Study on CTOD and microstructure in flash welded joints for 630-730 MPa grade mooring chains

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Abstract Three kinds of welding and heat treatment procedures are commonly used to make mooring chains for offshore structure in this paper. In order to determine the toughness, several specimens extracted from the welded joints and base metals are subjected to mechanical testing by means of Crack Tip Opening Displacement (CTOD) tests. Considering the data obtained, it can be recommended that the materials are safe enough in toughness to construct engineering structures (higher than the acceptable value specification by DNV).M2 tempered with 640℃ (for 60 minutes) presents the highest CTOD and yield strength, followed by M3 tempered with 650℃. M1 tempered with 600℃ presents the lowest CTOD and yield strength. That means tempering at 640℃ can obtain best toughness together with yield strength. The fracture surface and microstructure of the samples are characterized using scanning electron microscopy. Quantitative examinations including grain size analysis and carbide content measurements are carried out. The fracture parameter CTOD is correlated with the fracture surface and microstructures. The carbide contents of M2 and M3 are greater than those of M1 and the greater the carbide content is, the higher the CTOD value will be. And the grain size has the same trend.

Keywords Offshore,Welded joint, Mooring chain, CTOD, Microstructure

1. Introduction

As one of the most important components, mooring chain is playing a key role in the marine structure. When the operating depth becomes deeper, the higher demand is required especially when under the depth of 1000m. In the deep sea, the temperature of water is low and the environment is corrosive, so cracks easily occurs (especially for stud link chains).In the welding process, weld metal is heated to melt, and it experiences crystallization and solid transformation when it cools down; various parts of the weld joints are subjected to different thermal cycles which bring about the differentiation and heterogeneity. Toughness is the ability to resist crack initiation and propagation under external loads and the ability to absorb energy in deformation process. It is a comprehensive performance of the strength and plasticity. Compared with the materials with bad toughness, the good ones can prevent the procedure from micro-crack to macro-crack from happening therefore. to avoid the disaster . Because of the bad toughness, the micro-cracks in the weld joint shown in Fig.1 [1] may easily turn into macro-cracks, and the whole structure may break down suddenly.

Fig.1.Micro-cracks of weld joints

Crack Tip Opening Displacement (CTOD) test is widely used to evaluate the toughness of steel structures especially the marine steel. There have been some studies about the relationship between toughness and microstructure in the past years [2, 3]. This paper aims at a further study of this issue and seeks for some ways to improve the microstructure to make the toughness and strength better.

Then the cracks will not initiate and propagate. As is known that the strength and toughness are contradicted, when the toughness becomes higher, the strength normally goes down. There are three types of mooring chains in this study, the first one is weak in both toughness and strength but the last two have better performance. Some reasons can be found in the microstructure for this phenomenon.

2. Tests procedure

2.1. Material

There are three types of mooring chains in this study: M1 with the diameter of 160mm, M2 with 124mm and M3 with 125mm. The mooring chains are provided by Foshan Marine Anchor Chain Ltd. and the flash butt welding is adopted. The production process is shown as follows: Cutting bars → Induction preheating → Bending → Flash butt welding → Pressing → Continuous heat treatment → Mechanical tests. Table1 and Table2 have shown the Chemical composition of M1 (with the specimens 62-66), M2 (with the specimens 11-13) and M3 (with the specimens 1-3).

Table1. Chemical composition of M1（R3）

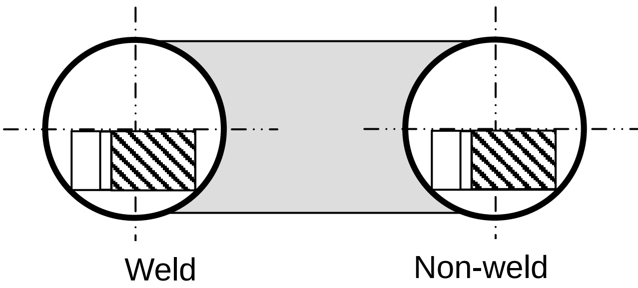
C	Si	Mn	P	S	Cr	Mo	Ni	Nb	Cu	Alt
0.27 -0.33	0.15 -0.35	1.40 -1.90	≤ 0.025	≤ 0.025	≤ 0. 25	≤ 0.08	≤ 0.30	≤ 0.05	≤ 0.20	0.020 -0.050

Table2. Chemical composition of M2 and M3 (R3S)

