Study on toughening mechanism of Ti on weld metal of high strength steel

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Abstract
The effect of Ti element on acicular ferrite microstructure of high strength steel weld was studied by scanning electron microscope (SEM), Transmission electron microscopy (TEM) and EDX spectrum analysis. The results show that Ti element content in a certain range can promote the precipitation of acicular ferrite in high strength steel weld metal. The increase of Ti content in the weld makes the Ti-rich inclusions increase, which is conducive to the formation of acicular ferrite. Charpy impact test results show that with the increase of Ti content, the impact toughness of weld metal increases first and then decreases. The tensile test results show that the tensile strength of weld metal increases and the elongation decreases with the increase of Ti content. There are high density dislocations and M-A components in acicular ferrite. M-A elements hinder the crack growth and improve the impact toughness of weld metal. When the Ti content is 0.253%, the impact energy of the weld metal is 155 J at -60 °C, and the impact toughness is the best.

1. Introduction
Low alloy high strength steel is widely used in energy, engineering machinery, bridge construction, vehicles and ships and other important industries of the national economy because of its high strength and high toughness. It is a kind of resource-saving steel, which can solve the problem of sustainable development brought by the increase of steel production to resource supply and environmental protection [1–3]. Q960 high strength steel has high strength and good plasticity toughness, which has been widely used in engineering. Replacing the traditional 300Mpa ordinary steel with high strength steel above 900Mpa can reduce the weight of the original component by 40% ~ 50%. In engineering machinery products, 50% ~ 70% of steel needs welding. Scholars believe that the impact toughness of high strength steel welded joints can be improved by alloying weld metal, adjusting solidification cooling time and postweld heat treatment [4–6]. Weld metal alloying is to design appropriate welding materials and add beneficial alloy elements to weld metal, which can not only ensure the strength of the joint, but also improve the impact absorption capacity of the joint. A large number of tests show that the effective method to improve the strength and toughness of Q960 steel weld is to obtain a large number of uniform fine acicular ferrite in the joint microstructure [7–9].

After the chemical composition guarantees to inhibit the formation of proeutectoid ferrite (PF) and side-strip ferrite (FSP), the cooling rate also affects the formation of acicular ferrite [10–12]. A acicular ferrite (AF) is a thermodynamically nonequilibrium microstructure, which is essentially bainite with intragranular nucleation. The difference between the two is that bainite nucleates at austenite grain boundaries, while acicular ferrite nucleates in non-metallic inclusions within austenite grains. Moderate cooling rate can promote the formation of acicular ferrite, slow cooling rate favors the formation of PF and FSP, excessive cooling rate promotes the formation of lath ferrite (LF) and martensite (M).

Titanium is one of the micro alloy elements commonly used in welding material preparation. Titanium flux cored wire has a large proportion in flux cored wire due to its good operation technology. In the weld metal, Ti can promote the nucleation and growth of acicular ferrite, which is one of the main means to enhance the
mechanical properties of weld metal. This is because titanium can form dispersed metallic inclusions in weld metal, promote acicular ferrite nucleation in austenite, refine grains, enhance strength and impact toughness of weld metal. Meanwhile, titanium oxide can also be used as a hydrogen trap to solidify a large amount of hydrogen and effectively reduce the content of diffusive hydrogen. Lei et al [13] studied the effect of Ti on the microstructure and properties of weld seam of Al matrix composites. Masahiko et al [14] studied the effect of Ti and B on the microstructure and toughness of pipeline steel weld.

Ti can strongly promote the formation of carbides, and form stable carbide aggregation in the weld metal. Ti element in weld metal can combine with O to form various Ti oxides, thereby reducing the oxygen content in weld metal. Because of the stability of TiO$_2$, it is not easy to dissolve, so it has a strong pinning effect on austenite. At the same time, the Ti$_2$O$_3$ cation vacancy concentration is large, which has a strong attraction to the surrounding C, Mn and other elements, so that the concentration of this element around the gradient difference increases the nucleation driving force, which is beneficial to the formation of acicular ferrite. Some studies have found [15] that when the Ti content in the weld metal is between 0.028% and 0.038%, the acicular ferrite structure accounts for a large proportion in the weld metal, but continues to increase the Ti content, and the acicular ferrite structure changes into bainite structure.

