Effect of High Heat Input on Toughness and Microstructure of Coarse Grain Heat Affected Zone in Zr Bearing Low Carbon Steel

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Microstructure evolution and impact toughness of simulated coarse grained heat affected zone (CGHAZ) in Zr bearing low carbon steel have been investigated in this study. Thermal simulator was used to simulate microstructure evolution of CGHAZ with high heat input welding thermal cycle at 1400°C peak temperature. Microstructure of CGHAZ consisted of high volume fraction of AF inside grain and GBF at prior austenite grain boundaries. Prior austenite grain size of CGHAZ increases with heat input increasing. Excellent impact toughness (more than 100 J) of CGHAZ with heat input of 1000 kJ/cm was obtained in this experiment. Impact toughness of CGHAZ with 400 kJ/cm (230 J) is the highest, because austenite grain size of CGHAZ with 400 kJ/cm favors the development of AF inside grain. Impact toughness is not only related with high angle boundaries but also with effective grain size. High supercooling of CGHAZ provided driving force for the AF transformation during welding thermal cycle, increasing the number of AF.

KEY WORDS: coarsen grained heat affected zone (CGHAZ); acicular ferrite (AF); impact toughness; microstructure; electron backscattered diffraction (EBSD).

1. Introduction

In order to enhance welding efficiency and reduce welding costs, high heat input welding process was applied in HSLA steels. The balance of high strength and good toughness in HSLA steels can be upset by welding thermal cycle characterized by rapid heating and high peak temperature, producing poor impact toughness at heat affected zone (HAZ), especially coarsen grained heat affected zone (CGHAZ) adjacent to the weld fusion line experiencing peak temperature up to 1400°C or higher.¹⁾

It is generally recognized that microstructure consisting of mainly acicular ferrite (AF) provides optimum weld metal and CGHAZ mechanical properties in viewpoint of strength and toughness.²⁾ The addition of TiN to steels is widely used to improve toughness in CGHAZ through pinning austenite grain boundaries and promoting AF transformation during welding thermal cycle.³⁾ However, it is reported that dissolution of TiN particles at higher temperature (1400°C) may result in loss in grain refinement capability of TiN.⁴⁾ Oxide metallurgy has a beneficial effect on the improvement of toughness in CGHAZ with high heat input welding thermal cycle because of high dissolution point and greater thermal stability.^{2,5)}

Relation of toughness and microstructure in CGHAZ with high heat input welding thermal cycle in Zr-bearing low-carbon steels is seldom studied. In this present study, specimens were subjected to different high heat input welding

thermal cycle at 1400°C peak temperature to simulated microstructure transformation in CGHAZ, excellent impact toughness with high heat input was obtain at CGHAZ, especially heat input of 1000 kJ/cm. We present results concerning the detailed effect of welding heat input on impact toughness and microstructure transformation at CGHAZ.

2. Experimental Procedure

2.1. Specimen Preparation

Experimental steels were made by use of vacuum induction melting furnace. The chemical composition of steel is: 0.08 C, 0.26 Si, 1.5 Mn, 0.005 S, 0.008 P, 0.008 Zr, 0.015 Ti, 0.0039 N, 0.02 V and 0.01 Nb (wt.%). The 100 mm × 100 mm ingot was reheated to 1200°C for 2 h, and rolled into 16 mm plate by thermo-mechanical control processing (TMCP) in the recrystallized zone and the non-recrystallized zone with cooling rate of 15–20°C/s, final cooling temperature of 650°C. And the as-rolled mechanical properties are as follows: yield strength 435 MPa, ultimate tensile strength 543 MPa, elongation 29% and average impact toughness 298 J (–20°C).

2.2. High Heat Input Welding Thermal Cycle Procedure

High heat input welding thermal cycle simulations were conducted on a thermo-mechanical simulator to study microstructure evolution and impact toughness changes in the CGHAZ. Simulated specimens were cut along the transversal direction of hot rolled steel plate and machined into dimensions 11 mm × 11 mm × 55 mm for CGHAZ simula-

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tions. High heat input welding thermal cycle was determined by the Rykalin mathematical heat transfer model to simulate the welding process.⁶⁾ The thermal cycle of the welding simulation is characterized by the peak temperature

Fig. 1. Schematic diagram of welding thermal cycle.