C	Si	Mn	P	S	Cr	Mo	Ni	Nb	Cu	Alt
0.23 -0.31	0.15 -0.30	1.15 -1.65	≤ 0.025	≤ 0.025	0.45 -0.75	0.20 -0.50	0.10 -0.20	0.02 -0.06	≤ 0.20	0.020 -0.050

2.2. CTOD and Charpy impact test

Three-point bending CTOD test was performed in accordance with BS7448:part2 [4] and EN 10225:2009[5] with WAW-1000kN tester controlled by computer, the testing temperature is -20℃. The schematic illustrations of CTOD test set-up is shown in Fig.3. According to the DNV's standard [6]: the specimen location is shown in Fig.2. The weld side specimen is named A specimen and the non-weld side one is named B specimen.



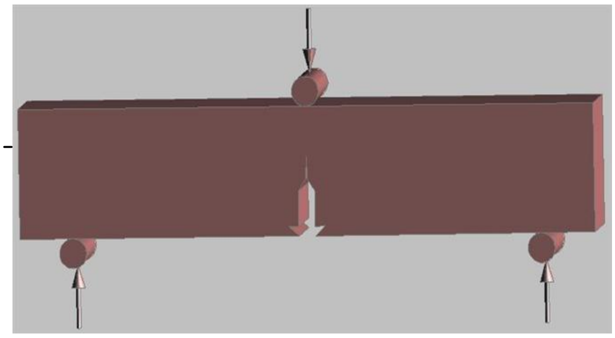


Fig.2. Location of CTOD test specimens Fig.3. schematic illustrations of CTOD test set-up

The specimens are prepared perpendicular to the rolling direction and the weld bead. The facility to make fatigue pre-crack is JXG-200kN computer controlled high-frequency fatigue tester. The position of machining notch has been figured out in Fig.3. In order to reduce the effect of the weld residual stress on the fatigue pre-cracking, the fatigue pre-cracking is divided into two steps according to BS7448 Part 2 and each step uses different fatigue stress ratios (R). For the first step, the stress ratio R=0.1 is used until the fatigue pre-crack has grown to a length of about 2.5 mm .In the second step, R is 0.7 and the fatigue pre-crack grown to 0.5mm. All the specimens are pretreated by local compression before pre-cracking. According to FV curve and other obtained data, CTOD value δ can be calculated referring with Eq. 1.

$$\delta = \delta_e + \delta_p = \left[\frac{FS}{BW^{3/2}} \cdot f\left(\frac{a_0}{W}\right) \right]^2 \frac{(1-\mu^2)}{2\sigma_s E} + \frac{r_p (W - a_0)}{r_p (W - a_0) + a_0 + z} \cdot V_p \qquad \text{Eq. 1}$$

Charpy impact was carried out according to DNV's standard, the testing temperature is -20℃. The samples were extracted through thickness notches, transverse to the weld bead and notched at the weld position. The average value of the three test results meets the specified requirement，no individual value is below the minimum average value specified.

2.3. Micro-analysis

The samples for metallographic and fracture analysis are extracted from the rupture specimens which have Conducted the CTOD fracture toughness tests. Positions to extract samples for microanalysis and sample geometry are presented in Fig.4. Samples A perform metallographic analysis. Other kinds of samples contain fracture surface and microstructure next to the cross-section are samples B. Samples B are along with the crack propagation direction and perpendicular to the crack surface.

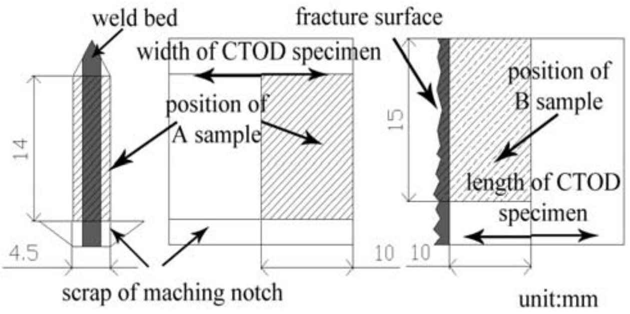


Fig.4. Position to extract samples for microanalysis

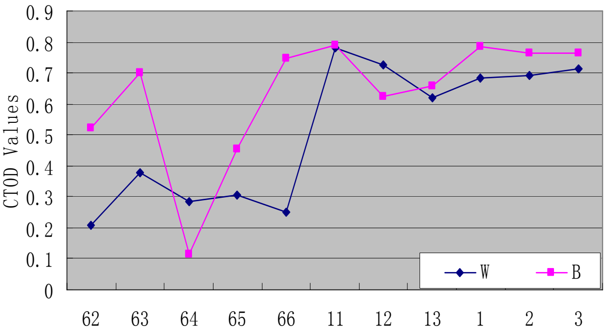


Fig.5.Tendency of CTOD values

The samples used to analyze microstructure should be grinded, polished and etched with 4% alcohol solution of nitric acid at first. Both the fracture surface and microstructure of samples were characterized using Scanning Electron Microscopy (SEM).

