In-situ observation on the influences of Ti on phase transformation of weld metal processed by high-heat input welding

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Abstract
The in-situ observation of the phase transformation processes of weld metal during high-heat input welding were carried out by a high temperature laser confocal microscope. The influences of Ti content on the phase transformation process were investigated. It was found that the Ti inclusions could act as the nucleation sites for \( \alpha \rightarrow \gamma \) transformation during the heating stage of welding thermo cycle and inhibit the growth of austenite grains. The number of inclusions was increased with increasing Ti content. During the cooling stage of welding thermo cycle, the inclusions could induce the nucleation of acicular ferrites when the Ti content was below 0.078%. With increasing Ti content, more acicular ferrites collided with each other and restricted their further growth. When the Ti content was increased up to 0.115%, a proportion of Ti atoms were dissolved in the matrix, which increased the hardenability and thus generated the lath bainite microstructure instead of acicular ferrite.

Keywords
In-situ observation, weld metal, acicular ferrite

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As one of main manufacturing processes, the welding has attached more and more attention in the shipbuilding, offshore platforms and other large equipment manufacturing field. For example, the welding accounts for nearly 30% in the whole cost of shipbuilding. Thus, improving the welding efficiency is of great significance in the large equipment manufacturing field. Under this background, the vertical electro-gas welding (EGW), electroslag welding and other high-heat input welding methods have received great attention.

On the condition of high-heat input welding, the mechanical properties of the welding line and weld metal are readily deteriorated due to the high peak temperature of the weld metal, prolonged retention at high temperature and coarse microstructures. The acicular ferrite (AF) is one of the medium-temperature (500–700°C) transformation products. The laths in the AFs normally interlock with each other, forming a high proportion of large angle grain boundaries. In addition, the AFs exhibit high-density dislocations. This kind of microstructure exhibits excellent low-temperature toughness, crack resistance and tensile properties. Thus, the AFs are normally considered as the ideal microstructure in the weld metal processed by high-heat input welding.
welding. In general, the AFs nucleate on the inclusions. In this way, the composition and distribution of inclusions show critical influences on the formation and development of AFs.\textsuperscript{6–8} As one of the common element in high-heat input weld metal, Ti has a strong binding force with oxygen. When the inclusion is formed with Ti and other elements, and the content of Ti is controlled within a reasonable range, the formation of AF structure can be effectively promoted in the inclusion, which would dramatically improve the mechanical properties of high-heat input weld metal. When the content of Ti is extremely low, the AF grain nucleation location is few, and its size is large due to the limited Ti inclusions. When Ti is excessive in the weld metal, it will not only fail to promote the formation of AF tissue, but also cause the formation of a large number of bainite tissue, which would seriously reduce the toughness of the weld. Normally, the effects of Ti content were investigated by analysing the microstructure and inclusion characteristics in the weld metal. The investigations on the microstructure during the phase transformation have not yet been reported.

In this work, the transformation processes in the weld metals with various Ti contents were observed during welding by the high temperature laser confocal microscope. This work aimed to reveal the influences of Ti contents on the microstructure evolution of the weld metal during the welding thermo cycle, laying theoretical basis for the study on high-heat input welding.

### Experimental methods

The alloy powers with various Ti contents were selected as the welding flux in the high-heat input welding flux-cored wires. The flux-cored wires with the diameter of 1.6 mm were produced by the flux-cored wire forming machine. The Q235 steels were welded with the vertical EGW method. The sizes of the welded sheets were 20 mm in thick, 1000 mm in width and 500 mm in length. During the welding process, the welding current, welding voltage and welding speed was 370A, 35V and 38 mm/min. As a result, the welding heat input was 205 kJ/cm. During the welding, the protective atmosphere was CO\textsubscript{2} + Ar and the cooling was carried out by circulating water. The chemical composition of the weld metal was examined by the JS-GP891 full spectrum direct reading spectrometer. The chemical compositions of three-weld metal were shown in Table 1. The Si, Mn and Ti could facilitate the formation of inclusions and provide the nucleation sites for the AFs. The B may prohibit the formation of ferrite and thus improve the fraction of AFs.

After mechanical polish and etching with 3\% nital, the microstructures of weld metals were examined by the optical microscope (OM) and JSM-6490 scanning electron microscope (SEM). The chemical compositions and distribution of elements of the inclusions were examined by the JXA-8530 field emission electron probe backscatter. The cylinder samples with the size of \( \phi 5 \times 5 \) mm were prepared. After polishing, these samples were put into the alumina crucible. Then, the microstructure evolution was observed by the high temperature laser confocal microscope. In order to simulate the microstructure evolution during actual welding, the employed welding thermo cycle was shown in Figure 1. The samples were heated to the peak temperature of 1400°C at the rate of 100°C/s and held for 5 s. After this, the samples were cooled to the room temperature at the rate of 1°C/s. During this process, lots of pictures were taken at the rate of five pictures per second by the high temperature laser confocal microscope.

