Design and Welding of Nodes for Offshore Foundation

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Jacket substructures are widely used in water depths of more than 20 meters for offshore wind turbines. The manufacturing process requires proper welding specifications for welding the different kinds of nodes, such as K-nodes, X-nodes, legs and braces. The welding quality of the nodes are governed by filler metals, welding bead flatness, residual stress, welding parameters and even welding gestures. In order to better control the welding quality of the nodes, a new design of the nodes as well as a suitable arc welding method were developed. As a result, the manufacturing efficiency for jacket assembly was greatly improved.

Keywords: Offshore, Jacket structure, Welding nodes, arc welding.

1. INTRODUCTION

In response to the global consensus on environmental protection, The Taiwan government formulated a new energy policy in 2016(1). The plan is to limit gas-fired power generation and coal-fired power generation to 50% and 30% respectively, and use green energy for the rest. It will also achieve the goal of abolishing nuclear energy by 2025. Therefore, the importance of wind power has been widely emphasized in recent years, and practical actions must be taken immediately. 16 out of the top 20 wind farms in the world are fortunately located in the Taiwan Strait. This fact provides excellent conditions for the development of offshore wind power in Taiwan and has attracted the attention of the international wind power system suppliers. Orsted, the world's largest wind power system manufacturer, launched several offshore wind power investment projects in Taiwan in 2018, and will gradually complete hardware construction by 2021. On this basis, the Taiwan government hopes that the large-scale offshore wind power generation facilities can promote domestic investments and accelerate industrial transformation. For long-term operation and development, the government also formulated policies to implement local procurement and assisted in establishing a local supply chain. Since offshore wind power generation structures require large amounts of steel, Taiwan's largest steel manufacturer, CSC, played a key role in material supply and ensured the supply chain, as well as providing the necessary technical assistance to local offshore structure manufacturers.

Although the Taiwan Strait has excellent conditions for wind power generation, it also faces severe challenges such as typhoons, earthquakes and strong ocean currents. As a result, the existing type of offshore wind power structure used in Europe may not be suitable here. A stronger and safer design was needed. The jacket substructure was chosen because it is widely used in offshore wind power generation systems where the water depth exceeds 20m. However, the jacket structure requires a large number of welds to connect different types of nodes, such as K nodes, X nodes, legs and braces(2,3,4). In addition, in order to obtain stronger welds while preventing stress concentration caused by the notch effect(5), additional internal welds are added for reinforcement, as shown in Figure 1. However, the limited space pointed out by the arrow in Figure 2 makes it difficult to perform a good weld. Even the most experienced welder cannot perform good welds under such situations, so gouging and repairing are usually required. These reasons make welding quality the key point to the success of fabricating the whole jacket structure. Therefore, the design of a good welding process and the use of parameter control so as to reduce welding deformation, welding defects, residual stress and to improve the mechanical properties of welds are important issues for local manufacturers(6). In this study, a new welding design for node connection method are discussed, and the manufacturing efficiency of jacket structure assembly were expected to be greatly improved.

2. EXPERIMENTAL METHOD

The steel grade used on the main jacket structure was 30 and 40mm S355ML(7) manufactured by CSC, which meets the DIN EN 10225 standards. The chemical composition is shown in Table 1. All nodes were assembled by flux-cored arc welding (FCAW) in the shop. In addition to FCAW, metal-cored arc welding (MCAW) and GMAW-solid-wires welding were also tested in the laboratory to optimize the welding process. The filler wire used in the shop was Ti 60 T-FD from Bohler and

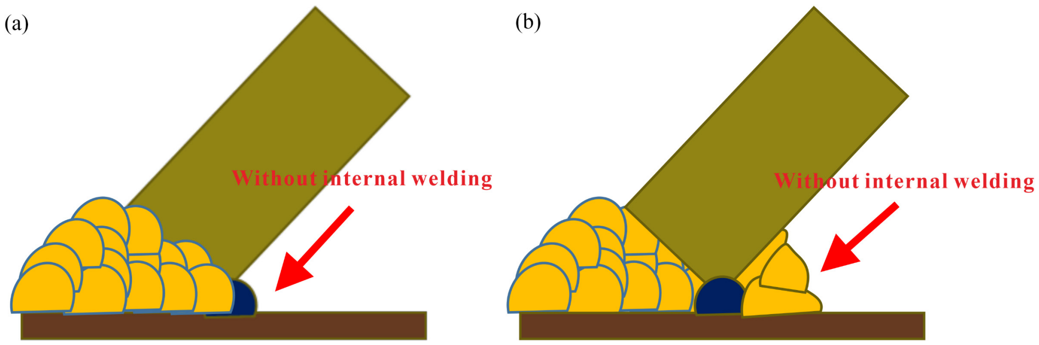


Fig.1. Two different welding designs of nodes: (a) in Europe and (b) in Taiwan. The blue area is the first bead.