3.Test Results and Discussions

3.1. CTOD and Charpy impact test results

Through the CTOD test, Vp and a0 are measured, then referring to equation1, the δ is obtained and listed in Table5 and Table6. CTOD values of M1 specimens (with the number 62-66) are greater than those of M2 and M3 (with the number 1-3 and11-13). Fig.5 shows the tendency of CTOD values and table 7 gives the Charpy impact energy of different specimens.

Table5. CTOD values of weld specimens

Specimen	W62	W63	W64	W65	W66	W11	W12	W13	W1	W2	W3
δ_u(mm)	0.210	0.379	0.285	0.307	0.252	-	-	-	-	-	-
δ_m(mm)	-	-	-	-	-	0.781	0.728	0.620	0.685	0.690	0.713

Specimen	B62	B63	B64	B65	B66	B11	B12	B13	B1	B2	B3

δ_u(mm)	0.524	-	0.114	0.454	-	-	-	-	-	-	-
δ_m(mm)	-	0.701	-	-	0.749	0.789	0.625	0.657	0.786	0.765	0.764

Table6. CTOD values of base metal specimens

Table7.Charpy impact energy of values of weld specimens

Specimen	W62	W63	W64	W65	W66	W11	W12	W13	W1	W2	W3
akv (J)	43	61	40.5	39.5	36.5	144	140	146	99	91	110

From Fig.6, some features can be found from the macro section: There are both stable and unstable cracks in the specimens of all; The crack propagation of M1（with the specimens 62-66）is unstable，large parts of the crack face of both base metal and weld. Lots of parts of the crack of base metal are grey and the bright parts are not straight, it experiences some plastic deformation with obvious signs of tearing; the cracks of weld specimens are bright without any obvious signs of tearing.

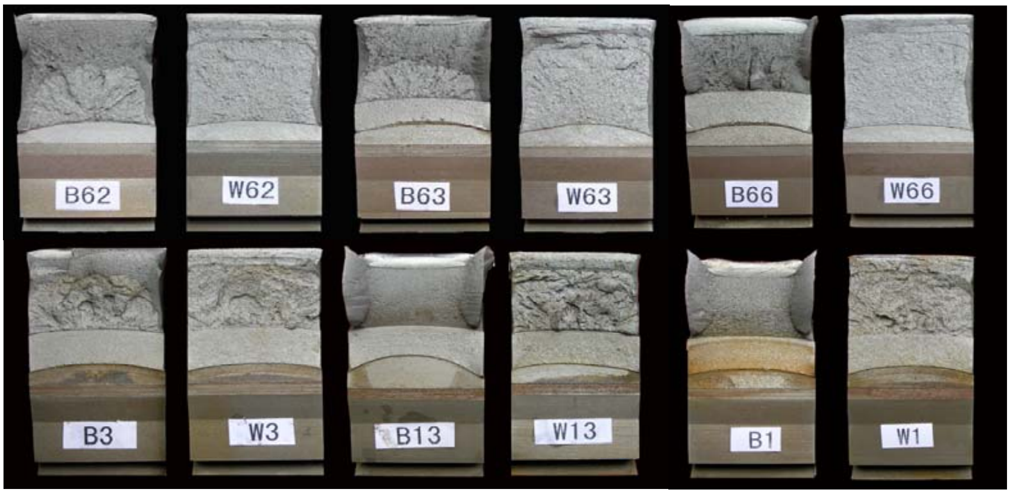


Fig.6. fracture cross-section of different CTOD specimens

All of these phenomena conform to the tendency of CTOD values. Both the crack propagation of base metal and weld of M1 and M2 are unstable, the rupture areas of the base metal are smooth with obvious 45°shear lip.

