Effects of Microalloying Elements on Microstructures and Toughness of Simulated HAZ in Quenched and Tempered Steels

W. S. Chang and B. H. Yoon

Abstract

A series of experiments has been carried out to investigate the effect of titanium, boron and nitrogen on the microstructure and toughness of simulated heat affected zone (HAZ) in quenched and tempered (QT) type 490MPa yield strength steels. For acquiring the same strength level, the carbon content and carbon equivalent could be lowered remarkably with a small titanium and boron addition due to the hardenability effect of boron during quenching process. Following the thermal cycle of large heat input, the coarsened grain HAZ (CGHAZ) of conventional quenched and tempered (QT) type 490MPa yield strength steels exhibited a coarse bainitic or ferrite side plate structure with large prior austenite grains. While, titanium and boron bearing QT type 490MPa yield strength steels were characterized by the microstructure in the CGHAZ, consisting mainly of the fine intragranular ferrite microstructure. Toughness of the simulated HAZ was mainly controlled by the proper Ceq level, and the ratio of Ti/N rather than titanium and nitrogen contents themselves. In the titanium-boron added QT steels, the optimum Ti/N ratio for excellent HAZ toughness was around 2.0, which was much lower than the known Ti/N stoichiometric ratio, 3.4. With reducing Ti/N ratio from the stoichiometric ratio, austenite grain size in the coarse grained HAZ became finer, indicating that the effective fine precipitates could be sufficiently obtained even with lower Ti/N level by adding boron simultaneously. Along with typical titanium carbo-nitrides, various forms of complex titanium- and boron-based precipitates, like TiN-MnS-BN, were often observed in the simulated CGHAZ, which may act as stable nuclei for ferrite during cooling of weld thermal cycles

Key Words : Microalloy element, Toughness, Heat affected zone, Quenched steel, Tempered steel.

1. Introduction

Most commonly encountered problems on the welding of quenched and tempered (QT) type 490MPa yield strength steels, which are widely used in the construction of oil storage tanks, pressure vessels, bridges, etc., are the occurrence of cold cracking and the deterioration of weld heat affected zone (HAZ) toughness. In general, as HAZ toughness decreases with the increase of heat input, the maximum heat input is strictly controlled to obtain the desired toughness. Therefore, by using a steel with low cold cracking susceptibility and good HAZ toughness, even when fabricated with high heat input welding processes, welding productivity could be increased markedly by the elimination of preheating and/or postheating and the application of high heat input welding.

To meet the demand for steel with these requirements, steel makers have improved steel making

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processes for structural steels to be cleaner and adopted the progressive reduction of carbon equivalent in order to increase weldability. To reach the low carbon equivalents demanded by recent specifications, the carbon content of these steels must be significantly reduced and in its absence alternative alloying additions used to obtain the required mechanical properties.

It is well-known that a small addition of boron in QT steels increases hardenability through its segregation at the austenite grain boundaries during the quenching process. Segregation of boron, moreover, was reported to suppress the cold cracking susceptibility of a weldment through the retardation of hydrogen diffusion[1]. All these results suggest that the carbon content of QT steels could be reduced significantly without losing their strength through the small addition of boron.

Since titanium is known to have a strong affinity for nitrogen, it was widely used in two different ways. For 300~400MPa yield strength steels, titanium is added for utilizing two effects. First, it enhances intragranular ferrite nucleation during austenite to ferrite phase transformation. Second, it is a grain growth inhibitor by the pinning effect of fine TiN particles. On the other hand, titanium is commonly added in boron-treated 500MPa~700MPa yield strength steels to fix nitrogen by forming titanium nitrides and enhance the hardenability effect of boron.

In these titanium added steels, the stoichiometric ratio between titanium and nitrogen has been commonly adopted as an indisputable designing guide for titanium-microalloyed steels. Excess titanium, however, is detrimental to HAZ toughness, so the titanium content should be controlled to the lowest amount possible in trying to produce a steel with excellent hardenability as well as good HAZ toughness. In this token, the effect of Ti/N ratio on the microstructure and toughness of simulated HAZ in QT steels containing aluminum, titanium and boron is studied

2. Experimental procedures

A series of steels were manufactured to investigate the effect of Ti/N ratio for Ti-B bearing QT type 490MPa yield strength steels. The chemical compositions, Ti/N and B/N ratio of the steels are listed in Table 1 with a conventional QT type 490MPa yield strength steel (R1) and boron added low carbon QT steel(R2). All the T series steels showed the same carbon content and carbon equivalent, while titanium, boron and nitrogen contents were varied, resulting in different Ti/N and B/N ratio. The T series steels were ingot casted by vacuum induction melting and hot rolled to 20 mm plates. Following a homogenization treatment at 1523K, the slabs were hot rolled to plates