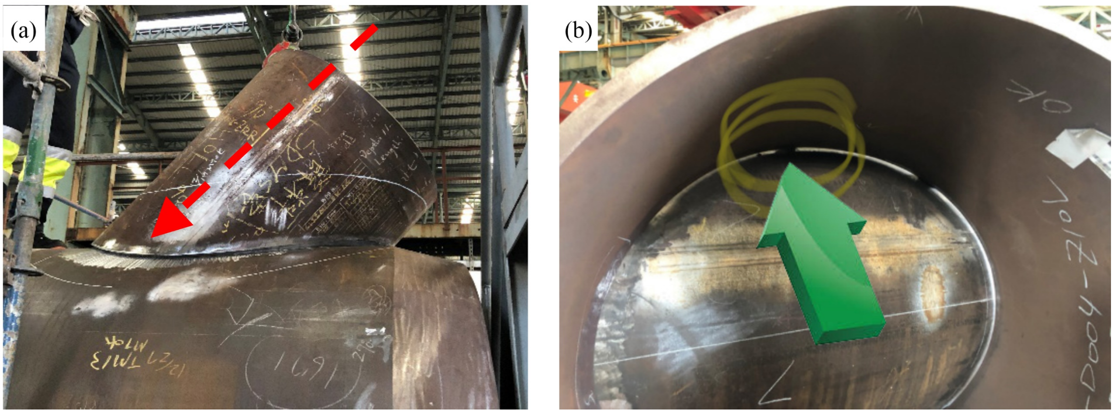


Fig.2. (a) The location of the inner weld direction on the node from an external perspective. (b) The location of the inner weld direction on the node from an internal perspective. The welder must overcome the narrow space and angle limitations.

Table 1 Main chemical composition of matrix steel and welding wires.

	C max	Si	Mn	P max	S max	Cr max	Mo max	Ni max	Al	Fe
										wt%
Matrix steel S355ML	0.20	0.5	0.15	0.035	0.030	0.30	0.10	0.50	0.020	Bal.
Ti 60 T-FD (FCAW) Welding deposition	0.07	0.45	1.3	------	------	------	------	0.85	------	Bal.
HL53T-MC (MCAW) Welding deposition	0.06	0.50	1.3	------	------	------	------	0.90	------	Bal.
SF-3A (FCAW) Welding deposition	0.05	0.50	1.5	0.01	0.006	------	------	0.35	------	Bal.
710M (MCAW) Welding deposition	0.05	0.7	1.5	0.015	0.015	------	------	------	------	Bal.
KM-56 (GMAW) Welding deposition	0.09	0.33	1.72	0.01	0.005	0.11	0.001	0.01	------	Bal.

those used in the laboratory were SF-3A from NSSW (Nippon Steel & Sumitomo Metal Welding Co.), HL53T-MC from Bohler, and KM-56 from Tientai. Table 1 also lists the main chemical composition of the welding wires. As shown in Figure 3, the node structure was welded manually in the shop, and the testing samples were welded by a robot in the laboratory. The groove adopted a single V-shaped design, and the bottom gap was 6-8 mm. According to WPS, the heat input per pass was controlled between 0.8~20 kJ/cm.

In order to optimize the welding quality, defect analysis is necessary. From past experience, it was found that most defects existed in the bottom of the welds and were almost invisible from the surface. For this reason, ultrasonic testing (UT) was used to locate defects after resting for 48 hours. Once the defects were located, oxy-acetylene cutting was first performed to cut the node into pieces, as shown by the yellow dashed lines in Figure 4 (a). They were then cut into smaller pieces, as shown by the green dashed areas in Figure 4 (a) a cross section sample was cut by a liquid cooled bandsaw machine as to reduce the artificial heat effect. Finally, the welding cross-sections were ground and polished for further observation (Figure 4 (b)).

In the laboratory, a Lincoln S-500 welding machine connected to a Fanuc M20iA robot was used to perform welding. Figure 5 shows a welding sample simulated in the laboratory. UT tests were performed to locate defects. Cross sections of the welds were also prepared for metallographic analyses. By comprehensively testing and examining the defect rates, mechanical properties and microstructures, the effects caused by the welding wires can be revealed and a better welding quality can be achieved.