3.2. Microstructure Analysis Results

Through the micro test using SEM, something about the microstructure can be obtained. Metallographs of the center of the weld and base metal of sample A in specimens (W62,W63,W66) of M1 are obtained. From the microstructure of base metal in W62A shown in Fig.7.a, ferrite and a small amount of martensite are presented. Fig.7.b shows the ferrite and cementite on the grain boundaries in the center of weld of W62A. The lath martensite, ferrite, sorbite and cementite on the grain boundaries are distinguished as is shown in Fig.7.c Carbide, sorbite and a little ferrite are found in Fig.7.d There are some ferrite, cementite and a little sorbite in Fig.7.e and Fig.7.f.

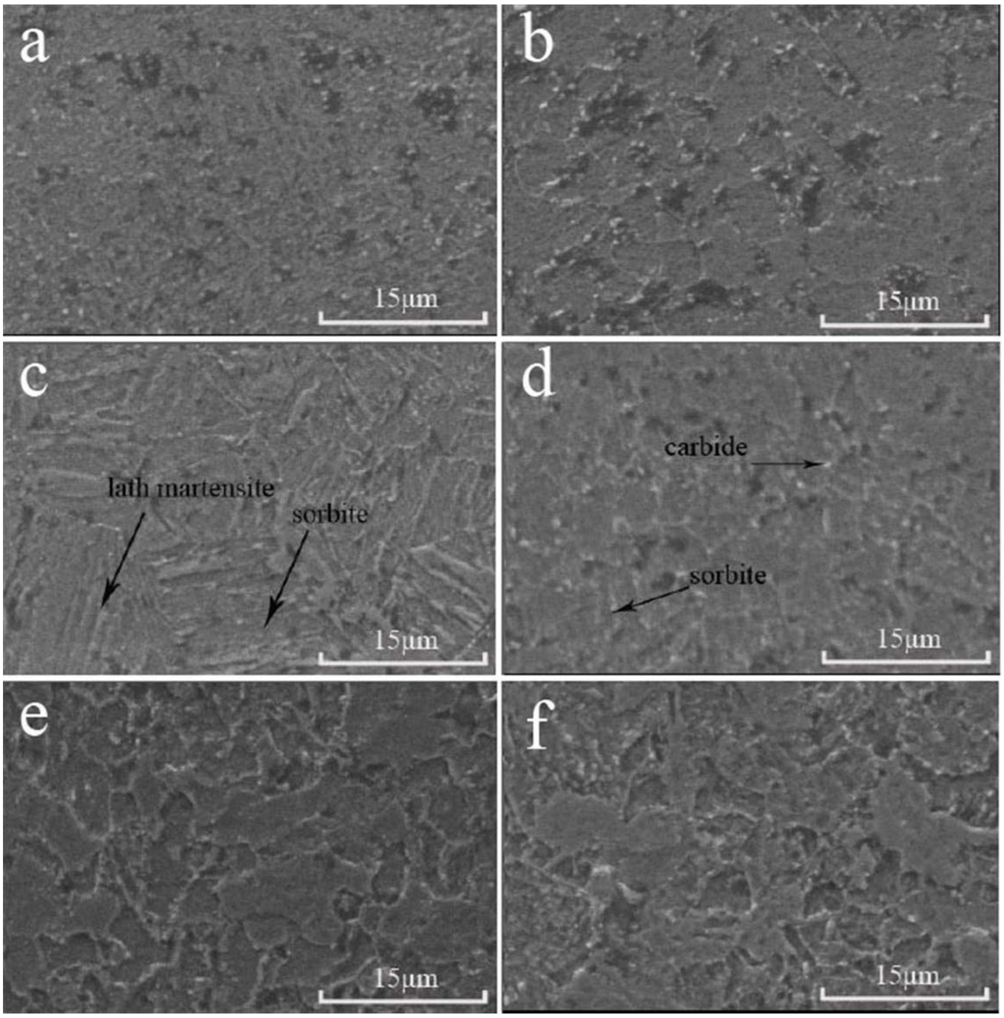


Fig.7. Microstructure of sample W62A,W63A and W66A
a.Base metal of W62A; b.Weld center of W62A; c.Base metal of W63A;
d.Weld center of W63A; e.Base metal of W66A; f.Base metal of W66A

The micro-morphology near the crack face is listed in Fig.8. Fig.8.a shows the microstructure near the crack of W62B: the grains have distinct directivity caused by plastic deformation and the elongated direction parallel to the crack face; Fig.8.b shows the secondary cracks, large inclusions, Carbide and ferrite near the fracture edge: The crack is caused by mixed influence of stress and inclusion; Fig.8.c shows the microstructure of W63B: there are lath martensite and sorbite without any deformation; Fig.8.d shows some inclusions but no secondary crack; Grains in Fig.8.e have obvious directivity and elongated direction perpendicular to the crack face. Secondary crack in Fig.8.f is classic facing a 45 ° angle with the main crack and the microstructure is ferrite and fine carbide.