### Table 1. Chemical composition of weld metal (mass %).

| Elements | C   | Si   | Mn  | S | Ti  | B | Fe |
|----------|-----|------|-----|---|-----|---|----|
| 1#       | 0.08| 0.23 | 1.85| 0.017| 0.078| 0.015| Bal |
| 2#       | 0.08| 0.31 | 1.83| 0.017| 0.093| 0.015| Bal |
| 3#       | 0.08| 0.28 | 1.89| 0.017| 0.115| 0.015| Bal |

![Figure 1. Schematic diagram showing the welding thermal cycle.](image-url)
Results

Microstructures and properties of the weld metal

The mechanical properties of the weld metals with various Ti contents under the condition of high-heat input welding were shown in Table 2. The tensile strength and impact energy of 1# weld metal with the lowest Ti content are the lowest as shown in Table 2. As the content of Ti increasing, the strength of weld metal increases. However, the impact energy at low temperature increases first and then decreases, which demonstrate that the mechanical properties of the weld metal can be affected significantly by the content of Ti. Generally, the mechanical properties of weld metal are determined by the microstructure, and the specific characterisation results of the microstructure were shown in Figure 2(a), (c) and (e) were the optical micrographs of the weld metals, while Figure 2(b), (d) and (f) were the SEM micrographs. As shown in Figure 2, a large number of nonmetallic inclusions appeared in the 1# weld metal when the Ti content was 0.078%. In addition, lots of AFs nucleated on these inclusions and they interlocked with each other (Figure 2(a) and (b)). With increasing Ti content, the number of inclusions was increased and the sizes of AFs were decreased in the 2# weld metal (Figure 2(c) and (d)), which increased the mechanical properties of the weld metal When the Ti

| Elements | $R_{m}$/MPa | $R_{p0.2}$/MPa | $\delta/\%$ | $A_{kv(-40\degree C)}/J$ |
|----------|-------------|----------------|------------|-------------------|
| 1#       | 561         | 448            | 24         | 72                |
| 2#       | 606         | 513            | 24         | 88                |
| 3#       | 745         | 617            | 22         | 58                |

Figure 2. Microstructures of weld metal: microstructure of the: (a) 1#, (c) 2# and (e) 3# weld metal, and SEM micrograph of the (b) 1#, (d) 2# and (f) 3# weld metal.
content was increased up to 0.115%, the microstructure was composed of lath bainite instead of the AFs (Figure 2(e) and (f)). The strength of weld metal were increased and the impact toughness were reduced greatly.

$\gamma \rightarrow \alpha$ phase transformation process

Figure 3 showed the in-situ observation of the $\alpha \rightarrow \gamma$ transformation process during the welding thermo cycle in the 2# weld metal. In this work, the high heating rate ($100^\circ C/s$) led to a high melt superheat in the weld metal. Thus, the $\alpha \rightarrow \gamma$ phase transformation initiated at $1263^\circ C$. At this moment, the inclusions acted as the nucleation sites of $\gamma$ grains and a few $\gamma$ grains appeared (Figure 3(a)). With increasing temperature, these $\gamma$ grains started to grow through the migration of grain boundaries and the larger grains swallowed the smaller ones. When the $\gamma$ grain boundaries encountered the inclusions, the migration of grain boundaries was prohibited (Figure 3(d)). This indicated that the inclusions might inhibit the migration of grain boundaries, leading to the refinement of the $\gamma$ grains. Figure 4 revealed the final microstructures in these three-weld metals after the welding thermo cycles. It was found that the grain sizes of 1# weld metal was the highest, while those in 2# and 3# joints were quite similar.

$\gamma \rightarrow \alpha$ phase transformation process

Under the condition of high-heat input welding, the $\gamma \rightarrow \alpha$ transformation appears during the cooling stage of welding thermo cycle. Figure 5 showed the in-situ observation of the $\gamma \rightarrow \alpha$ transformation process in the 1# weld metal. As shown, when the temperature was higher than $615^\circ C$, the weld metal was remained in austenite phase region, fine inclusions were filled in the austenite matrix and there was no phase transformation (Figure 5(a)). When the temperature was decreased to $593^\circ C$, the AFs nucleated at some inclusions (Figure 5(b)). With decreasing temperature, more AFs started to nucleate, collided with the previous AFs and restricted the growth of previous AFs (Figure 5(c)). When the temperature was decreased to $545^\circ C$, the AFs interlocked with each other and the prior austenite was completely replaced by the AFs.