(T_p), cooling time from 800°C to 500°C ($\Delta t_{800-500}$) and heat input energy (E). The high heat input welding thermal cycle parameter and curves is schematically shown in **Fig. 1** and **Table 1**. The specimens were rapidly heated to peak temperature (T_p) of 1 673 K (1 400°C) with heating rate of 100°C/s and cooled at different cooling time for range of 800°C to 500°C to be equivalent to welding heat input of 100 kJ/cm, 200 kJ/cm, 400 kJ/cm, 800 kJ/cm and 1 000 kJ/cm.

2.3. Impact Toughness Tests

After CGHAZ simulation, the specimens were machined

Table 1. Parameter of high heat input welding thermal cycle.

Peak Temp. (°C)	Holding Time at Peak Temp. (sec)	$\Delta t_{800-500}$ (sec)	Heat Input (kJ/cm)
1 400	1	137.5	100
1 400	1	214	200
1 400	3	325	400
1 400	30	730	800
1 400	60	818	1 000

Fig. 2. Microstructure of base metal and CGHAZ with different heat input welding thermal cycle, (a) base metal, (b) 100 kJ/cm, (c) 200 kJ/cm, (d) 400 kJ/cm, (e) 800 kJ/cm and (f) 1 000 kJ/cm.

into standard Charpy-V-notch samples with dimensions 10 mm × 10 mm × 55 mm and then subjected to impact tests at −20°C on an Instron Dynatup 9200 series instrumented drop weight impact tester.

2.4. Metallographic Observations

The metallographic observation region was fixed near the monitoring thermocouple and then polished using standard metallographic procedures and etched with 3 vol% Nital in order to reduce the error resulting from relatively uneven cooling rate. The microstructure of CGHAZ was examined using optical microscopes (OM). And prior austenite grain size was measured with the line intercept method based on low magnification OM. Fracture surface observation and crystallographic orientation feature analysis were carried out by use of scanning electron microscopy (SEM) equipped with an electron backscattered diffraction (EBSD) system. The scanned area for EBSD analyses is about 250 μm × 250 μm with scanning step of 1 μm.

3. Experimental Results

3.1. Microstructure of Base Metal and CGHAZ

Figure 2 shows optical micrographs of base metal and CGHAZ with high heat input welding thermal cycle. Microstructures of base metal were mainly composed by ferrite and pearlite. Microstructure of CGHAZ consisted of high volume fraction of AF inside grain and grain boundaries ferrite (GBF) at prior austenite grain boundaries. It is noted that small volume fraction of side plate ferrite (SPF) growing into grain at austenite grain boundaries was observed at CGHAZ with heat input of 1 000 kJ/cm, as shown in Fig. 2(f), because of long time cooling from 800°C to 500°C, which is favorable to element diffusion during transformation. It should be point out that although supersaturation drive SPF nucleation at grain boundaries,⁷⁾ the supersaturation is also favorable to AF nucleation inside gain when the time cooling from 800°C to 500°C is short. AF transformation time is very short relative to the time SPF transformation.⁸⁾ AF firstly nucleated inside grain during cooling, occupying most nucleating space, inhibiting SPF nucleation at gain boundaries. Therefore, small volume fraction of SPF observed at the side of which the number of AF is small in the specimen with heat input of 1 000 kJ/cm.

Figure 3 shows variation of austenite grain size of CGHAZ with high heat input welding thermal cycle. It can be found that austenite grain size of CGHAZ increases with heat input increasing due to long holding time at peak temperature, as shown in Table 1.