In the aspect of the effect of alloy elements on weld, Al, Mn, Cr and other elements have been studied more, while the effect of Ti on high strength steel weld is rarely studied. The flux-cored wire has become a research hotspot in the design of high strength steel welding materials because of its easy composition adjustment, fast welding speed, good weld formation and high welding quality [16–20]. Therefore, in this paper, flux-cored wire was developed by ourselves and Q960 high strength steel welded joint was prepared by fusion pole self-protection welding, and the influence rule of Ti element on impact toughness of weld metal was discussed.

### 2. Experiments

#### 2.1. Experimental materials

In the experiment, Ti, Mn, Mo, Cr, Ni, Mo, ferric boron and other powders with a purity of more than 99.9% were selected as raw materials. Before use, the powders should be dried at 150 °C for 5h to remove water. The raw materials are added to the steel strip, rolled and drawn to produce a flux-cored wire of Φ1.6mm.
The steel plate used in the experiment is Q960 high-strength steel, whose size is $300\,\text{mm} \times 100\,\text{mm} \times 10\,\text{mm}$. Its main element content is shown in Table 1, and its tensile strength, elongation and impact toughness are shown in Table 2.

### 2.2. Experimental methods

Before welding, Q960 steel plate is processed into a groove of $60^\circ$, and both sides of the groove are polished smooth, then cleaned with acetone alcohol solution and dried. Welding adopts fusion electrode self-protective welding, welding current is $260 \sim 280\,\text{A}$, welding voltage is $28 \sim 30\,\text{V}$, welding speed is $320 \sim 350\,\text{mm min}^{-1}$, inter-layer temperature is controlled at $100 \sim 120\,\text{°C}$, welding 5 layers and 7 passes, welding joint schematic diagram is shown in Figure 1.

The weld microstructure samples were prepared according to the standard metallographic preparation method [21]. The metallographic samples were analyzed by S-3400N scanning electron microscope and the composition of inclusions was analyzed by energy dispersive spectrometer. The G2F20 field emission transmission electron microscope was used for microstructure observation and micro-area analysis. The electrolyte is 95% absolute ethanol and 5% perchloric acid, and the electrolysis parameters are $-30\,\text{°C}$, $75 \sim 100\,\text{V}$, $50 \sim 80\,\text{mA}$. GNT 200 electronic universal testing machine was used to measure the tensile strength and elongation at break. The impact energy of samples was measured by JB-30B impact testing machine.

### 3. Experimental results and discussion

#### 3.1. Microstructure and metallic inclusions

The content of alloying elements in weld metal is shown in Table 3. It is found that micro inclusions play an important role in the nucleation of acicular ferrite. The results show that the micro inclusions which are beneficial to the nucleation of acicular ferrite are heterogeneous in structure and composition, and there is a ‘plastic distortion zone’ around the inclusions. Therefore, the effect mechanism of inclusions on acicular ferrite can be analyzed by thermal stress field model around inclusions.

When there are inclusions in the weld metal, due to the different coefficient of thermal expansion between the inclusion and the weld base, a large stress field will be generated in the matrix around the inclusion during the cooling process of the weld metal. When the stress concentration exceeds the yield stress of the matrix, a large number of dislocations will be generated around the inclusions, which creates conditions for the nucleation of acicular ferrite and becomes the effective position for acicular ferrite nucleation. Assuming the radius of spherical inclusions in weld metal is $R_1$, the radius of the elastic zone around the inclusion is $R_2$, the radius of plastic zone around inclusion is $R_3$, the stress around the inclusion can be expressed by formulas (1) ~ (4) [22].