Fig.5. Lincoln S-500, combined with a Fanuc M20iA robot, performs welding in the laboratory.

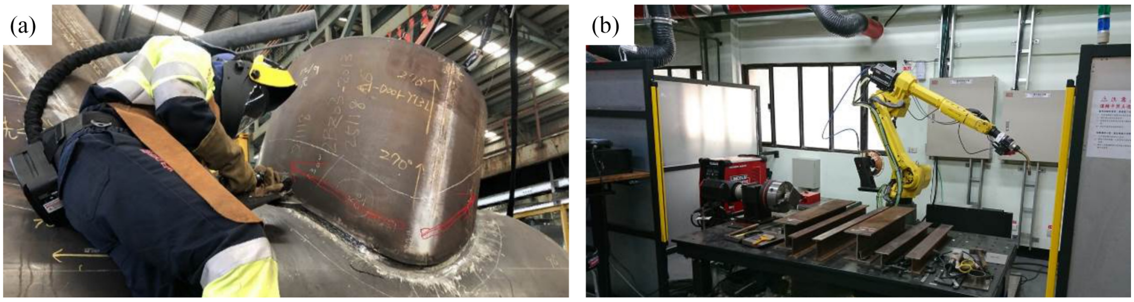


Fig.3. (a) Welding was manually performed in the shop, and (b) welding was done by a robot in the laboratory.

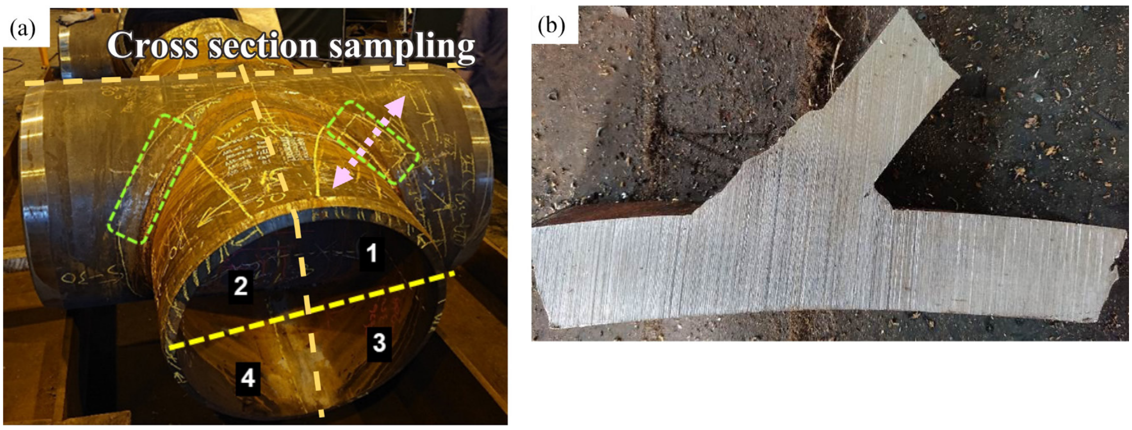


Fig.4. Sampling preparation of the welded node. (a) cutting indications, (b) cross-section of the weld.

3. RESULTS AND DISCUSSIONS

3.1 Defects Analysis of Node Parts

Based on the equivalent carbon content concept of steel, cold cracking sensitivity should not be the issue for S355ML. It means that bad weldability of this type of steel was not anticipated, and the welding cracks should not occur easily. However, there were cracks detected by UT inspection on some nodes which were welded and rested for 48 hours. Figure 6 is a macro cross-section metallography of the welding zone. The defects are indicated by red arrows. It was found that these defects seemed to have been formed on the initial beads of the original or repairing welds. Based on past experience, most engineers would be of the opinion that these defects were related to hydrogen embrittlement, and could be eliminated by increasing the preheating temperature and the intermediate welding temper process. Unfortunately, temperature control did not show to play a key role in reducing defects in this case. Other approaches must be considered.

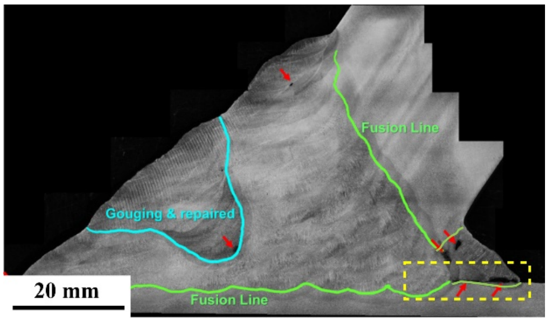


Fig.6. Macro cross-section metallography of welding zone. Defects are indicated by red arrows.

