Microstructure and cryogenic toughness of 316LN austenite stainless steel weld metal welded by NG-MAG arc welding

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Abstract—Using narrow-gap Metal Active Gas (NG-MAG) arc welding, the low-temperature impact toughness and microstructures of the 316LN welded joints have been researched and characterized by Charpy impact test, optical microscopy, scanning electron microscopy and transmission electron microscopy. The results show that the low temperature toughness in the as-welded state is 132J and the toughness of the post-weld heat treatment was 112J. There are many dimples in the impact fracture, which indicated plastic fracture. The ferrite is located at the austenite grain boundary and exhibits a strip shape with a width of about 400 nm.

1. INTRODUCTION
With the continuous reduction of fossil energy and the increasing energy demand in the world, cleanly and environmentally friendly nuclear power has gradually entered the field of human vision. The International Thermonuclear Experimental Reactor (ITER) device was first proposed by the United States and the Soviet Union in 1985, and quickly received responses from other countries and regions in the world[1-3]. As the material used for the PF magnet support structure of the ITER device, 316LN austenitic stainless steel works at liquid nitrogen temperature. Due to the particularity of the working environment, the PF structure was required to obtain an impact toughness value (AKV 100 J) at liquid nitrogen temperature (-196 C), which means that the mechanical properties of 316LN austenitic stainless steel, especially the low temperature toughness of welded joints, are particularly important[4,5].

Toughness is one of the most important mechanical properties for materials. Improving and controlling toughness of materials is a task for materials science. Microstructural constitutes, phase morphology and phase distribution can lead to significantly different fracture resistance values. Microstructural design is an important approach for enhancing material behavior at the macroscopic scale[6]. AISI 316LN austenitic stainless steel has been extensively used in industry due to the excellent mechanical properties in a wide range of temperature. Especially in cryogenic conditions, the 316LN exhibits good plasticity and relatively high impact toughness, since the face centered cubic structure is maintained. So 316LN stainless steel thick plate is selected as the leading candidate of International Thermonuclear Experimental Reactor toroidal field coils structure.
The narrow gap metal active gas (NG-MAG) arc welding has a small opening before welding, which saves a lot of energy and materials, and can also improve welding efficiency. Due to the small groove, a low heat input is required during the welding, which can reduce the overheating of the weld, avoid the possibility of coarse grain in the weld, refine the weld grain and increase the weld strength\(^{[7,8]}\). At the same time, the metallurgical protection effect of the weld zone is better, and the weld metal with higher metallurgical purity can be obtained. Therefore, the NG-MAG welding technology has many advantages and has been widely used in the field of medium and heavy plate structure welding.

Previous research showed that the weld parameters, heat input and shield gas would determine structures, dendrite morphology, and texture, which could affect cryogenic toughness of the weld joint. For example, Read at al. verified delta ferrite would deteriorate the cryogenic toughness of the weld joint due to its low temperature brittleness. So the chemical composition of welding materials and level of welding heat input will directly affect the phase structure and further impact the cryogenic toughness of the weld joint. Moreover, morphology of the dendrite, plastic deformation and crack propagation behavior further affects the capability of energy absorption of welding materials\(^{[9-11]}\). It is found that interdendritic region is usually enriched with the molybdenum element accompanied with high local concentration of dislocation, which will harden the local austenitic phase.

In general, mechanical properties of welding materials by TIC arc welding are better than other arc welding. However, the NG-TIG arc welding exhibits unsatisfied producing efficiency in the low welding speed\(^{[12]}\). In this paper, based on the ITER project, the material 316LN used in the PF magnet support structure is selected as the research object. On the basis of the MIG welding technology, the 316LN austenitic stainless steel is welded by narrow gap gas shielded welding, and the cryogenic toughness of weld was studied.

### 2. EXPERIMENTAL PROCEDURE

#### 2.1 Materials Preparation

The welding system which is designed and manufactured by Wuhan University Welding Research Institute, mainly consists of gas supply system, wave wire feeding system, weld seam tracking system, narrow gap welding moment, welding trolley walking system, STT cooperative control arc welding power source, control system and cooling system. According to the characteristics of the base metal, the welding method uses a quaternary mixed gas of 77% Ar + 20% He + 2% CO\(_2\) + 1% N\(_2\) as a shielding gas. The thickness of base metal is 100mm, and the welding wire diameter is 1.2mm with the speed of 4.0mm/s. The weld metal was solution treated after being welded.