3.2. Impact Toughness of Base Metal and CGHAZ

Figure 4 shows Charpy impact toughness of base metal and CGHAZ with different heat input welding thermal cycle tested at −20°C. Excellent impact toughness (more than 100 J) of CGHAZ with heat input of 1 000 kJ/cm was obtained in this experiment. It is noted that impact toughness of CGHAZ with 400 kJ/cm (230 J) is the highest, because austenite grain size of CGHAZ with 400 kJ/cm favors the development of AF inside grain, contributing to refinement of microstructure of CGHAZ. A coarser austenite grain size to reduce grain boundary surface area may

then be required in order to shift the balance of ferrite nucleation from the austenite grain boundaries to the intragranular regions (assuming inclusions are inert substrates) because of long holding time at peak temperature, so that high volume fraction of AF are kinetically favorable. It can be found that when heat input is more than 400 kJ/cm, the impact toughness significantly decreased, because of further increased austenite grain size to more than a critical value. This result is consistent with the conclusions proposed by Lee and Pan,⁹⁾ who have reported that the volume fraction of AF begin to be reduced with further increased austenite grain size to more than a critical value in Ti-killed steels without and with addition of Ca. And they founded that the cover of CaO on the surface layer of Ti-oxides enlarged the disregistry between inclusions and ferrite and reduced the strain field set up in austenite around inclusions. However, it should be pointed out that the critical value of austenite grain size for AF transformation can be different for various steel grades.

Figure 5 shows fracture surface of CGHAZ with 400 kJ/cm and 1 000 kJ/cm. It is found that fracture surface of CGHAZ with 400 kJ/cm exhibited dimple fracture mode, which allows CGHAZ with 400 kJ/cm to absorb more energy dur-

Fig. 3. Austenite grain size of CGHAZ with heat input of 100 kJ/cm, 200 kJ/cm, 400 kJ/cm, 800 kJ/cm and 1 000 kJ/cm.

Fig. 4. Charpy impact toughness of base metal and CGHAZ with heat input of 100 kJ/cm, 200 kJ/cm, 400 kJ/cm, 800 kJ/cm and 1 000 kJ/cm.

Fig. 5. Morphologies of fracture surface at CGHAZ with heat input of (a), (b) 400 kJ/cm and (c), (d) 1000 kJ/cm.

Fig. 6. Variation of vickers hardness with different heat input.

ing fracture. Fracture surface of CGHAZ with 1000 kJ/cm reveals brittle fracture mode, in which river pattern appears.

Figure 6 shows Vickers hardness of CGHAZ with high heat input welding thermal cycle decrease with increase the heat input. The lowest hardness value occurs at CGHAZ with 1000 kJ/cm, which demonstrates appearance of soft microstructure, such as GBF, due to low cooling rate from 800°C to 500°C at heat input of 1000 kJ/cm, as shown in Fig. 2(f).

3.3. Crystallographic Characteristics of CGHAZ

Figure 7 shows crystallographic characteristics of CGHAZ with heat input of 100 kJ/cm, 400 kJ/cm and 1000 kJ/cm.

Large crystallographic grain size with various orientation exhibited at CGHAZ with 1000 kJ/cm, as shown in Fig. 7(e). The microstructure with predominant AF has a small crystallographic grain size, as shown in Figs. 7(a) and 7(c), which is defined as a cluster of points sharing the same crystallographic orientation.¹⁰⁾ The blue lines stand for high misorientation boundaries of 15° or more, and red line for low misorientation boundaries of 2–15° in image quality maps shown in Figs. 7(b), 7(d) and 7(f). The high misorientation grain or packet boundaries can efficiently arrest propagation of cleavage micro-crack,^{11,12)} however, low misorientation boundaries never lead to noticeable deviation of the cleavage crack.¹²⁾ Effective grain size of CGHAZ with heat input of 100 kJ/cm, 400 kJ/cm and 1000 kJ/cm measured is about 16.4 μm, 28.5 μm and 45.2 μm, respectively, base on EBSD results.