As shown in the micro-metallographic of the poor fusion zone (Figure 7, of the yellow area in Figure 6), it is quite obvious that these defects are mainly slag inclusions and poor fusion at the welding interface. The EDS analysis indicates that Ti, Al, O, Si rich inclusions deposit along the micro crack in the poor fusion zone (Figure 8). This contamination usually comes from the residual slag caused by FCAW process. Normally, slag should be completely removed before another welding pass is applied. However, due to the limited space caused by the small angle between the two welding objects, it is difficult to remove the slag completely and it may be that some is left. Residual welding slag usually accumulates

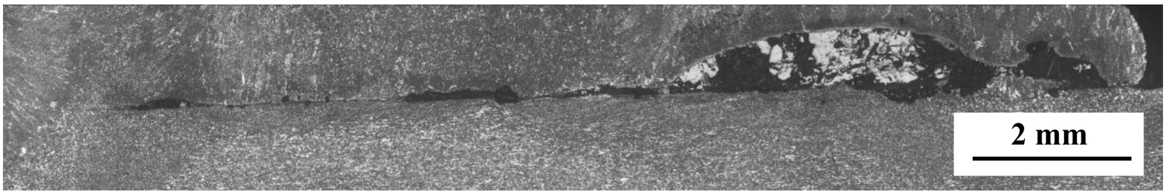
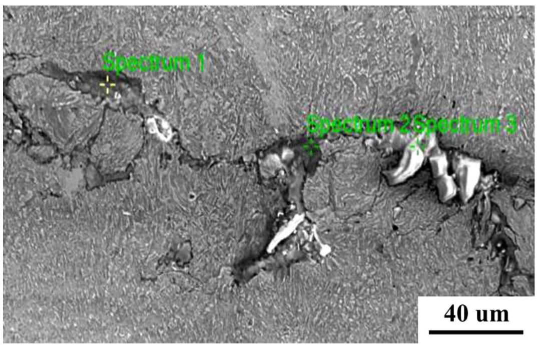


Fig.7. Micro-metallographic of the poor fusion zone indicated in the yellow box area in figure 6.



Spectrum	C	O	Na	Mg	Al	Si	S	Ca	Ti	Mn	Fe
Spectrum 1	24.63	36.71	0.23	0.13	4.62	0.37	0.25	0.37	---	0.31	32.39
Spectrum 2	29.34	26.84	0.14	0.12	8.80	0.51	0.18	0.45	---	0.41	33.21
Spectrum 3	28.51	34.35	0.62	0.22	0.49	9.81	---	---	1.72	19.55	4.72

Fig.8. SEM and EDS analyses of inclusions along a micro crack in the poor welding zone.

and causes extensively poor fusion between internal weld passes. If the residual stress accumulates in the subsequent welding process, the cracks may by initialize and thus causing serious problems.

Except for the slag problem, both the microstructure and hardness in the welding zone met the requirements of offshore foundations. As shown in Figure 9, not only acicular ferrite (AF), high temperature ferrite and Widmanstätter ferrite (WF) are also formed along the retained austenite grain boundary in the welding zone. As a result, the welding zone exhibits a higher hardness than other areas, between HV177 and HV280 (Figure 10). Fortunately, there is no abnormal point with high hardness so there is no problem with the weldability of S355ML. Bending tests show that the welds have excellent material toughness (Figure 11), and can withstand a large bending motion without cracking. From the above observations, it is believed that welding defects are caused by incomplete slag removal and insufficient depth of a single welding pass for FCAW. A new welding process is suggested to modify the welding process so as to improve the welding quality of the node.

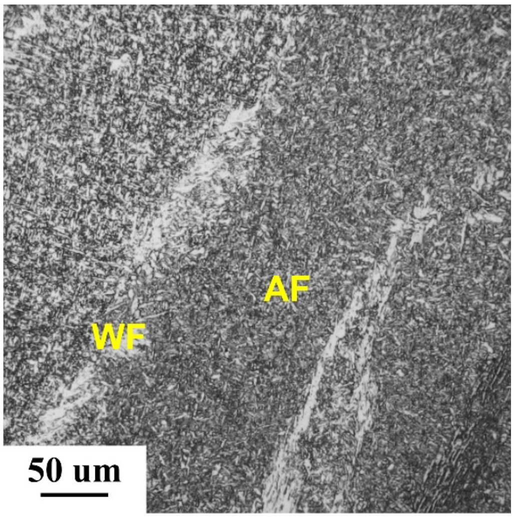


Fig.9. Microstructure of weld metal by FCAW.