When the inclusion size is $0 < R < R_1$:

$$F_1 = 0$$

When the inclusion size is $R_1 < R < R_3$:

$$F_2 = Y_2$$

When the inclusion size is $R_3 < R < R_2$:

$$F_2 = Y_2 \left[ \frac{R_3}{R} \right]^3$$

Then there are:

$$\sigma = \frac{3}{2} \left[ \Delta T \frac{\Delta T}{Y_2} + \left[ 1 - \mu_2 \right] \frac{R_3}{R_1} \right]$$

| Table 3. Chemical composition of alloy elements in weld metal (mass, wt%). |
|---|
| Si | Mn | Ni | Cr | Mo | Al | Ti | B | Fe |
|---|
| 0.52 | 1.14 | 0.72 | 0.66 | 0.41 | 0.76 | 0.047 | 0.013 | Bal. |
| 0.53 | 1.16 | 0.72 | 0.71 | 0.37 | 0.83 | 0.096 | 0.011 | Bal. |
| 0.55 | 1.18 | 0.68 | 0.69 | 0.46 | 0.74 | 0.201 | 0.018 | Bal. |
| 0.56 | 1.21 | 0.63 | 0.74 | 0.48 | 0.85 | 0.253 | 0.010 | Bal. |
| 0.55 | 1.18 | 0.82 | 0.72 | 0.33 | 0.71 | 0.350 | 0.012 | Bal. |
| 0.58 | 1.15 | 0.78 | 0.77 | 0.37 | 0.80 | 0.486 | 0.014 | Bal. |
In the formula, $Y_2$ is the yield strength of the weld metal, $\Delta \alpha$ is the difference in thermal expansion coefficient between the weld base and inclusions, $\Delta T$ is the temperature change interval difference, $\mu_2$ is Poisson’s ratio, $E_2$ is the elastic modulus of weld metal matrix.

Therefore, the elastic modulus and thermal expansion coefficient of weld metal matrix and inclusions play an important role in the size of plastic zone and nucleation of new phase. The difference of thermal expansion coefficient between inclusions and austenite has an important effect on the nucleation of acicular ferrite. Because the difference in thermal expansion coefficient between inclusions and austenite will cause large strain of austenite. From the point of view of energy, dislocations formed by this strain can reduce nucleation energy of ferrite. The greater the difference between the two, the greater the stress field intensity, the greater the strain and plastic zone.

Assuming that acicular ferrite nucleation occurs on screw dislocations, as shown in figure 2. It is assumed that there is a disk with a thickness of $dl$ and a radius of $r$ from the nucleus. The interface of the crystal nucleus is non-coherent, after nucleation, the change of free energy [23] is:

\[
\Delta G = \frac{2\pi r^2 d_1}{\sqrt{\frac{2G}{3\pi}}} \left( \frac{\Delta \alpha}{\Delta T} \right) \left( \frac{\mu_2}{\mu_1} \right)^2
\]
In the formula, $\Delta G$ is the volume free energy, $\sigma$ is surface energy, $b$ is Poisson’s ratio, $V_P$ is molar volume, $\frac{\mu b^2}{4\pi} \ln r - C$ is total strain energy of screw dislocation.

Gomez Ramirez [24] calculated that when the volume free energy is 480 J mol$^{-1}$ and the surface energy is 0.24 J m$^{-2}$, the energy required for homogeneous nucleation is 7.06 ev, while that for dislocation nucleation is only 0.93 ev. Therefore, it is proved that the inclusion dislocation is beneficial to the nucleation of new phase.

