Microstructure Evolution and Toughness Variation of Simulation HAZ with Large Heat Input Welding for E40 Ship Plate Steel

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Abstract: This Charpy impact toughness and microstructure evolution of simulated heat affected zone (HAZ) for E40 ship plate steel have been investigated in this experiment. Simulation of large heat input welding was conducted by thermal simulator to research microstructure evolution of HAZ at 1400℃ peak temperature. Results show that microstructure at HAZ was mainly composed of high intensity of acicular ferrite (AF) and intragranular ferrite (IGF), and grain boundaries ferrite (GBF). Hardness of HAZ decreases with heat input (HI) increasing. Impact toughness for steel specimens with HI of 500 kJ / cm was 141 J. TiN precipitates nucleation and growth at HAZ was analyzed by TEM, indicating that TiN size increases and the number of TiN decreases at HAZ with HI increasing. The reason is that the specimens with HI of 400 kJ / cm has longer cooling time from 800℃ to 500℃ than 120 kJ / cm, which is favorable to growth of TiN particle at HAZ.

1. Introduction
Microalloyed steel manufactured by thermo-mechanically controlled rolling process (TMCP) is considered as a good choice to improve strength and gain superior toughness. [1-6] It is well known that welding thermal cycle is detrimental to mechanical properties of HSLA steels, especially at coarse-grained heat affected zone (CGHAZ), resulting in poor impact toughness. With the rapid development of economy, the large heat input welding (HI>100 kJ / cm) was used more and more, which play an important role in reducing the cost and increasing production efficiency.

In welding process, the impact toughness at HAZ is not only related with microstructure, austenite grain size and precipitates, but also with parameters of welding simulation, such as HI and peak temperature. [7] For a given steel chemistry, parameters of welding simulation have main significant effect on the impact toughness at HAZ. [8]

Although many researches about microstructure and mechanical properties at HAZ at peak temperature of 1350℃ have been reported, little information has been focused on the peak temperature of 1400℃ [9]. In this work, effect of large heat input on microstructure and mechanical properties of HAZ at 1400℃ were investigated in the experiment. Effect of HI on TiN particle precipitate at HAZ during cooling process was also discussed in detail.
2. Experimental procedures
Experimental steel was made by 20kg vacuum melting furnace. Table 1 shows the chemical composition of the E40 ship plate steel. The ingot was hot-rolled into thickness of 14 mm by TMCP. The hot as-rolled strength and toughness at low temperature are shown in as Table 2.

| C   | Si  | Mn  | P   | S   | Ti  | N    | Other |
|-----|-----|-----|-----|-----|-----|------|-------|
| 0.08| 0.20| 1.50| 0.008| 0.003| 0.016| 0.0044| trace |

| Yield Strength / MPa | Ultimate Tensile Strength / MPa | Elongation / % | Impact Toughness (-20℃) / J | Average Impact Toughness (-20℃) / J |
|----------------------|---------------------------------|---------------|-----------------------------|-----------------------------------|
| 440                  | 560                             | 29            | 280                         | 330                               | 320                               | 310                               |

It is very difficult to determine the exact position of HAZ, so in the present study, welding simulation was carried out by a thermo-mechanical simulator to examine microstructure and toughness for steel specimens at HAZ with different heat input. The specimens were made into 11 mm × 11 mm × 55 mm for HAZ simulations. According to the Rykal-2D model, [10] HI of 120 kJ / cm, 280 kJ / cm, 400 kJ / cm, and 500 kJ / cm were fixed. Heating rate and peak temperature (T_p) were 100℃/ s and 1400℃, respectively. The parameter and curves for large heat input welding simulation is presented in Fig. 1 and Table 3.

![Fig. 1 Schematic diagram of welding thermal cycle](image-url)

| Heat input kJ / cm | Peak temperature / ℃ | Holding time at peak temperature / s | t 8 / 5 / s |
|--------------------|-----------------------|--------------------------------------|-------------|
| 120                | 1400                  | 3                                    | 198         |
| 280                | 1400                  | 3                                    | 269         |
| 400                | 1400                  | 3                                    | 325         |
The steel specimens with welding simulation were processed into standard Charpy-V-notch (CVN) samples (10 mm×10 mm×55 mm). Impact toughness was carried out at -20℃ by drop weight impact tester. The micro-hardness was determined by hardness-tester.

In order to observe microstructure at HAZ, specimens were etched with 3% nital, and optical microscopes (OM). The scanning electron microscopy (SEM) was used to analyze the microstructure and inclusions in detail. The nucleation and growth of TiN particles at HAZ were researched by transmission electron microscopy (TEM) for carbon replica. The distribution of particles sizes was conducted by a quantitative image analyzer.