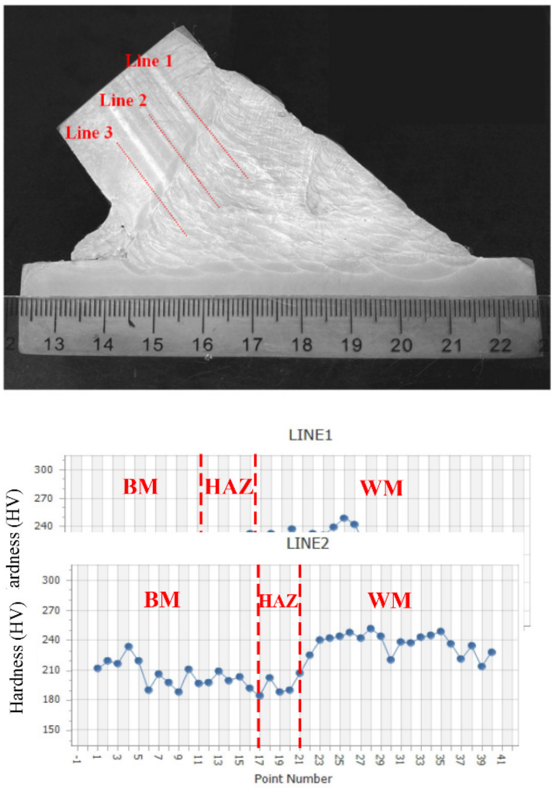


Fig.10. Hardness distribution of welding cross-section of a node.

3.2 Laboratory Testing and New Welding Process Development

In order to estimate the severity of the remained slag caused by FCAW, welding was first performed on a flat surface of a plate with a V groove. The same welding wire and slag grinding procedure as in the shop were used on the laboratory weld. It was found that even in such a simple condition, a completely clean weld was hard to obtain. It can be seen (Figure 12) from the EDS mapping results directly that a large amount of Si, Mg, Na, Ti and other flux components are left on the surface

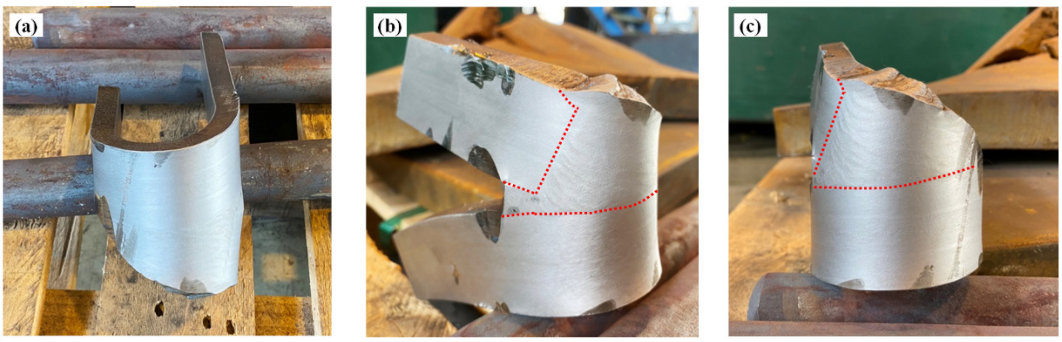


Fig.11. Results of the bending tests for node welding zone. The area indicated by the red dotted line is the weld bead.

of the weld. (Figure 12). Therefore, in the workshop where the operation space is limited, the slag contamination might be even worse and cause more defects.

Since MCAW and GMAW-solid-wire have no slag discharge problems, these two welding processes may be more suitable for the jacket welding. As shown in Figure 13, there are significant differences in macrostructure and hardness distribution between FCAW and MCAW.