A small weld cross-sectional area could reduce the weld residual stress of the weld and the use of weld material, and could avoid the occurrence of incomplete penetration. The 316LN austenitic stainless steel of this subject was welded with double U-shaped grooves. After welding, some of the welded parts were subjected to post-weld heat treatment at 600 °C for 2 hours. The low temperature toughness test was performed on the welds after welding and after heat treatment.

#### 2.2 Characterization

The samples of the impact test were taken from the narrow gap flat butt welding test piece, and the interception position of the sample is shown in Figure 1. The processed impact sample was cooled to liquid nitrogen temperature (-196 °C) by using a cooling device. After the temperature of the test piece was stabilized, the test piece was quickly taken out, and the Charpy impact test was performed by using a pendulum impact tester. The low temperature toughness of the weld was the average of three impact tests.

After the Charpy impact test, the microstructure observations of base metal, heat affected zone and weld were carried out by metallographic microscope (Olympus GX71 Japan), scanning electron microscopy (FEI QUANTA 250 American) and transmission electron microscopy (JEM 2100, Japan). Before OM and SEM observations, the samples were mechanically polished and chemically etched in an acidic water solution containing 30%HCl and 30%HNO\(_3\) (volume fraction) for 2 minutes. TEM
Sample were prepared by first grinding down the sample to approximately 80um thick and thereafter further thinned down to electron transparency by double-jet electro polishing. SEM was also used to observe the fracture morphology of impact samples.

3. RESULTS AND ANALYSIS

3.1 Impact test
The low temperature toughness test was performed on the NG-MAG welded 100 mm thick 316LN welded and post weld heat treated welds. The results are shown in Table 1.

| Sample | Condition                              | $A_{kv}$ (J) |
|--------|----------------------------------------|--------------|
| 1      | As-welded                              | 132          |
| 2      | Post-weld heat treatment at 600°C for 2h| 111          |

It can be seen from the table that the low temperature impact toughness of the weld is very good in the welded state and the post-weld heat treatment state. The impact value of the joint weld in the as-welded state is 132J, and the low-temperature impact value of the post-weld heat treatment state is 111J. The toughness of both joints meets the technical requirements of the ITER.

It has been proved that the early micro voids formed by the dislocation tangle within dendritic subgrains weakened the capability of strain energy absorption. With increasing external deformation, microvoids coalesced. Comparing the low temperature toughness in the as-welded state and the low temperature toughness in the post-weld heat treatment state, it is found that the impact value in the as-welded state is a little higher than the impact value in the heat-treated state. This shows that when the 316LN with a thickness of 100mm is welded by the NG-MAG, it is not necessary to perform post-weld heat treatment, which could greatly save the welding process and welding cost. It also shows that the NG-MAG not only ensures the welding quality of thick plate, but also is a very economical welding method.

3.2 Metallographic analysis
The figure 1 shows the metallographic structure of the weld and heat affected zone of 316LN austenitic stainless steel by NG-MAG welding as-welded and post-weld heat treated state. It can be seen from the Fig.1(a) and Fig.1(b) that under the welding process, the weld is a thin layer of ferrite wrapped with austenite, and the austenite grain production has a certain directional. But the directionality is not obvious, and there is no fish bone tissue. The grain size of the weld heat affected zone is significantly larger than that of the weld bead.
Figure 1. Welded joint metallography
(a) weld of sample 1 (b) heat effect zone of sample 1
(c) weld of sample 2 (d) heat effect zone of sample 2

Fig. 1(c) and Fig. 1(d) shows the metallographic structure of 316LN after NG-MAG welding with post heat treatment at 600 °C for 2 h through air cooling. It can be seen that the weld microstructure is very uniform and the growth is directional, and there is no the current fish bone tissue after heat treatment. The grain size of the weld heat affected zone is significantly larger than that of the weld, and the average grain size of the heat affected zone is slightly larger than that of the heat affected zone die, but it is not obvious.