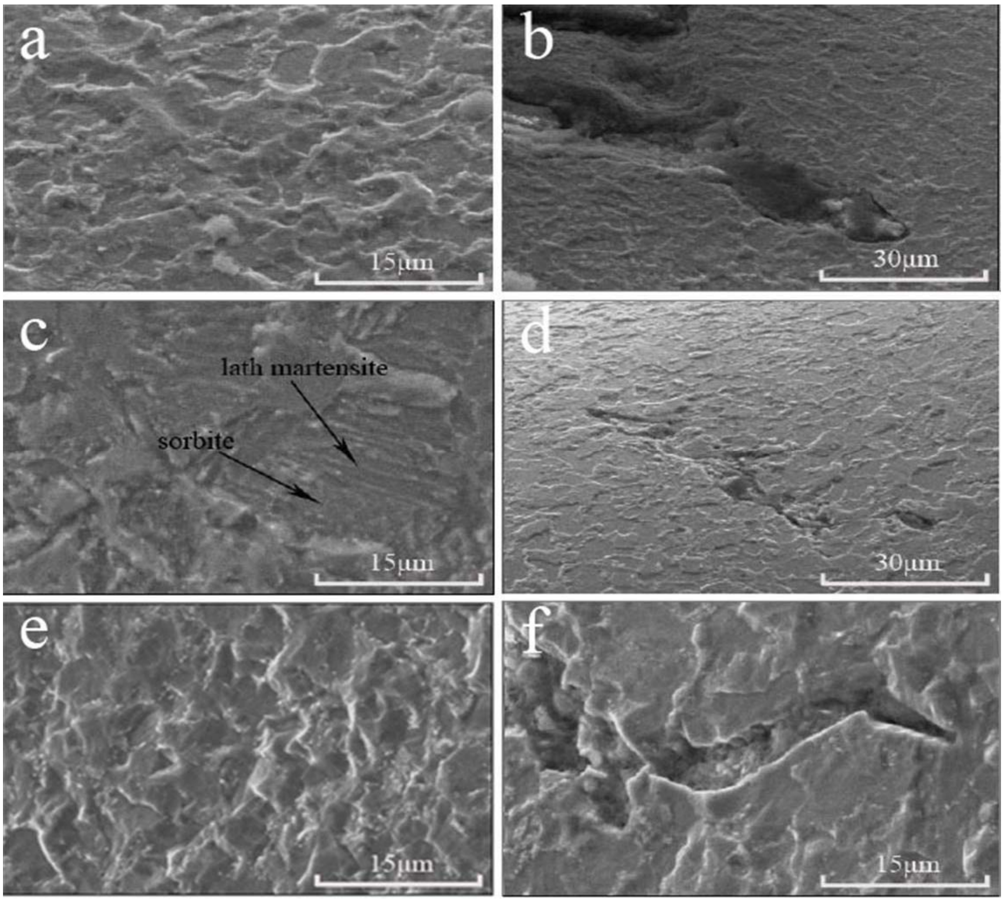


Fig.8. Microstructure of sample W62B,W63B and W66B
a.Near crack edge in W62B; b.Secondary crack of W62B; c.Near crack edge in W63 b.d.Inclusion in W63B; e. Near crack edge in W66B; f.Secondary crack of W66B

