarized in Table 3. It is seen that bainitic microstructure was obtained within a wide range of cooling rates. With the increase of cooling rate, the proportion of bainite is increased until martensite formation. When the cooling rate was too large (60 °C/s), fully martensite was formed.



(a) 0.05 °C/s (b) 5 °C/s (c) 60 °C/s

Fig. 3 Optical microstructures in the specimens cooled at different cooling rates

Table 3 Proportion of constituents at different cooling rates

specimen	Cooling rate (°C/s)	Cooling time ($t_{8/5}$/s)	Proportion			
			F (%)	P (%)	B (%)	M (%)
1#	0.05	6000	29	5	66	0
2#	0.1	3000	15	3	82	0
3#	0.3	1000	7	2	91	0
4#	0.5	600	1	2	97	0
5#	1.0	300	0.5	1	98.5	0
6#	5.0	60	0	0	100	0
7#	10	30	0	0	100	0
8#	20	15	0	0	100	0
9#	35	8.57	0	0	83	17
10#	60	5	0	0	0	100

When the cooling rate was between 5-20 °C/s, the microstructure was fully bainite. The corresponding heat input can be calculated by three-dimensional thermal conductive equation:

$$t_{8/5} = (0.67 - 5\times10^{-4}T_0)\eta' E\left[\frac{1}{500-T_0} - \frac{1}{800-T_0}\right]F_3$$

where the $t_{8/5}$ is the cooling time from 800 °C to 500 °C, T_0 is the experimental temperature, T_0=100 °C in this experiment, η' is the thermal efficiency, η' =0.9, E is the heat input, F_3 is shape factor. Therefore it can be seen from the above equation that when the heat is in the range of 25-100 kJ/cm, the microstructure in the CGHAZ will be fully bainite, which has good comprehensive mechanical properties.

The typical microstructure of the CGHAZ is shown in Fig. 4. Acicular ferrite laths or plates are indicated by arrows. The absorbed energy of V-notch impact test of steel plate samples welded by submerged arc welding with a heat input of 50 kJ/cm was 41 J at the fusion line and 180 J at the fusion line + 2 mm. These results suggested that the high-strength structural steel plates had excellent low temperature impact toughness with large heat input welding.

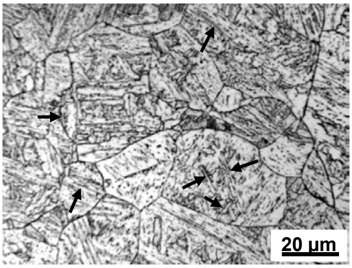


Fig. 4 Optical micrograph of the CGHAZ.

Discussion

Not only does the Zr-Ti elements have the effect of combined deoxidation, but also forms the evenly dispersed stable oxidized particles at high temperatures. These particles can promote

the formation of acicular ferrite and have the effect of pinning the austenite grain boundary, inhibiting the growth of austenite grains in the CGHAZ and thus improving the weldability.
Large and strip-like MnS particles decrease the toughness, ductility and fatigue strength. When MnS particles are refined and evenly dispersed, the mechanical properties of steels will be improved [8]. The inclusions in the matrix are shown in Fig. 2. It is seen that the size of the inclusions is sub-micro and micro-scale, there was no big MnS particle due to the Zr addition. Recent study shows that Zr has the positive effect on the morphology of sulfides [9]. With the help of Zr-Ti combined deoxidation, many fine and evenly dispersive oxysulfides were formed. These fine oxysulfides have important effect on improving the mechanical properties.

The suitable size (~ 1μm) inclusions can promote the formation of acicular ferrite [10]. Acicular ferrite laths or plates are formed by multiple nucleation on intragranular inclusions. They are also formed on the broad faces of pre-formed ferrite laths or plates. These pre-formed acicular ferrite laths or plates partitioned big austenite grains into small and separate regions, and the growth of later formed bainite was confined in these small regions and resulted in fine-grained mixed microstructures [11].

Conclusions

(1) Micron and sub-micron complex Zr-Ti oxides were formed and MnS particles were refined and spheroidized in the steel matrix due to the combined deoxidization. These fine particles not only promoted the formation of acicular ferrite but also had the effect of pinning austenite grain boundaries.

(2) The Zr-Ti microalloyed high-strength structural steels had superior weldability. The absorbed energy reached 41 J at the fusion line and 180 J at the fusion line + 2 mm when the steel plates were welded by submerged arc welding with a heat input of 50 kJ/cm.

(3) The low carbon design and suitable amount additions of Ni, Cr, Cu and Mo were also responsible for fine bainitic microstructure and resulted in the low temperature toughness of the high-strength offshore structural steels.

Acknowledgements

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