Some scholars believe that [25, 26] the nucleation of acicular ferrite in weld metal of high strength steel is on the oxide inclusions of Ti and Mn, and this oxide inclusion is a single structure. Thermodynamic analysis shows that Ti is more likely to exist in the form of TiO, Ti$_2$O$_3$, Ti$_3$O$_5$ and TiO$_2$ with O in the weld metal than TiN with N. Among these oxides of Ti, TiO is the most stable oxide due to the lowest Gibbs free energy, and it is also the most easily formed oxide of Ti, so it can be used as the nucleation center of acicular ferrite. However, the TEM
The morphology of inclusions in the weld metal shown in Figure 3(a) can be clearly seen. The inclusions are not a single structure, but are divided into several different layers. The EDX spectrum is shown in Figures 3(b)–(d). The chemical composition of the weld metal is 1.37\% Mn, 1.55\% Mo, 0.94\% Cr, 1.24\% Ni, 0.06\% Nb, 0.49\% Ti, 0.055\% B, 0.077\% N by chemical analysis. Figure 3(b) shows that the core A region of the inclusions is mainly oxides of Ti, Mn, Al and Si; The B zone of inclusions is dominated by Cu and Mn sulfides, as shown in Figure 3(c). Further analysis of the interface between region A and region B showed that region C contained a certain amount of B and N elements, as shown in Figure 3(d), which was speculated to be BN compound.

The microstructure of 0.047\% Ti and 0.253\% Ti weld metal was observed by scanning electron microscopy, as shown in Figure 4. The composition of micro-inclusion is analyzed by energy spectrum. The element content of inclusion is shown in Table 4. It can be seen from Table 4 that the micro inclusions in the weld metal are complex oxygen sulfides formed by Ti, Mn and Al. With the increase of Ti content, the number of micro inclusions increases, the size decreases, and the shape is close to spherical. On the other hand, with the increase of Ti content, the microstructure of acicular ferrite in weld metal increases, so it can be concluded that the complex oxygen sulfide rich in Ti plays an important role in promoting the nucleation of acicular ferrite.

The specimen in 0.35\% Ti was observed under SEM, as shown in Figure 5. The acicular ferrite is nucleation and growth around the core of nearly spherical micro-inclusions, which size is between 0.5 \(\mu\text{m}\) and 1 \(\mu\text{m}\). The results show that the micro inclusions are oxygen sulfides of Ti, Mn and Si. This further indicates that the addition of Ti can increase the number of micro inclusions and increase the proportion of acicular ferrite. Some scholars have studied [27, 28] that in Ti oxides, TiO, TiO\(_2\), and Ti\(_2\)MnO\(_4\) have a good B-N crystal phase relationship with \(\alpha\)-Fe, which is conducive to the formation of acicular ferrite structure, and there is a K-S relationship between the generated ferrite and the parent austenite.

Figure 6 shows the morphology of micro inclusions with different Ti contents. When there is no Ti element, the size of micro inclusions in the weld metal is large and the number is small, as shown in Figure 6(a). When the content of Ti is between 0.201\% and 0.35\%, the size of micro inclusions is small, the distribution is dispersive.
and the quantity is large, as shown in figure 6(b). When the content of Ti element in weld metal reaches 0.486%, the size of micro inclusions becomes larger and the number is less. Because the size, distribution and number of micro-inclusions have an important influence on the formation of acicular ferrite, the statistics of micro-inclusions in weld metal with different Ti contents are carried out, and the results are shown in table 5. When there is no Ti in the weld metal, 55% of the micro inclusions are smaller than 2 μm, and 10% are more than 3 μm. With the increase of Ti element, the small-sized micro inclusions increase. When the content of Ti increases to 0.253%, 85% of the micro inclusions are smaller than 2 μm. When the content of Ti continues to increase, the large size micro inclusion increases, the micro inclusion greater than 3 μm can reach 30%, and the micro inclusion smaller than 2 μm is only 35%.

The central and marginal regions of 0%Ti, 0.253%Ti and 0.486%Ti microinclusions were analyzed by energy spectrum. In the Ti-free welds, the central area of the micro-inclusion was mainly Mn and Si oxides, while the marginal area was Mn sulfide and Al and Mg oxides. When the content of Ti is 0.253%, the central area of the micro-inclusion is dominated by the oxides of Ti, Mn and Al, while the marginal area is dominated by the oxides of Si and Al and the sulfide of Mn. When Ti in the weld metal increases to 0.486%, the micro inclusion center is dominated by the oxides of Ti and Mn, and the edge area is dominated by the oxides of Al, Mn, Mg and Si, and the sulfide of Mn. The micro-inclusion structure of acicular ferrite is mainly composed of oxides in the center and oxides and sulfides in the edge.