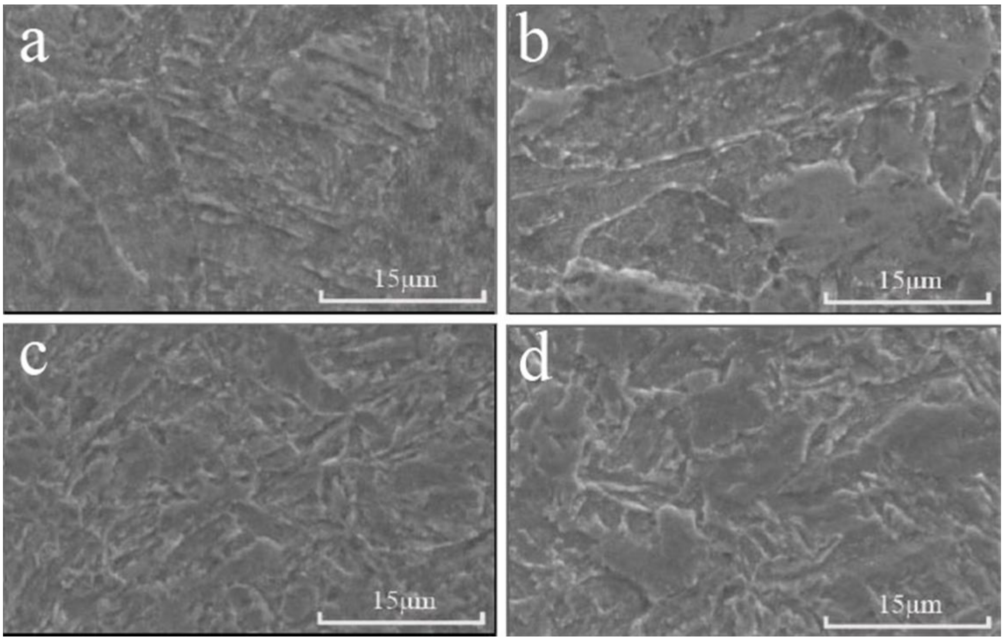


Fig.9. Microstructure of sample W3A and W13A
a.Base metal of W3A; b.Weld center of W3A; c.Base metal of W13A； d.Weld center of W13A

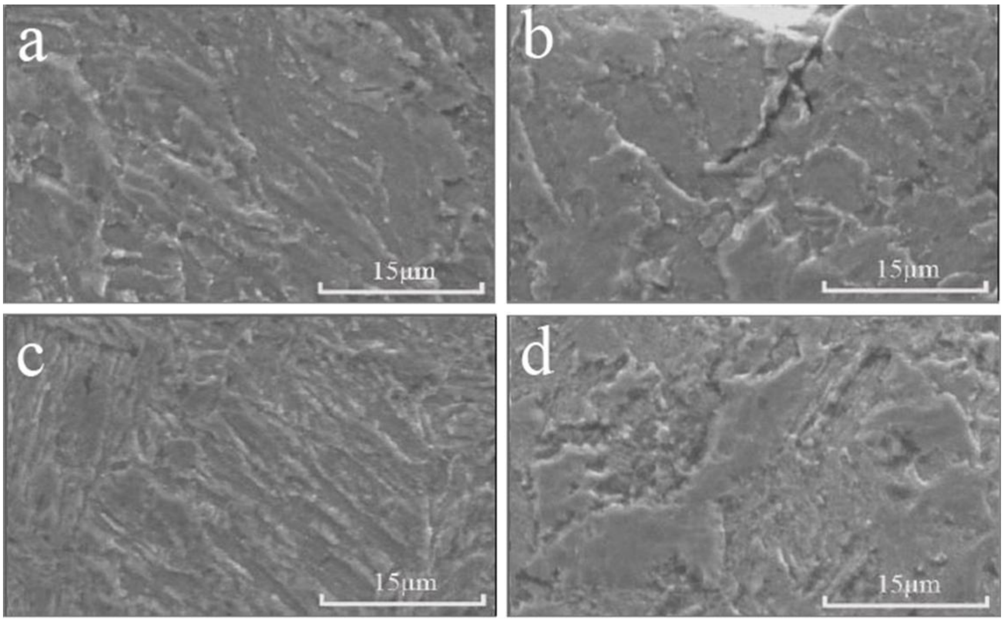


Fig.10. Microstructure of sample W3B and W13B
a.Near crack edge in W3B; b.Secondary crack of W3B;
c.Near crack edge in W13B; d.Cavity near crack edge in W13B

Fig.9 and Fig.10 show the microstructure of W3 and W13 coming from M2 and M3 respectively. Fig.9.a shows some lath martensite and ferrite; Fig.9.b shows ferrite and sorbite; the grains in the microstructure of base metal in W13A shown in Fig.9.c are so fine and disorganized. There are sorbite and ferrite in Fig.9.d; Fig.10.a shows some sorbite, a small amount of martensite and a small amount of carbide precipitation on the edge of fracture face in W3B; Fig.10.b shows the secondary cracks caused by small holes near the fracture edge of W3B and the crack is smaller than that in Fig.8.b and Fig.8.f. The crack direction is approximately perpendicular to the cross-section. There are martensite and sorbite in Fig.10.c and ferrite and sorbite in Fig.10.d.