Table 1 Chemical compositions of the used steels (wt. %)

Steels	C	Si	Mn	P	S	Ni	V	Ti	B	Al	N	Ceq	Ti/N	B/N
T1	0.10	0.23	1.37	0.018	0.004	0.22	0.04	0.0	0.0019	0.07	0.0043	0.35	0	0.44
T2	0.10	0.23	1.36	0.017	0.004	0.22	0.04	0.0018	0.0012	0.07	0.0057	0.36	3.16	0.21
T3	0.10	0.22	1.40	0.017	0.004	0.22	0.04	0.0016	0.0003	0.08	0.0061	0.35	2.62	0.05
T4	0.10	0.22	1.39	0.017	0.004	0.21	0.04	0.0016	0.0007	0.08	0.0086	0.35	1.86	0.08
T5	0.10	0.23	1.41	0.016	0.004	0.22	0.04	0.0017	0.0010	0.08	0.0054	0.35	3.15	0.19
T6	0.11	0.25	1.43	0.018	0.004	0.22	0.04	0.0018	0.0016	0.08	0.0084	0.36	2.14	0.19
T7	0.12	0.23	1.38	0.018	0.004	0.22	0.04	0.0024	0.0009	0.08	0.0082	0.37	2.93	0.11
T8	0.12	0.23	1.38	0.018	0.004	0.22	0.04	0.0034	0.0019	0.08	0.0087	0.37	3.91	0.22
T9	0.10	0.25	1.44	0.017	0.004	0.22	0.04	0.0009	0.0005	0.08	0.0074	0.36	1.22	0.07
T10	0.10	0.25	1.45	0.017	0.004	0.23	0.04	0.0017	0.0022	0.08	0.0087	0.36	1.95	0.25
T11	0.09	0.24	1.40	0.017	0.004	0.21	0.04	0.0014	0.0022	0.06	0.0040	0.34	3.50	0.55
R1	0.14	0.34	1.44	0.017	0.005	0.12	0.04	-	-	0.04	0.0060	0.44	(0.16 Mo)	
R2	0.09	0.30	1.38	0.017	0.005	-	0.05	-	0.0017	0.04	0.0050	0.40	(0.12 Cr 0.14 Mo)	

in 20mm thickness. These plates were reaustenitized at 1203K and water quenched with the cooling rate of 40 ℃/sec, and tempered at 923K for an hour.

Full-size specimens for Charpy impact tests were machined from both tempered plates and simulated HAZs. The applied thermal cycle for HAZ simulation is defined by a 135 ℃/s heating rate, a 1623K peak temperature and a 50s cooling time from 1073K to 773K ($\triangle T_{8/5}$), which is equivalent to 60 kJ/cm of heat input when submerged arc welding a 23 mm plate without preheating[2]. To investigate the grain coarsening behavior of steels with different Ti/N ratio, the peak temperature(T_p) of simulated HAZ was changed in the range between 1223K and 1623K.

In order to assess austenite grain size (AGS), ten image frames (magnification x100) in each specimens were selected, and then the program in image analyzer (Quantimet 570, Cambridge Instruments) gives an AGS number in this area.

3. Results and discussion

3.1 Simulated HAZ toughness and microstructures

To investigate the effect of microalloyings on HAZ toughness, the variations of Charpy impact energy of the simulated CGHAZ for steels R1, R2 and T11 were compared in Fig. 1, as a function of $\triangle T_{8/5}$. At any cooling rates, titanium-boron added T11 steel has significantly improved impact energy than those of R1 and R2 steels. T11 steel shows unique toughness variation with increasing cooling time. That is, toughness does not decrease until the cooling time of $\triangle T_{8/5}$ increases up to 100 sec. In addition, CVN energy at -10℃ of T11 steel is over 200J, regardless of $\triangle T_{8/5}$.

Microstructures observed in the simulated CGHAZ(T_p 1623K, $\triangle T_{8/5}$ 50s) are illustrated in Fig. 2. Once weld thermal cycle corresponding to CGHAZ is applied, microstructures of conventional R1 and boron added R2 steels are changed to coarsened upper bainite and ferrite side plate, which may result in deteriorating toughness in the CGHAZ. While, CGHAZ microstructure of titanium and boron added T series steels is predominantly composed of uniform and fine intragranular ferrite.