3. Results

3.1 Parametric Microstructure at HAZ
Fig.2 shows microstructures evolution at HAZ with HI of 120~500 kJ/cm. The microstructure at HAZ were mainly composed by significant amount of AF and GBF along with original austenite grain boundaries in the specimens with HI of 120~500 kJ / cm. It can be found that small volume fraction of intragranular ferrite (IGF) appeared inside austenite grain in Fig.2 B. It was observed that the intensity of IGF increased inside austenite grain with HI increasing, as shown in Fig.2 D.

3.2 Impact Toughness
Fig.3 presents the impact toughness at -20℃ for base metal and HAZ with HI of 120~500 kJ / cm. Average absorbed energy at base metal is more than 310 J, but the average absorbed energy at HAZ rapidly decreases. Excellent impact toughness (141 J) at HAZ with HI of 500 kJ / cm was obtained in this work. It can be found that impact toughness at HAZ decreased with HI increasing. It should be noted that the impact toughness variation is mainly influenced by the intensity of AF at HAZ with welding thermal cycle, as shown in Fig.2. It is recognized that AF can efficiently deflect or arrest cleavage crack propagation due to its interlocked arrangement, and refine microstructure to improve impact toughness at HAZ.

![Fig.2 Microstructures evolution of HAZ with welding simulation thermal cycle, A - 120 kJ / cm, B - 280 kJ / cm, C - 400 kJ / cm and D - 500 kJ / cm, respectively.](image-url)
3.3 Hardness
Fig. 4 demonstrates the relationship of Vickers hardness between welding heat input. It is observed that Vickers hardness at HAZ decreased with HI increasing. The lowest Vickers hardness was obtained at HAZ with HI of 500 kJ / cm, which illustrates some soft microstructure appearance at HAZ, such as GBF and IGF, due to long cooling time from 800°C to 500 °C at HAZ with heat input of 500 kJ / cm, as shown in Fig.2 D.

![Fig.3 Variation of Vickers hardness with different heat input](image1)

![Fig.4 Charpy impact toughness of base metal and HAZ with heat input of 120 kJ / cm, 280 kJ / cm, 400 kJ / cm and 500 kJ / cm, respectively.](image2)

4 Discussion

4.1 Precipitation behavior of TiN at HAZ
It is recognized that TiN precipitate particle can efficiently pin austenite boundaries during welding thermal cycle, which contributes to refinement of microstructure, improving the impact toughness at HAZ. Fig.5 shows that morphology of TiN precipitate particle at HAZ with HI of 120 kJ / cm and 400 kJ / cm was observed by TEM. It can be found that the size of TiN precipitate particle at HAZ with HI of 400 kJ / cm is larger than 120 kJ / cm, and the shape is rectangular. It should be noted that the volume fraction of small size (< 50 m) TiN precipitate particle at HAZ with HI of 120 kJ / cm is obviously higher than 400 kJ / cm, as shown in Fig.6. According to Oswald ripening process [11], when the fraction of particles reaches an equilibrium state, precipitation and growth occurs, and the particles coarsening starts at later. TiN precipitate particle at HAZ with HI of 400 kJ / cm has longer cooling time from 800°C to 500 °C than 120 kJ / cm, which is favorable to growth of TiN particle at HAZ. Therefore, an increase in heat input increases TiN particle size and decrease number of TiN particle at HAZ, which is consistent with the conclusion by Joonoh Moon. [12]

![Fig.5 TiN precipitation at HAZ with heat input of A-120 kJ / cm and B-400 kJ / cm, respectively.](image3)
4.2 Effect of HI on IGF transformation at HAZ

It is established that the formation of AF nucleation on inclusions is at higher temperature at HAZ [13]. During the cooling processing at HAZ, GBF firstly nucleated grain boundaries because of small energy barrier, and then AF rapidly formed on inclusions and the other place, [14] leading to the interlocked microstructure, as shown in Fig.7. These AF clearly divided prior austenite grain into many smaller and separated regions. At later the growth of IGF was confined in smaller region, which is attributed to refinement of microstructure at HAZ. It is found that the high intensity of IGF presented in specimen with HI of 500 kJ / cm, which is responsible for the number of AF laths or plates inside austenite grain. It has been reported that the fraction of AF decreased with HI increasing at HAZ in low carbon steel. [15] High supercooling of HAZ with 120 kJ / cm provided driving force for the AF nucleation and growth during transformation from austenite to ferrite, favoring to the formation of AF at HAZ during cooling process. And growth of AF is inhibited because of small cooling rate from 800 ℃ to 500 ℃ at HAZ with HI of 500 kJ / cm, reducing driving energy for the nucleation and growth of AF. Therefore, significant amount of IGF appeared at HAZ with HI of 500 kJ / cm.