Figure 6 revealed the in-situ observation of the $\gamma \rightarrow \alpha$ transformation process in the 2# weld metal. As shown, although the Ti content in the weld metal was increased, the transformation temperature range in 2# weld metal was in consistent with that in 1# weld metal. The only difference was that the nucleation sites of AFs were improved in 2# weld metal, which increased the probability of the collision of the AFs. This was inconsistent with the microstructure of the weld metal in Figure 2.
Figure 7 showed the in-situ observation of the γ → α transformation process in the 2# weld metal. As shown, when the Ti content was as high as 0.115%, the transformation temperature range was greatly decreased. The transformation temperature was decreased to 494°C, which was below the temperature range of AF and the AFs could not be formed at the inclusions. Instead, the lath bainite nucleated along the austenite boundaries and extended into the interior of austenite grains. Finally, the austenite was replaced with the lath bainite at the end of transformation process.

Discussion

Figure 8 revealed the distribution of inclusions in 1# weld metal. In this work, 10 electron probe backscatter micrographs were obtained in each weld metal. Then, the number and size distribution of the inclusions were derived from these micrographs. Figure 9 showed the distribution of inclusions. As shown, the 1# weld metal exhibited the minimum number of inclusions. With increasing Ti content, the total number of inclusions was increased. However, when the Ti content was
increased up to 0.115%, the increased number of the inclusions in 3# weld metal was not obvious. This indicated that the Ti content could significantly influence the distribution of the inclusions. However, when the Ti content was beyond the range, the number of inclusions did not change.

Figure 10 revealed the map scanning results of the inclusions in the 1# weld metal. As shown, the interior...
of inclusion was mainly composed of Ti, Si and Mn. During the solidification process of flux-cored wires, Ti, Si, Mn and other deoxidising elements first combined with the oxygen and then the oxide precipitated. Then, a few MnS particles were precipitated on the edge of inclusions. As shown in Figure 1, the Ti containing oxide directly contacted the matrix after the re-melting of the MnS particles on the edge of inclusions. Because of the low mismatch between the oxide and austenite, the activation energy of the nucleation of austenite grain on the oxides were decreased. Thus, during the transformation process, the austenite grains were readily nucleated on the inclusions (Figure 3(a)). With the further increasing temperature, the inclusions inhibited the growth of austenite grains by inhibiting the migration of grain boundaries (Figure 3(d)). In general, the influences of second particles on the grain growth of austenite grains were expressed by Zener equation. This equation was as follows:

\[ R = \left(\frac{4}{3}\right) \cdot (r/f) \]

where \( R \) is the radius of austenite grain, \( r \) is the radius of second particle and \( f \) is the volume fraction of second particle.

As shown in the Zener equation, the austenite grain size is closely related with the distribution of inclusions. Normally, the larger number of fine inclusions lead to smaller austenite grain size. As shown in Figure 9, the 1# weld metal had the lowest Ti content, the least inclusions and the minimum sites for the nucleation of austenite grains. As a result, the 1# weld metal exhibited the highest austenite grain size. With increasing Ti content, the number of inclusions was increased and the austenite grain size was decreased in 2# weld metal. However, when the Ti content was further increased, the distribution of inclusions in 3# weld metal was only slightly changed, leading to slightly-changed austenite grain size (Figure 4).

During the cooling stage of the welding thermal cycle, the Mn and S atoms in the matrix are absorbed by the oxides with the core of \((\text{Ti,Mn})_2\text{O}_3\). As a result, the MnS is generated on the edge of the inclusions, producing a low-Mn zone which was called as Mn-depleted zone (MDZ). As one of the austenite stabilised elements, the decreased Mn content increased the \(\text{Ar}_3\) temperature on the surface of inclusions. This promoted the nucleation and growth of AFs and thus generated the AFs in Figure 10. This indicated that the distribution of inclusions had significant influences on the nucleation of AFs. With increasing Ti content, the number of inclusions in the 2# weld metal was increased, increasing the probabilities of collision of the AFs and restricting the development of AF microstructure (Figure 6). However, although the Ti content was increased in the 3# weld metal, the number of inclusions was not increased. This indicated that the extra Ti existed in the form of atom instead of oxides. This increased the hardenability and thus led to the formation of lath bainite microstructure (Figure 7).

Conclusions

The transformation process of weld metal was investigated by the high temperature laser confocal microscope in the weld metal processed by high-heat input welding. The influences of Ti content on the phase transformation process were investigated. The main conclusions are as follows:

1. During the heating stage of welding thermal cycle, the Ti inclusions acted as nucleation sites for the \(\alpha \rightarrow \gamma\) transformation and prohibited
the growth of austenite grains. With increasing Ti content, the austenite grain size was further refined due to the increased Ti oxides.

2. During the cooling stage of welding thermal cycle, the inclusions in 1# weld metal induced the nucleation and growth of AFs. With increasing Ti content, the probabilities of the collision of the AFs were improved. When the Ti content was increased up to 0.115%, the extra Ti appeared in the solid solution state in the 3# weld metal. This increased the hardenability of the weld metal and thus led to the formation of lath bainite.

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