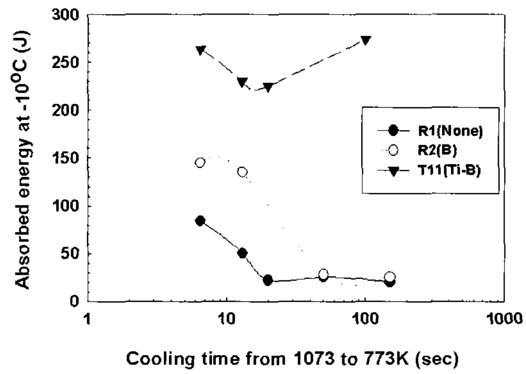

Fig. 1 The variation of impact absorbed energy as a function of $\triangle t_{8/5}$

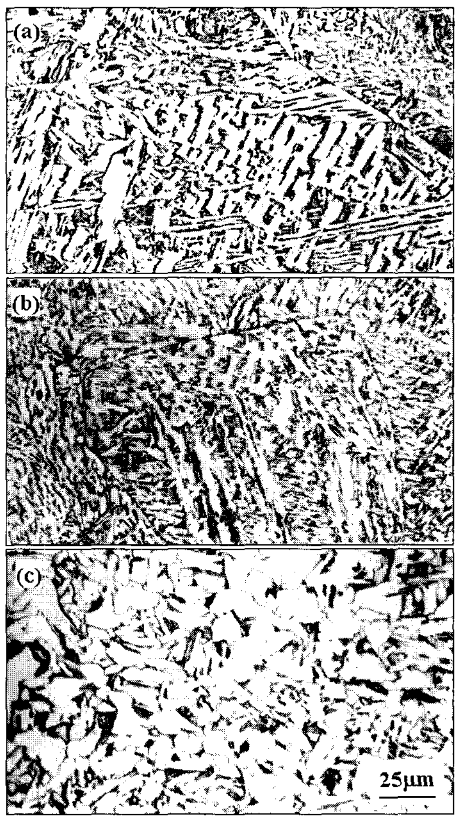

Fig. 2 Comparison of CGHAZ microstructures of (a) R1, (b) R2, and (c) T11 steels

Transmission electron micrographs, Fig. 3, reveal various complex precipitates, consisted of TiN, MnS and BN, formed in the CGHAZ of titanium and boron added T series steels. In boron added R2 steel, boron may easily form boron nitride during weld thermal cycle of slow cooling rate such as $\triangle T_{8/5}$ 50s. Such a formation of BN could reduce soluble nitrogen to some extent, however, the hardenability effect of boron could also be reduced under the high heat input welding condition. Further, boron nitride itself could not exert as grain refiner and/or enhancer of phase transformation so that it could not expect to improve HAZ toughness effectively. On the other hand, CGHAZ of titanium and boron added steels contains not a few complex precipitates, which are thermally stable at high temperature, resulting in fine and uniform ferrite microstructure and guarantee good toughness in the CGHAZ.

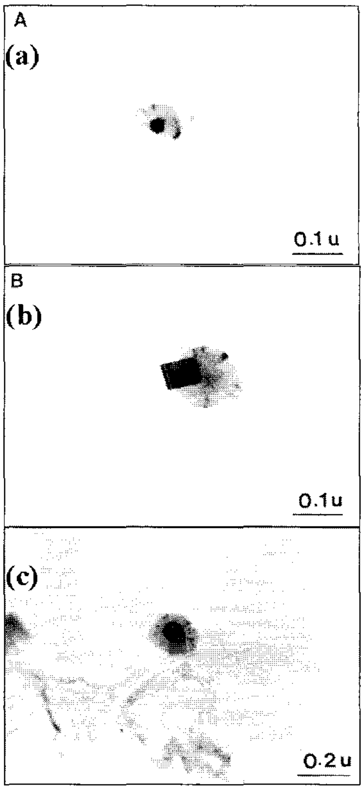

Fig 3 TEM micrographs showing (a) MnS-BN, (b) TiN-BN, and (c) MnS-TiN-BN type complex precipitates observed in simulated CGHAZ of T11 steel

3.2 Effect of Ti/N on austenite grain size and HAZ toughness

Fig. 4 shows the variation of the impact absorbed energy (at -10℃) of the simulated CGHAZ(T_p 1623K, $\triangle T_{8/5}$ 50s) with the Ti/N ratio of steels. Compared to the titanium-free boron added steel, titanium and boron added steels exhibit improved HAZ toughness. However, with increasing Ti/N ratio, impact absorbed energy tends to decrease. This result is inconsistent with the general design rule of Ti/N stoichiometric ratio for acquiring maximum HAZ toughness improvement.