When there is no Ti in the weld metal, the center of micro inclusions is MnO and SiO₂, and the edge is MnS, Al₂O₃ and MgO. When the weld metal contains 0.253% Ti, the micro inclusion centers are mainly TixOy, MnO and Al₂O₃, and the edges are mainly SiO₂, Al₂O₃ and MnS. When the weld metal contains 0.486% Ti, the micro inclusion centers are mainly TixOy and MnO, and the edges are mainly SiO₂, Al₂O₃, MnO, MgO and MnS. It can be seen that with the increase of Ti content in weld metal, the structure of micro inclusions has changed, but MnS is always in the edge area of micro inclusions, and the core of micro inclusions changes from Mn-Si-O to Ti-Mn-Al-O, and then to Ti-Mn-O.

During the post weld cooling process of high strength steel weld metal, the dissolved s and O precipitate due to the decrease of solid solubility. The oxides such as MnO and SiO₂ have high melting point, during the cooling process, oxides first precipitate, followed by sulfides. The number of oxides formed first is large, and the number of sulfides such as MnS formed later is small, which can only be nucleated with oxides as the core, and always

| Proportion of micro inclusions (%) | 0 ~ 1 μm | 1 ~ 2 μm | 2 ~ 3 μm | ≥3 μm |
|----------------------------------|---------|---------|---------|------|
| Weld line                        |         |         |         |      |
| 0% Ti                            | 10      | 45      | 35      | 10   |
| 0.253% Ti                        | 50      | 35      | 15      | —    |
| 0.486% Ti                        | 5       | 30      | 35      | 30   |

Figure 7. Impact test specimen of weld metal.
remains outside the oxides. Finally, the complex structure with oxide as the core and sulfide as the outer layer was formed. When there is Ti element in the weld metal, TiO, Ti₂O₃ and TiO₂ are formed in turn with the decreasing temperature. There are a lot of cation vacancies in Ti₂O₃, which can easily attract Mn, C, Si and other elements around the weld metal, resulting in the decrease of the alloy element concentration around the inclusion. Because Mn³⁺ and Ti³⁺ have the same ionic radius, Ti₂O₃ is more likely to attract Mn around inclusions, resulting in Mn poor zone around the inclusions, thus increasing the chemical driving force and promoting the nucleation of acicular ferrite.

When there is no Ti element in the weld, the inclusions are mainly composed of MnO and SiO₂ due to the high content of Mn and Si. When the Ti content in the weld metal increases, Ti enters into the inclusions, and some Mn and Si are reduced. The oxides of Ti and Al enter the core of the inclusions, and then MnO and SiO₂ are gradually squeezed to the edge of the inclusions. When the content of Ti element reaches the maximum, a large number of Ti oxides are formed, pushing the rest oxides to the edge of inclusions. Therefore, when the mass fraction of Ti is between 0.2% and 0.35%, a large number of ti-mn-al-o inclusions can be formed in the weld, which effectively promotes the nucleation of acicular ferrite.

The formation of acicular ferrite in weld metal must be carried by the nucleation center. As mentioned above, the oxides of Ti can be used as nucleation carriers of acicular ferrite. When the micro inclusions in the weld metal exist in the grain boundary, it will promote the ferrite nucleation of the side plate. When the micro inclusions in the weld metal are located in the grain, they are conducive to becoming the nucleation core of acicular ferrite, which can refine the grain and improve the toughness.

3.2. Mechanical property
The weld zone and heat affected zone of welded joint are selected to make impact specimen, as shown in figure 7. The impact properties at 25°C and −60°C were tested. The size of impact specimen was 10 mm × 10 mm × 55 mm,
V-notch and depth of 2 mm. The instantaneous pendulum velocity is 5 m s$^{-1}$, and the impact test sample is perpendicular to the welding direction. Five samples are taken from each group to calculate the average value.