3.3. Discussions about the results

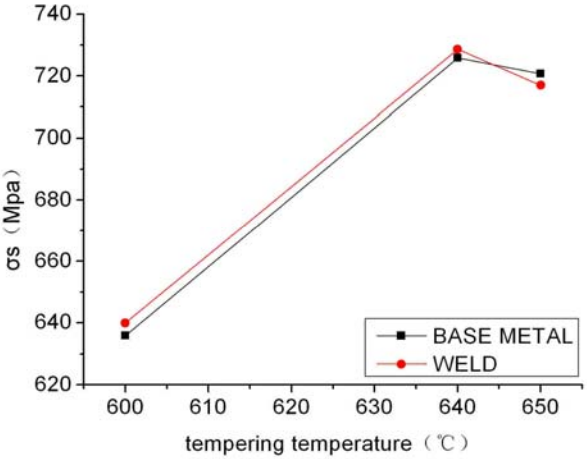


Fig.11.CTOD-tempering temperature

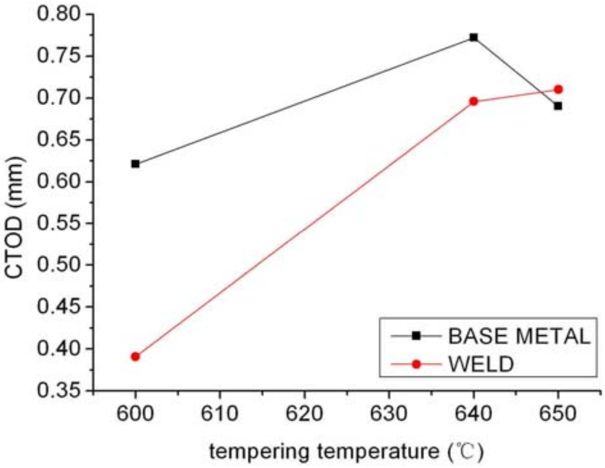


Fig.12. σs-tempering temperature

Some studies have shown that the large inclusions and the secondary cracks caused by them are bad for the toughness [7]. Compared with the W13 and W3, there are more secondary cracks and inclusions in the microstructure and micro-fracture photographs of W62, W63 and W66 while the CTOD values conform to the rule. The sharp crack tips of the secondary crack in W62B, W63B and W66B indicate that it is relatively easy to expand compared with that of W3B and W13B. At the same time, the toughness conforms to this phenomenon. Grains of martensite and sorbite near the fracture face with small deformations may be caused by the content of carbide. There are mainly martensite in the base metal and sorbite in the weld center. The content of carbide particle between the spaces of α-phase in the weld and base metal of M1 is more than that of M2 and M3.

The relationship between tempering temperature and CTOD values and between tempering temperature and yield strength are shown in Fig.11 and Fig.12. The specimens tempered with 640℃(for 60 minutes) show the highest CTOD values and yield strength from the figures. That means tempering at 640℃ can obtain good toughness together with yield strength. This result is different with related reference [8,9]: increasing of tempering temperature (at 600-650 ℃) will makes the toughness worse.

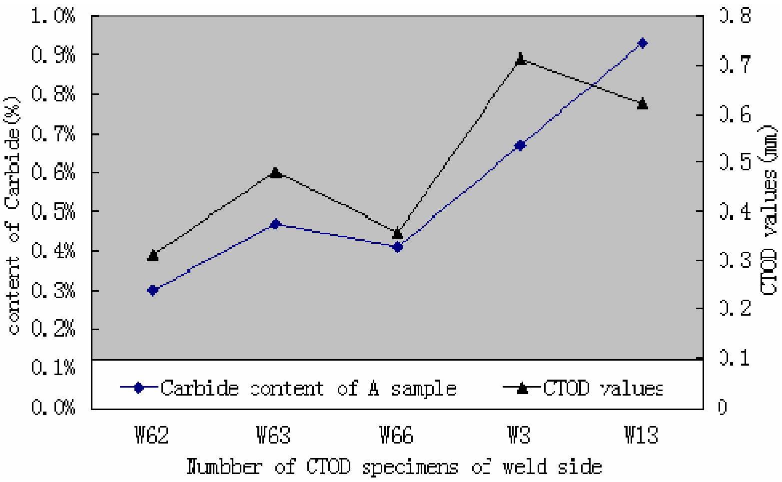


Fig.13. Variations in CTOD values and carbide content

According to the law of Dreiser, the quantitative measurements of content of carbide and grain size grade of weld center and the base metal in W62A, W63A, W66A, W3A, and W13A have been presented through using computer image processing system on scanning electron microscope images. Distribution of the content of carbide and the relationship with the CTOD are shown in Fig.13.The distribution of grain size grade and relationship with CTOD are shown in Fig.14.