The austenite grain coarsening behavior of titanium and boron added steels with different Ti/N ratio was compared at various peak temperatures. Fig. 5 shows

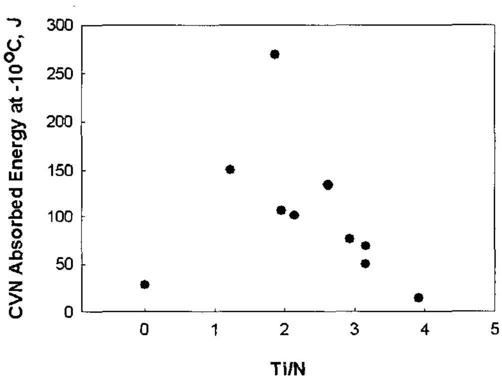

Fig. 4 The variation of the impact absorbed energy in the simulated HAZ at -10℃ with the Ti/N ratio of steels

the variation of austenite grain structure with Ti/N ratio quenched at 1623K. Again, titanium added steels reveal finer austenite grain size compared to titanium-free steel. However, austenite grain size of titanium and boron added steels seems to be coarsened with increasing Ti/N ratio.

The variation of austenite grain size (AGS) quenched at 1223K~1623K with Ti/N ratio is measured by image analyzer and displayed in Fig. 6. At lower austenitizing temperatures, the difference in Ti/N ratio does not display clear effect on AGS. On the

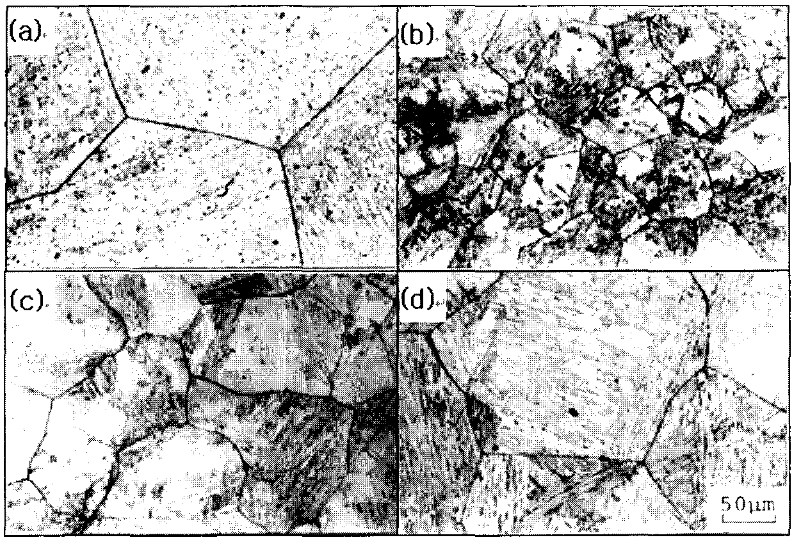

Fig. 5 The variation of austenite grain structure with Ti/N ratio quenched at 1623K
(a) T1 (Ti/N=0) (b) T9 (Ti/N=1.86) (c) T3 (Ti/N=2.62) (d) T2 (Ti/N=3.16)

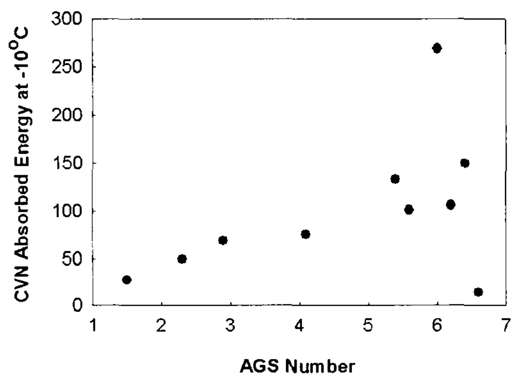

Fig. 6 The variation of austenite grain size quenched at 1223K~1623K with Ti/N ratio

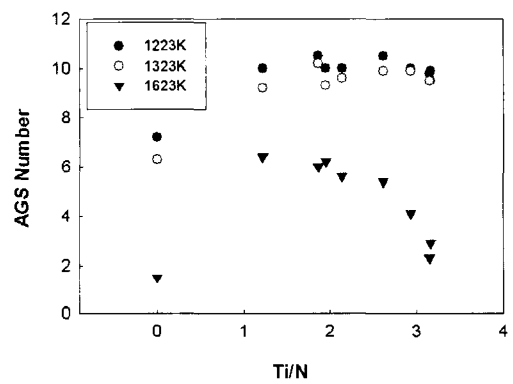

Fig. 7 The variation of impact absorbed energy with austenite grain size

other hand, AGS number of steels quenched at 1623K decreases remarkably with the Ti/N ratio approaching to the stoichiometric ratio. The measurement is well consistent with the previous microstructural observation.