Comparing the metallographic structure of the as-welded and post-weld heat-treated states, the weld grain size of the as-welded state is not uniform, and a very obvious growth direction is not observed. However, the weld granules in the tempered state after welding are uniform in size and obvious in growth direction, which is not conducive to the crack propagation.

There are not many precipitates in the heat affected zone in the two states. Moreover, under the NG-MAG welding method, the weld grain size of the 100 mm thick 316LN is relatively uniform, and there is no elongated columnar crystal, and the precipitation phase of the heat affected zone of the 316LN weld of 100 mm thickness is small.

3.3 SEM analysis
An excellent style manual for science writers is The impact fractures of the as-welded and post-weld heat treated states were scanned and observed as shown in the figure 2.

Figure 2. Morphology of weld seam impact test fracture
(a) & (b) sample 1, (c) & (d) sample 2

Figure 2 shows the 200-fold fracture scan morphology. The fractures of the specimens have high-low undulations and different step-like microstructures. It can be seen from the figure 2 that the second
phase is distributed at the bottom of the fracture dimple, indicating that the mechanism of the fracture is microporous aggregate fracture.

Due to the large amount of alloying elements in the 316LN austenitic stainless steel, during the welding process, the hot melted weld will precipitate a large amount of metal compounds and many carbides and nitrides during the cooling and solidification process. The welding process also introduces inclusions into the weld, so there are many second phase particles in the weld.

In the impact test, since the second phase is generally brittle with respect to the substrate, the second phase particle will first break when subjected to an impact load; or the second phase may be deformed due to the difference in elastic modulus with the matrix. Inconsistent, finally separated from the substrate, forming micropores\(^\text{[13]}\). The formation of micropores will gradually grow up due to the entry of dislocations; when subjected to tensile or impact loads, a plurality of micropores are connected to form microcracks due to plastic rheology, and the new micropores will continue to be necked. And connected with the crack, the crack advances a certain length, and the resulting crack continues to grow until it breaks.

3.4 TEM analysis

The structure of austenite grains in the weld and the form, distribution and size of ferrite in the weld were observed by transmission electron microscopy. The results are shown in the figure 3.

![Figure 3. Morphology of Austenitic and ferrite in welds under bright fiels image. (a) sample 1; (b) sample 2](image)

It can be seen that there are a large number of dislocations inside the weld $\gamma$-austenite, which may be due to the high temperature stage of the welding process in the weld formed by the internal stress of the weld due to the welding heat cycle during the welding process\(^\text{[14]}\). The peritectic reaction ($L + \delta = \gamma$) is distributed at the grain boundary of the austenite, and its shape is elongated and the width is about 400 nm.

Due to the fast cooling speed of the weld, the high-temperature $\delta$-ferrite is not fully converted into $\gamma$-austenite. Because the NG-MAG weld has a small weld bead and small welding heat input, fast cooling speed of the weld, so the 316LN stainless steel will retain a certain amount of ferrite in the weld. Moreover, the relevant literature shows that in the weld of austenitic stainless steel, the content of ferrite has a great influence on the impact toughness of the weld.
4. DISCUSSION

4.1 Fracture mechanism

It can be seen from the scanning fracture at the low magnification shown in figure 4 that in the impact toughness test of the weld impact specimen at low temperature, the samples 1 and 2 undergo a large deformation before the fracture. A distinct fiber zone, radiation zone and shear lip can be seen on the fracture of sample 1. The surface of the fiber area is uneven and irregular, and it is gray-colored and has no metallic luster. The relatively flat is the radiation area, which is slightly brighter than the fiber area; the shear lip is formed by necking due to plastic deformation. The fracture of the sample 2 was small due to the small plastic deformation and the area of the shear lip was small, and the fracture was almost entirely composed of a fiber region where the convexity and the concave were not. The fracture morphology of sample 1 and sample 2 is very similar. The center of the fracture is a rough and uneven fiber area, and the radiation area is small, and the shear lip area is large. It can be judged that the fractures of the four samples belong to plastic fracture.