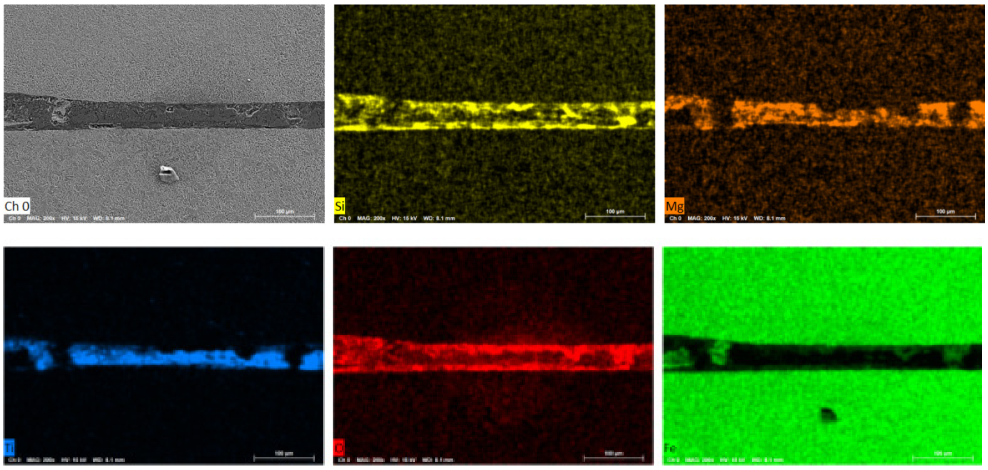


Fig.12. EDS mapping result for simulated weld surface after strong surface grinding. (using NSSW FCAW wire)

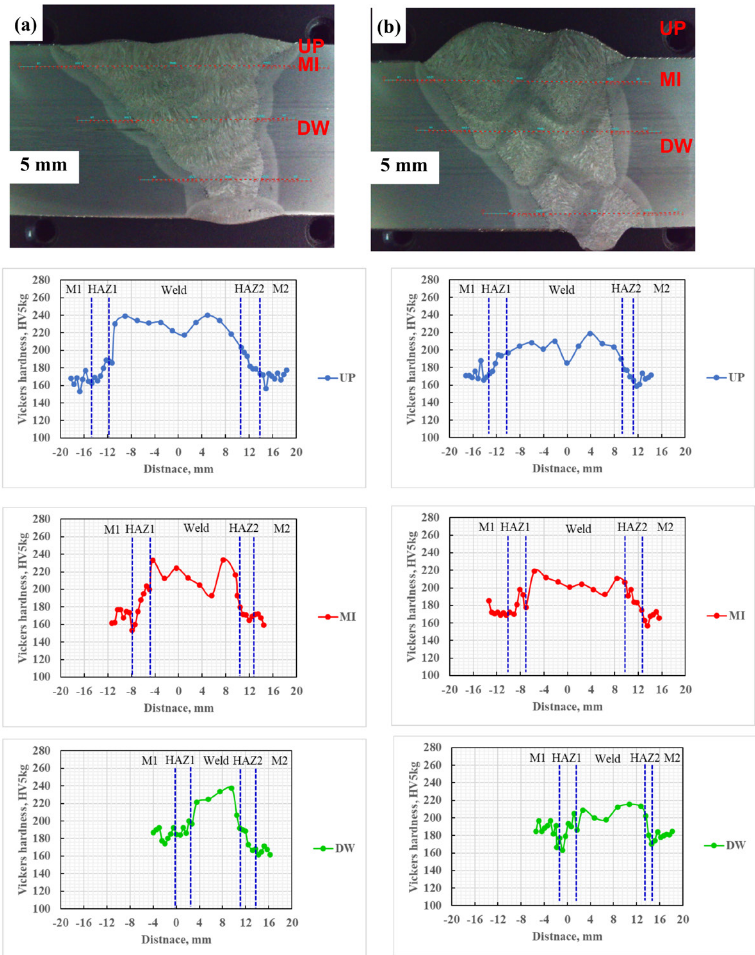


Fig.13. The macro-metallography of weldment and hardness distribution of (a) FCAW and (b) MCAW weldment

The welding penetration of MCAW is obviously deeper than FCAW. Deep bead penetration usually helps to break up the residual slag of previous welds, so the defects on the initial weld beads were avoided with slight grinding. In contrast, the FCAW must be thoroughly ground to obtain a defect-free weld as shown in Figure 13 (a). Moreover, the hardness of the MCAW weld zone is lower than that of the FCAW as an overall weld metal and is similar to the base metal. It can be expected that the residual stress is reduced after welding, and cracks can be better controlled in the welding zone and heat-affected zone.