As shown in Fig. 7, low temperature HAZ toughness of titanium and boron added QT steels is improved with increasing AGS number. Therefore, the above observations in Figs. 4 and 6, showing the effect of Ti/N ratio on the microstructure and the toughness respectively, are well coincident.

3.3 Calculation of soluble and insoluble titanium

Titanium in steel is either soluble titanium or combined titanium, which, for example, forms nitrides. As it is titanium nitride that mainly influences grain coarsening behavior during weld thermal cycle, it is a prerequisite to estimate the soluble and insoluble titanium at the maximum heating temperature corresponding to coarsened grained HAZ. Following R. Habu, et al.'s methodology[3] in which the status of titanium, aluminum and boron of steels was estimated

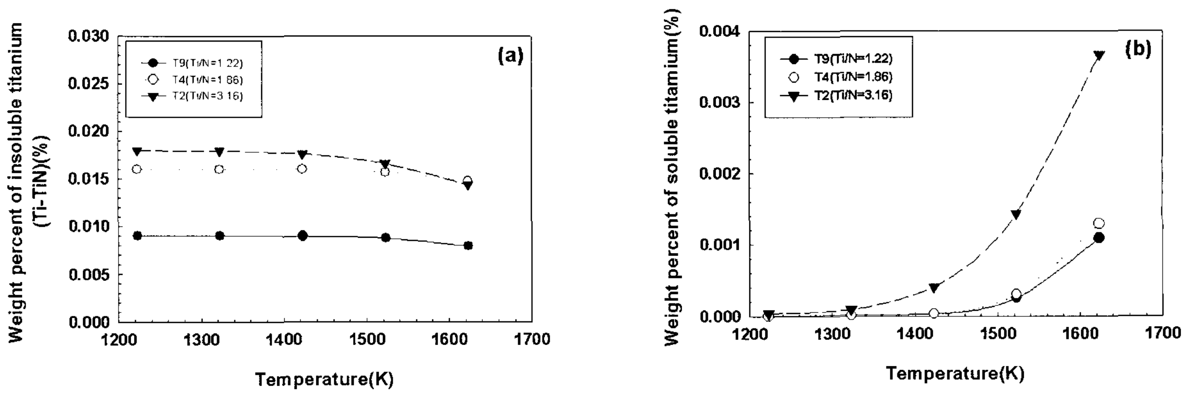

Fig. 8 The calculation results of (a)insoluble and (b) soluble titanium for steels with different Ti/N ratio.

using thermodynamic analysis in the Al-Ti-B-N system, the soluble and insoluble titanium at various austenitizing temperatures of steels in the Al-Ti-B-N system were estimated.

Fig. 8 shows the calculation result of (a) insoluble and (b) soluble titanium for steels with different Ti/N ratio. In case of T4 steel with Ti/N ratio of 1.86, insoluble titanium is similar to T2 steel with Ti/N ratio of 3.16. However, soluble titanium of T2 steel with Ti/N ratio of 3.16 increases remarkably than those of steels with Ti/N ratio of 1.86 and 1.22. That is, the optimum Ti/N ratio forming fine precipitates, which result in fine and uniform ferrite microstructure and guarantee good toughness in the CGHAZ is about 2.

4. Conclusion

1. A significant improvement of HAZ toughness in titanium and boron added quenched and tempered(QT) type 490MPa yield strength steels is attributed to the formation of fine and uniform intragranular ferritic microstructure which may be produced effectively by complex precipitates, consisting of TiN, BN and MnS.

2. In the titanium-boron added QT steels, the optimum Ti/N ratio for excellent HAZ toughness was around 2, lower than the Ti/N stoichiometric ratio of 3.4. With reducing Ti/N ratio from the stoichiometric ratio, the austenite grain size in the coarse grained HAZ became finer, indicating that the effective fineprecipitates could be sufficiently obtained even with lower Ti/N level by adding boron simultaneously.

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