Figure 4. Microscopic morphology of fracture at low magnification
(a) sample 1; (b) sample 2

It has been observed that the optical microscopic metal graphs of the 316LN weld metal after impact tests and compared the experimental crack propagation paths with the simulation results. Location of “V” notch determined the impact direction and propagation path of the cracks. When “V” notch was located on the top parallel to the cross section and fracture morphology of dendritic microstructure zone. The great discrepancy in dimples characteristic revealed the segregation in the processing of microvoids nucleation, coalescence and final fracture between dendritic arm and interdendritic region. Local plastic deformation should occur in the elongated dendritic arm area at the first due to the different hardness between dendritic arm and interdendritic region. The migration of dislocation would be retarded by the interdendritic region and was limited in the elongated dendritic arm area, enhancing the localized deformation in dendritic arm\[15\]. Then slip lines crossed at the center of dendritic arm and resulted in early microvoids which weakened the base metal capability of strain energy absorption. Finally, microvoids coalesced along the center line. So the crack propagated along the long axis of the dendritic microstructure with directionality, which reduced the possibility of bifurcations and turns of the crack tip, resulting on less energy absorption.

4.2 Effect of ferrite on fracture toughness of weld

Previous research work reported that 316LN austenitic stainless steel thick plate weld joint welded by conventional welding methods showed undesirable cryogenic impact toughness, whose value reached approximately 40J. A great breakthrough has been made in improving the cryogenic toughness of 316LN weld metal by using Narrow Gap Metal Active Gas arc welding. With NG-MAG, the cryogenic impact toughness of weld metal could exceed 100J. It has been reported that α-ferrite, phase and x phase had been detected in 316LN weld joints by single sided single pass submerged arc welding\[16\]. And it has been pointed out that the presence of α-ferrite would deteriorate the cryogenic toughness due to its low temperature brittleness.

The influence of ferrite content in the austenitic weld on the mechanical properties of the weld has been a hot topic. The base metal of this test is 316LN, which is a full austenite structure at room temperature, but there is a high temperature residual ferrite in the weld. Body, the appearance of ferrite
is a double-edged sword for weld performance. On the one hand, the solubility of impurity elements S, P, etc. in ferrite is higher than that of austenite, which can avoid the enrichment of impurity elements such as S and P at the grain boundary to form low-melting eutectic, and reduce the thermal crack sensitivity.\cite{17} In the high-temperature peritectic reaction, the residual ferrite can disrupt the growth direction of the austenite coarse columnar crystal and refine the austenite grains. On the other hand, the yield strength of the body-centered cubic ferrite increases sharply with the decrease of temperature, and finally is higher than the fracture strength, which causes the ferrite structure to directly fracture when it is subjected to impact load at low temperature without yielding. It is characterized by brittle fracture. The presence of ferrite increases the low temperature brittleness of the weld and reduces the low temperature impact toughness of the austenitic stainless steel weld.

For samples 1 and 2 of narrow gap MAG welding, the ferrite content in the weld was measured by the metallographic method. The literature \cite{29} pointed out that at 3V, the solution prepared by using 10% KOH and 90% distilled water can be used to show ferrite. The corrosion results for samples 1 and 2 are shown in Figures 5.

![Figure 5. Metallographic phase after corrosion with KOH solution](a) sample 1; (b) sample 2)

Using the graphics processing software, the black area in the picture was counted, and the average ferrite content of sample 1 was 48.8%, and the average ferrite content of sample 2 was 38.6%, which may be due to the board. The difference in thickness results in a different weld cooling rate during the welding process.

5. CONCLUSIONS
In this paper, 100mm thick 316LN austenitic stainless steel was welded by NG-MAG. The low temperature toughness of welds in the as-welded and post-weld heat treated state was tested. The fracture morphology of the weld was analyzed and following conclusions could be made.

1) The Charpy impact test results show that using NG-MAG method to weld 100mm thick 316LN austenitic stainless steel, the low temperature toughness of the joint could meet the ITER requirement and does not require post-weld heat treatment.

2) There is no fishbone structure in the weld of 316LN austenitic stainless steel thick plate. The weld bead size becomes more uniform after heat treatment than as-welded.

3) Microscopic analysis of the fracture shows that the fracture mode belongs to plastic fracture, and the fracture surface is distributed with deeper and deeper dimples. The ferrite is located at the austenite grain boundary and exhibits a strip shape with a width of about 400 nm.

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