GMAW-solid-wire welding also showed the similar effect with MCAW. In Figure 14, the bottom weldment was welded by GMAW-solid-wire, and the top half by FCAW (NSSC filler wire). As shown in Figure 14, the lower part had deeper penetration and there was no defect inside the welds. On the contrary, the FCAW region still had poor fusion in the initial welding bead. These demonstrated that the bad slag removing process for FCAW significantly affected the subsequent welding quality for jacket joints. However, the wire core contains Ti element which is believed to form TiO_2 to inhibit the original austenitic grain growth during welding solidification, so the relatively fine microstructure and acicular ferrite (Figure 15) can be obtained in the FCAW weld metal. This kind of structure usually has a better strength and a low-temperature toughness. In contrast, the filler wires used for MCAW and GMAW-solid-wire in this study did not contain any grain refinement element (such as Ti, Nb or V) in the wire composition, and weldment had insufficient hardenability. Therefore, the coarse grains and ferrite precipitations in the boundaries are the main structure and could deteriorate the low-temperature impact toughness. According to the test results, the strength of the welding wires are of the same level, the low-temperature impact toughness of the weldment of MCAW and GMAW-solid-wire is about 10% lower than FCAW at -40°C (90~100 J vs 110~120 J). Nevertheless, the low-temperature impact toughness of MCAW and GMAW-solid-wire weld metal still remains 3 times higher than the engineering specification (31 J). As a result, they are usable processes for the case.

In fact, the splash can be better controlled for the FCAW process. It makes doing the jobs easier and is better adopted by general welders in the shop. However, MCAW and GMAW-solid-wire is quite beneficial to reduce welding defects, especially in the difficult slag removal areas due to limited space. Welding with MCAW or GMAW-solid-wire for the initial beads can effectively avoid poor fusion caused by welding slag. On the other hand, if the groove is large enough to remove the slag easily, FCAW is recommended and can make impact toughness of the weldment higher. For these reasons, a hybrid welding process helps to improve not only the welding quality, but also the efficiency. On the other hand, if the filler wire contains sufficient grain refining elements and has sufficient hardenability, the MCAW or GMAW-solid-wire process will also be the ideal choice for offshore structure welding.

4. CONCLUSION

1. The welding defects of node structure usually comes from the residual slag caused by FCAW process. Residual welding slag continues to accumulate and extensively cause poor fusion between internal weld passes. If the residual stress accumulates in the subsequent welding process, the cracks may be intensified and causes serious problems. In the workshop where the operation space is limited, the slag contamination by FCAW may be even worse and cause even more defects.

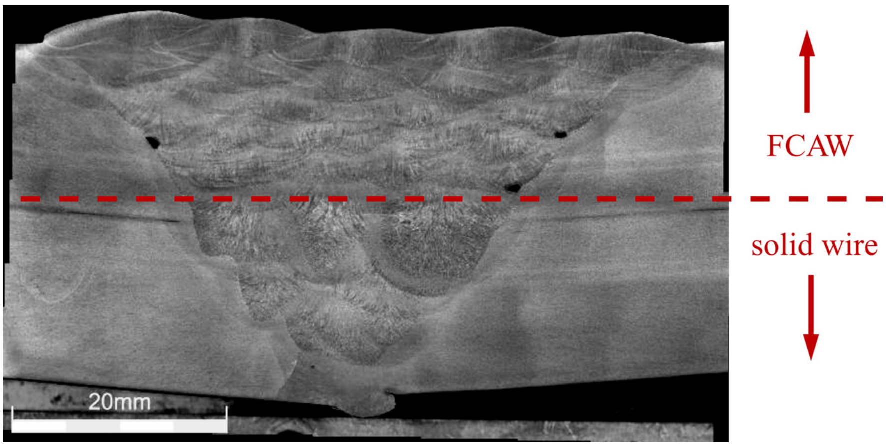


Fig.14. The macro-metallography of simulated GMAW weldment (Upper is flux cored wire；Bottom is GMAW-solid-wire)