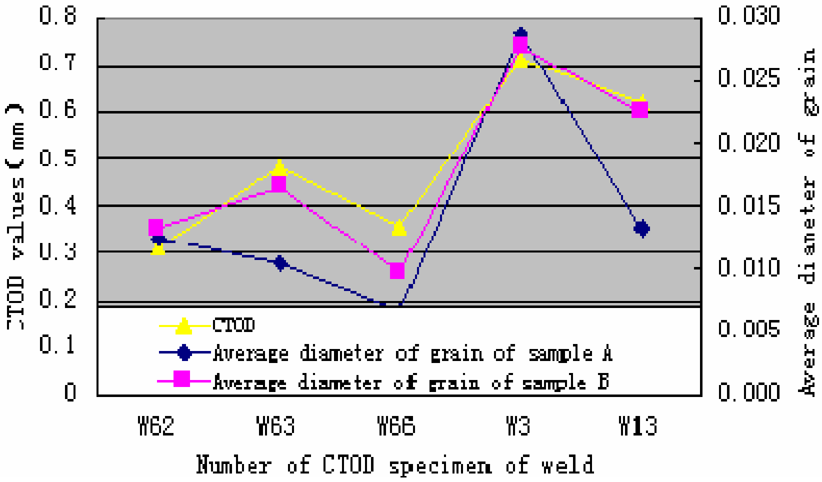


Fig.14. Variations in CTOD values and Grain size grade

Fig.13 shows that the carbide contents of M2 and M3 are greater than those of M1 and the greater the carbide content is, the higher the CTOD value will be. This situation conforms to the reference [10]. The grain size grades vary with the positions of the samples: weld center, base metal or near the edge of fracture face. The higher the grain sizes grade are， the lower the CTOD values will become, which is contrary to the common law. The specific reasons can be summarized as follows: 1. The CTOD values of M2 and M3 are all very large (all greater than 0.6 mm) and all the CTOD values are highly discrete. All the CTOD values are higher than the acceptable value 0.15 specified by DNV. That means the materials are safe enough in toughness for constructing engineering structures. However, the CTOD（toughness）is a macro concept and reflects the mechanical properties of the macro-structure. Samples for microscopic analysis are only taken from a small part of the macro-structure and the microscopic image is just a small part of the sample. Because of the existence of one-sidedness, it cannot reflect the overall situation of the organization. 2. The analysis of the forms of the grains (for the lath martensite in base metal, the strength is determined by the carbon content, but substructure plays an important role in toughness. It can be organized as follows: The compositions of microstructure in the weld center are mainly sorbite, ferrite and cementite mixture. Carbides are mainly distributed in the ferrite in the weld of M1, but those of M2 and M3 are fine and distributed on the grain boundaries. This is the reason why the specimens have better toughness and higher strength in M2 and M3. 3. From the contrast of alloy elements in Table 2 and Table 3, the contents of Cr and Mo in M2 and M3 are higher than those of M1. According to reference [10], the high content of Cr and Mo is good for strength but bad for toughness when the Mn content is near 1.6%.

4.Conclusions and Further studies

Through the results and discussions，some conclusions can be drawn as follows:

1. M2 tempered with 640℃ (for 60 minutes) presents the highest CTOD and yield strength, followed by M3 tempered with 650℃. M1 tempered with 600℃ presents the lowest CTOD and yield strength. That means tempering at 640℃ can obtain good toughness together with yield strength.

2. The fracture parameter CTOD is correlated with the microstructures. The carbide contents of M2 and M3 are greater than those of M1 and the greater the carbide content is, the higher the CTOD value will be. The grain size has the same trend .

In the discussions of this paper， limitations and one-sidedness also have been put forward in the study of the relationship between CTOD toughness and microstructure. More experimental and theoretical analysis is needed in the further studies.

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