4. Discussion

4.1. Effect of High Angle Boundaries on Impact Toughness of CGHAZ

High misorientation angle boundaries can effectively arrest micro-cracks propagation, while low misorientation angle boundaries can not be contribute to noticeable deviation of cleavage cracks.¹¹⁾ It is recognized that threshold value of high misorientation boundaries is usually defined at 15°, because the grain boundaries with misorientation more than 15° can deflect or arrest the cleavage crack propagation according to many literature.^{11,13)} Fraction of high angle boundaries (more than 15°) of CGHAZ with heat input of 400 kJ/cm is obviously larger than that of 100 kJ/cm and

Fig. 7. Crystallographic characteristics of CGHAZ with heat input of (a) and (b) 100 kJ/cm, (c) and (d) 400 kJ/cm, (e) and (f) 1 000 kJ/cm, (a), (c) and (e) orientation image maps, (b), (d) and (f) image quality maps.

1 000 kJ/cm based on EBSD results, as shown in **Fig. 8**. Meanwhile, the corresponding impact toughness (230 J) of CGHAZ with 400 kJ/cm is the highest, as shown in Fig. 4. It is worth noting that the fraction of high angle boundaries of CGHAZ with heat input of 1 000 kJ/cm is slightly larger than that of 100 kJ/cm, however, the corresponding impact toughness (120 J) of CGHAZ with 1 000 kJ/cm is lower than that (150 J) of 100 kJ/cm. This result can be explained by

taking account of the effective grain size of CGHAZ. Small effective grain size can effectively arrest crack propagation, improving impact toughness of CGHAZ. During specimen experiencing heat input of 1 000 kJ/cm welding thermal cycle, grain size becomes coarser, especially the nucleation of GBF at prior austenite grain boundaries, because of longer cooling time from 800°C to 500°C. Therefore, the impact toughness is not only related with high angle bound-

Fig. 8. Distribution of misorientation angle at CGHAZ with heat input of 100 kJ/cm, 400 kJ/cm and 1 000 kJ/cm.

Fig. 9. Distribution of aspect ratio of ferrite inside austenite grain.

aries but also with effective grain size.

4.2. Effect of Heat Input on AF Transformation at CGHAZ

Each ferrite inside austenite grain can be characterized individually by its morphological parameters: maximum length $L_{\max}$, maximum width $W_{\max}$ and aspect ratio ($L_{\max}/W_{\max}$) measured based on the optical micrographs. AF was defined as ferrite with aspect ratio ($L_{\max}/W_{\max} > 3$) more than 3 in this study.¹⁴⁾ The detailed morphologies of ferrite inside austenite grain at CGHAZ with 100 kJ/cm, 400 kJ/cm and 1 000 kJ/cm are shown in Fig. 9. It is found that the number of AF at CGHAZ with 100 kJ/cm and 400 kJ/cm is higher than that with 1 000 kJ/cm, which is responsible for excellent toughness at CGHAZ. However, much fine AF, aspect ratio more than 7 or more, was observed at CGHAZ with

1 000 kJ/cm. High supercooling of CGHAZ with 100 kJ/cm and 400 kJ/cm provided driving force for the AF transformation during welding thermal cycle, increasing the number of AF. AF transformation is similar to bainite transformation.⁸⁾ AF transformation is very fast at some temperature range with shearing mechanism. But the growth of AF is inhibited owe to small cooling rate at CGHAZ with 1 000 kJ/cm, lacking of driving energy for the further growth of AF.

5. Conclusions

(1) Microstructure of CGHAZ with high heat input thermal cycle consisted of high volume fraction of AF inside grain and GBF at prior austenite grain boundaries. Austenite grain size of CGHAZ increases with heat input increasing due to long holding time at peak temperature.

(2) Excellent impact toughness (more than 100 J) of CGHAZ with heat input of 1 000 kJ/cm was obtained in this experiment. Impact toughness of CGHAZ with 400 kJ/cm (230 J) is the highest, because austenite grain size of CGHAZ with 400 kJ/cm favors the development of AF inside grain.

(3) Impact toughness is not only related with high angle boundaries but also with effective grain size. High supercooling of CGHAZ provided driving force for the AF transformation during welding thermal cycle, increasing the number of AF.

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