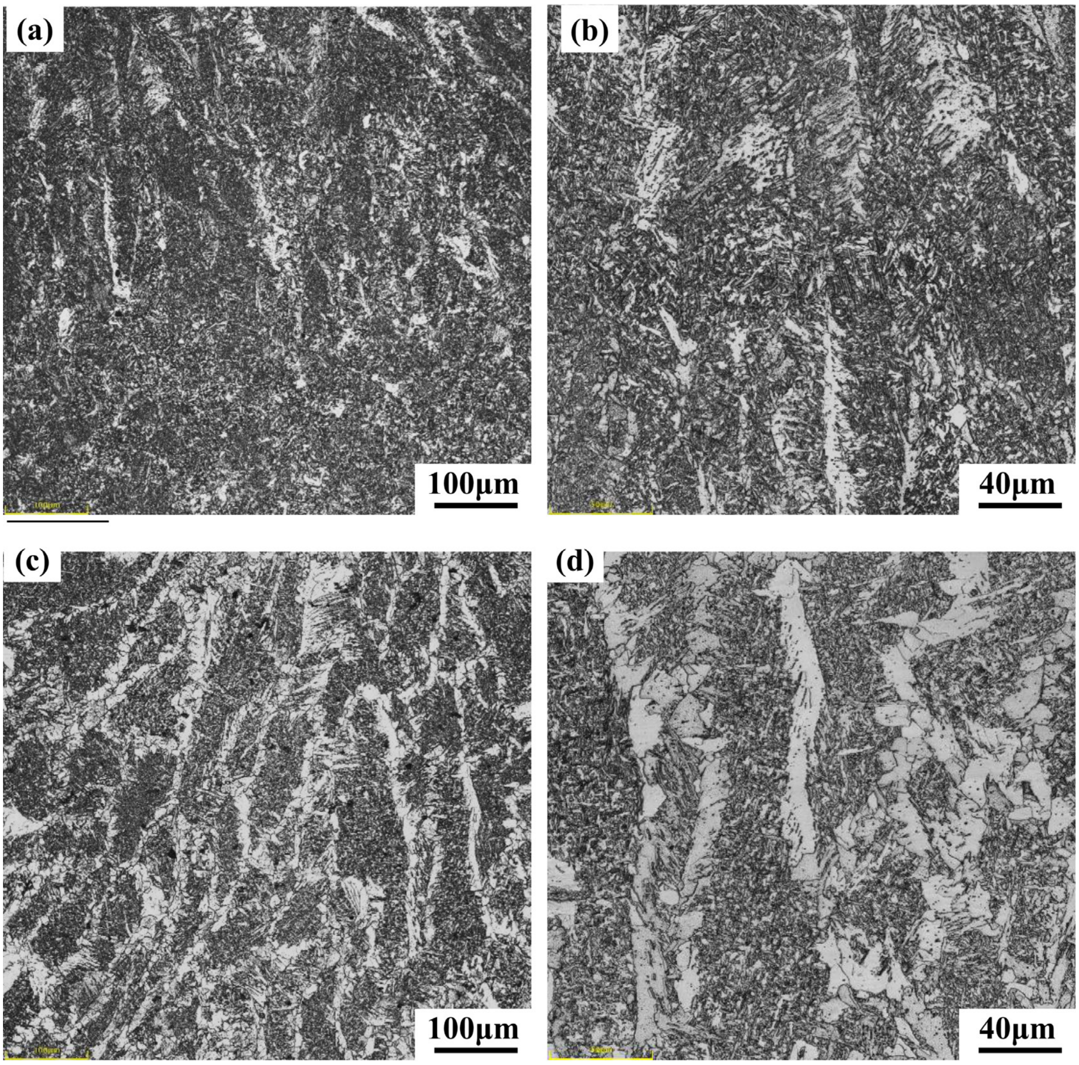


Fig.15. The metallography of weldment (a) FCAW; (b) FCAW; (c) MCAW; (d) MCAW.

2. The welding penetration of MCAW and GMAW-solid-wire are obviously deeper than FCAW. Deep penetration helps to break up the residual slag on the surface of the previous welds and avoids defects on the initial weld beads. Similar hardness between the weld zone and the base metal for MCAW and GMAW-solid-wire leads to less residual stress after welding. A better control on cracks can be expected in the welding zone and heat-affected zone.
3. Although FCAW has a serious slag residual problem, its wire core contains Ti element which forms TiO_2 during welding. TiO_2 can inhibit the original austenitic grain growth during welding solidification. The relatively fine microstructure and acicular ferrite can be formed in weld metal, so the structure welded by FCAW usually has better strength and low-temperature toughness. In contrast, the filler wires used for MCAW and GMAW-solid-wire did not contain any grain refinement element and usually led to insufficient hardenability. The coarse grains and boundary ferrite precipitations are the main structure and could deteriorate the low-temperature impact toughness.
4. The hybrid welding process helps to improve not only the welding quality, but also the efficiency. Welding with MCAW or GMAW-solid-wire for the initial beads can effectively avoid poor fusion caused by welding slag. After that, FCAW is recommended to make impact toughness of the weldment higher and to work more easily if the groove is large enough to easily remove the slag. On the other hand, if the filler wire contains sufficient grain refining elements and has sufficient hardenability, the MCAW or GMAW-solid-wire process will also be an ideal choice for offshore structure welding.

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