5. Conclusions

(1) Excellent impact toughness (141 J) at HAZ with HI of 500 kJ / cm was obtained in this work. The toughness of HAZ at -20℃ decreased with HI increasing. Impact toughness variation of HAZ is related to intensity of AF at HAZ with welding thermal cycle.

(2) TiN precipitate particle at HAZ with HI of 400 kJ / cm has longer cooling time from 800℃ to
500 °C than 120 kJ / cm, which is favorable to growth of TiN particle at HAZ. Therefore, an increase in heat input increases TiN particle size and decrease number of TiN particle at HAZ.

(3) AF effectively divided original austenite grain into many smaller and separated regions. The growth of IGF at later is confined in smaller region. High supercooling of HAZ with 120 kJ / cm provided driving force for the AF nucleation and growth during transformation from austenite to ferrite, favoring to the formation of AF, resulting in the appearance of significant amount of IGF at HAZ with HI of 500 kJ / cm.

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References
[1] Wu K M, Inagawa Y, Enomoto M. Three-dimensional morphology of ferrite formed in association with inclusions in low-carbon steel[J]. Materials Characterization, 2004, 52(2):121-127.
[2] Thompson M, Ferry M, Monohar P A. Simulation of Hot-band Microstructure of C-Mn Steels during High Speed Cooling[J]. Isij International, 2001, 41(8):891-899.
[3] Shanmugam, Ramisetti, N.K, et al. Effect of cooling rate on the microstructure and mechanical properties of Nb-microalloyed steels[J]. Materials Science & Engineering A, 2007, 460(1):335-343.
[4] Pereloma E V, Bayley C, Boyd J D. Microstructural evolution during simulated OLAC processing of a low-carbon microalloyed steel[J]. Materials Science & Engineering A, 1996, 210(1-2):16-24.
[5] Fang X, Fan Z, Ralph B, et al. The relationships between tensile properties and hole expansion property of C-Mn steels[J]. Journal of Materials Science, 2003, 38(18):3877-3882.
[6] Ai J H, Zhao T C, Gao H J, et al. Effect of controlled rolling and cooling on the microstructure and mechanical properties of 60Si2MnA spring steel rod[J]. Journal of Materials Processing Technology, 2005, 160(3):390-395.
[7] Ion J C, Easterling K E, Ashby M F. A second report on diagrams of microstructure and hardness for heat-affected zones in welds[J]. Acta Metallurgica, 1984, 32(11):1949,1957-1955,1962.
[8] Dolby R E. Advances in welding metallurgy of steel[J]. Metal Science Journal, 2013, 10(1):349-362.
[9] Chai F, Yang C F, Su H, et al. Effect of Zr addition to Ti-killed steel on inclusion formation and microstructural evolution in welding induced coarse-grained heat affected zone[J]. 2008, 21(3):220-226.
[10] Rykalin N N. Calculation of heat processes in welding[M]. Translation at the European Commission. Office for Official Publications of the European Communities, 2011:183-201.
[11] Moon J, Lee C, Uhm S, et al. Coarsening kinetics of TiN particle in a low alloyed steel in weld HAZ: Considering critical particle size[J]. Acta Materialia, 2006, 54(4):1053-1061.
[12] Moon J, Jeong H, Lee J, et al. Particle coarsening kinetics considering critical particle size in the presence of multiple particles in the heat-affected zone of a weld[J]. Materials Science & Engineering A, 2008, s 483–484(1):633-636.
[13] Zhang D, Terasaki H, Komizo Y I. In situ observation of the formation of intragranular acicular ferrite at non-metallic inclusions in C–Mn steel[J]. Acta Materialia, 2010, 58(4):1369-1378.
[14] Shi M, Zhang P, Zhu F. Toughness and Microstructure of Coarse Grain Heat Affected Zone with High Heat Input Welding in Zr-bearing Low Carbon Steel[J]. Transactions of the Iron & Steel Institute of Japan, 2014, 54(54):188-192.
[15] Shi M, Zhang P, Wang C, et al. Effect of High Heat Input on Toughness and Microstructure of Coarse Grain Heat Affected Zone in Zr Bearing Low Carbon Steel[J]. Transactions of the Iron & Steel Institute of Japan, 2014, 54(1):188-192.