Figure 8 shows the change of impact energy of weld with Ti content at room temperature and low temperature. With the increase of Ti, the impact energy of weld metal increases first and then decreases. The best value of impact energy at $-60^\circ$C is 155 J, and Ti content is 0.253%. The relationship between impact toughness and Ti element can be described from two aspects. On the one hand, the increase of Ti-rich micro-inclusions due to the increase of Ti content is conducive to the formation of acicular ferrite in weld metal, which is conducive to improving the impact toughness of weld metal; on the other hand, the transition alloy elements into the ferrite structure will produce solid solution strengthening effect, weakening the impact toughness of weld metal. As a ferrite forming element, too much Ti will increase the austenite transformation temperature and form a coarse network ferrite structure. At the same time, the combination ability of Ti and O is very strong. In the welding process, Ti plays a role of early deoxidation, protecting other alloy elements in flux cored wire from being burned into the weld metal, thus enhancing the solid solution strengthening effect. The impact energy of weld metal decreases.

The welded joint is selected to make tensile specimen, as shown in figure 9. The tensile strength and elongation at break were measured, and the average value of 3 samples in each group was taken.

Figure 10 shows the effect of Ti content on the tensile properties and elongation of weld metal. With the increase of Ti content in the weld metal, the tensile strength increases and the elongation decreases, but when the Ti content reaches 0.253%, the tensile strength increases slightly. Combined with figure 8 and figure 10, when Ti element content is very low, the ferrite in weld metal is mainly proeutectoid ferrite and sidebar ferrite, with less...
acicular ferrite; when the Ti content reaches 0.201% and 0.253%, the acicular ferrite structure increases, and the proeutectoid ferrite and side plate ferrite decrease. When Ti content reaches 0.486%, acicular ferrite decreases and proeutectoid ferrite increases. In Q960 steel weld, Ti is a strong carbonitride forming element, and its oxidation property is also strong. Therefore, it is easy to form Ti oxides and carbonitrides after welding, which can refine the grain size and enhance the strength and plastic toughness of the weld metal. There are two opposite effects of Ti in the weld metal. One is that Ti is a ferrite forming element, which can increase the temperature of transformation from austenite to ferrite during the solidification of weld metal, which is conducive to the precipitation of proeutectoid ferrite; on the other side, the solid solution of Ti in the weld metal can reduce the diffusion rate of C in austenite, thus inhibiting the transformation from austenite to ferrite. The results show that the precipitation of proeutectoid ferrite is reduced, and the carbonitride of Ti precipitated from ferrite at lower temperature has the effect of precipitation strengthening. The decrease of proeutectoid ferrite is beneficial to the improvement of strength and toughness, and the precipitation of precipitation strengthening phase is beneficial to the improvement of strength, but it is harmful to the toughness. Therefore, when the Ti content of weld metal is low, the grain refinement effect of Ti oxides and carbonitrides, and the inhibition effect of proeutectoid ferrite plays a leading role. With the increase of Ti content, the strength increases, and the toughness also improves. When the Ti content is high, the precipitation strengthening plays a leading role, so the strength increases and the toughness decreases with the increase of Ti content.

Figure 11. TEM morphology of weld metal.

Figure 12. TEM microstructure morphology of acicular ferrite and inclusions in 0.253% Ti weld.
3.3. Microstructure characteristics of ferrite

From the perspective of weld metal metallurgy, it is necessary to have a large amount of acicular ferrite to obtain good impact toughness, and the amount of proeutectoid ferrite and side plate ferrite should be reduced as much as possible. This is because acicular ferrite is formed in the original austenite grain, with a certain ratio of length to width, and the laths are interlaced by large angle grain boundaries. Due to the different sizes of acicular ferrite, the material is braided together, which makes the fracture propagation of the material subject to great resistance and shows good impact toughness. In addition, acicular ferrite has subcrystalline structure and high density of dislocation, which leads to the increase of weld metal strength [29–31]. Therefore, whether from the strength or toughness point of view, high strength steel weld metal to obtain acicular ferrite microstructure effect is obvious.

Figure 11 shows the TEM structure of weld metal (chemical composition is 1.14% Mn, 0.57% Si, 0.36% Mo, 0.66% Cr, 0.84% Ni, 0.42% Ti, 0.022% B, 0.76% Al). It is further confirmed that the acicular ferrite structure is a structure of interlocking and staggered distribution between laths, and there are high-density dislocations in the lath. It is the existence of these structures that hinders the crack propagation, twists and turns, consumes more energy, and improves the low-temperature impact toughness of weld metal.

Figure 12 is transmission electron microscope morphology of acicular ferrite in 0.253% Ti weld. It can be seen that the acicular ferrite microstructure with micro inclusions as the core nucleation has high density dislocation, which effectively increases the path and energy required for crack propagation, and can improve the strength and impact energy of weld.

The acicular ferrite is the product of intermediate temperature transformation. A acicular ferrite consists of many fine nonparallel ferrite laths, interlaced radially between strips. The average grain size is between 4 μm and 5 μm, and the aspect ratio is between 4:1 and 8:1. Under high-power transmission electron microscope, needle-shaped ferrite has many sub-structural organizations, such as M-A components and high density dislocation. Formation of M-A component is because during the phase transformation of weld metal, when the particles conducive to the nucleation of acicular ferrite are formed in austenite, the growth of austenite-ferrite interface is hindered, and excessive carbon segregation around grain boundaries. The austenite subsequently undergoes martensite transformation during the subsequent cooling process, which fails to convert to ferrite, these martensite and carbon - rich retained austenite form M-A components.

Under the SEM, M-A is a homogeneous bright white tissue, as shown in figure 13(a). The organization details of the TEM are shown in figure 13(b), the alloy elements can make more obvious distribution of acicular ferrite laths while increasing the stability of austenite, and the M-A components are distributed between needle-shaped ferrite bars in ribbon form. Properly increasing the cooling speed allows fine dispersal and the number of M-A components is reduced. 'As the cooling rate increases, the M-A components and dimensions increase, displaying rods and blocks, and when the cooling rate decreases, the austenite breaks down into ferrite and cementite.'

In needle ferrite, the M-A element improves the strength and toughness of the weld metal. M-A components are hard and brittle, and needlelike ferrite can improve weld strength. When cracks occur in weld metal, dislocations form clusters around M-A because M-A components and bends prevent the cracks from causing dislocation. The dislocation cluster is jammed by the M-A component, which blocks the propagation of the crack and changes its direction. Apply pressure to join the resulting cracks and pass through the M-A component in the original direction of expansion and continue to expand forward. Therefore, the M-A component affects the movement of cracks, by fixing the dislocation produced by the cracks and changing the
direction of the cracks, thus improving the toughness of the needle-like ferrite. Therefore, the weld contains a lot of needlelike ferrite to improve strength and low temperature impact toughness.

4. Conclusion

(1) When the mass fraction of Ti is between 0.2% and 0.35%, a large number of Ti-Mn-Al-O inclusions will be formed in the Ti weld, which effectively promotes the nucleation of acicular ferrite.

(2) At room temperature and low temperature, with the increase of Ti, the impact energy of weld metal increases first and then decreases. At $-60 \, ^\circ\text{C}$, the optimum impact energy is 155 J, and the Ti content of the weld is 0.253%. With the increase of Ti content in weld metal, the tensile strength increases and the elongation decreases, but the tensile strength increases slightly when the Ti content reaches 0.253%.

(3) The acicular ferrite has high-density dislocations, which improves the strength and impact properties of weld metal. The M-A component in acicular ferrite can pin the dislocation generated by the crack, thereby improving the toughness of the weld.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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