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Microstructure Evolution and Mechanical Properties of Friction Stir Welded Thick HSLA Steel

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ABSTRACT

Friction stir welding (FSW) is known for joining low softening alloys metals such as aluminum, magnesium and copper, however joining of high softening alloys like steel, titanium and nickel base alloys is still a challenge due to tool material stringent property requirements and its availability. Presently, due to development new generation tool material FSW of high softening alloys is possible and also reported. FSW can effectively join different grade of low thickness steel, however the questions about joining thick section steel still remains a challenge.

In this paper, FSW of 7 mm, 12 mm and 24 mm thick HSLA steel in single and double pass was carried out to develop the processing window for defect free weld joints and understanding the structure-property correlation. The increase in thickness of the base metal resulted in generation of higher load, higher heat input and consequently lower cooling rate. Therefore, the microstructure obtained after FSW in different thickness of steel also shows varying microstructures (grain boundary ferrite, acicular ferrite, widmensttan ferrite and upper bainite). Optical and scanning electron microscope (SEM) with electron back scattered diffraction (EBSD) detector was utilized to characterize the microstructure of FSW nugget zone. Tensile and hardness properties were also evaluated and correlated with the microstructure.

Key words: Friction Stir Welding; High Strength Low Alloy Steel (HSLA); Microstructure; Tensile Properties; Scanning Electron Microscopy

1.0 INTRODUCTION

The market of naval pressure vessel is growing at a rapid pace and in order to meet the increased industrial and service requirements more efficient designs and manufacturing conditions are being investigated [1,2]. In particular the weight saving can be achieved by using higher strength steel and also by improving manufacturing condition by innovation processes and design. The use of advanced high strength steel for the pressure vessel, hull and super structure is a solution which allows a significant weight saving by reduction of structure thicknesses. The manufacturing process must be accordingly adapted for these grades of advanced steel. With reference to above, the development of innovative and high productivity welding processes should also assessed ensuring the quality of the weld; in terms of weld defects, distortions and flatness of the structure, improvement of the hygiene and safety with regard to the manufacturing processes, better controllability, improvement of serviceability and repair.

The fusion welding processes has its own limitations such as it requires preheating, filler metal and inert gases and tools for minimizing the distortions. Also welding defects like lack of fusion, porosity, inclusions, cold cracking, and undercuts are commonly observed and requires reworks for repairing and finishing. On the other hand, the friction stir welding (FSW), which is a solid state welding process without filler can be used as an alternative welding process and thus eliminates the disadvantages associated with the fusion welding process. Currently, the FSW method is a matured process for welding of low softening metals like aluminum, still there are many scientific and technological hurdles for high softening metal like steel, titanium and nickel base alloys [3,4]. Recent investigations have demonstrated the feasibility and advantages of this process in high strength low alloy steel (HSLA) for a thickness of about 6 to 12 mm in terms of lower grain size in heat affected zone (HAZ), better weldability and producing no fumes in particular hexavalent chromium. Moreover, the investigations were mostly carried out in small specimens and do not demonstrate the industrial feasibility and limited tool life [5,6]. The recent developments in the tool materials for FSW of high softening metals is the key for welding of steels. To our knowledge FSW on higher thickness steel (>12 mm) is not investigated and reported in past. The present investigation focuses on the assessment of FSW process on thick steel and also to demonstrate FSW process in terms with the specific requirements of shipyards and tool life. The present study also present the characterization of welded joints for optimized welding parameters and analysis when compared to conventional welding process.

2.0 EXPERIMENTAL DETAILS

The steel used for the present is HSLA grade of steel which is close to HY 100 steel in terms of properties and performance. The chemical composition and mechanical properties are listed in **Table 1** and **Table 2**.

Table 1 : Chemical composition of HSLA Steel

% Max.	C	Wi	Mn	P	S	Cr	Cu	Mo	V	Ni
HSLA	0.15	0.25	0.50	0.0	0.01	0.5	0.25	0.40	0.009	4.8

Table 2 : Mechanical properties of HSLA Steel

Mechanical Properties	YS (MPa)	UTS (MPa)	% Elongation
HSLA	710 ± 10	890 ± 10	15 ± 2

The butt welding coupons of size 1000 X 100 X 8 mm, 1000 X 100 X 12 mm and 1000 X 100 X 24 mm are FSW welded using indigenous developed 100 kN thermal assisted friction stir welding machine having Megastir® water cooled tool holder with temperature telemetry system. The W-25 Re tool was used for FSW trials, for 8 mm, 12 mm and 24 mm having tapered cylindrical pin with pin length of 7.8 mm, 11.7 mm and 12.2 mm (two pass welding), respectively was used for the FSW welding trials. Incase of 8 and 12 mm thickness single side full penetration weld was performed, however in case of 24 mm thick steel two side/pass welding was performed. The conventional manual metal arc welding (MMAW) was carried on HSLA plate of coupon size 1000 X 100 X 24 mm for comparison for properties and microstructure.

Nondestructive tests were carried out for both FSW and MMAW welded coupons. After visual inspection phased array ultrasonic and x-ray radiographic test were conducted to find defects in both MMAW and FSW weld coupons.

Destructive testing was performed to evaluate the joint strength and toughness welded coupons. Transverse tensile tests (three specimens), charpy impact test (-20 °C) and Vickers Hardness (HV5) were carried out according to respective ASTM standards. In addition to transverse tensile test, longitudinal tensile test were also conducted on the welded coupons to evaluate the strength and ductility.

3.0 RESULTS AND DISCUSSIONS

The optical (at 500X and 2500X magnification) and scanning electron microscopy (SEM) (at 3000X magnification) microstructure of the base metal which is a quenched and tempered HSLA steel consist of banded ferrite with iron carbide microstructure with an average grain size of 12 ± 2 μm.

The mosaic crossectional macrostructure of FSW welded 8 and 24 mm HSLA steel and MMAW welded 24 mm steel is presented in **Fig. 2 (a), (b)** and **(c)** showing different zone such as nugget zone, TMAZ zone, HAZ and base metal.

The macroscopic examination of the welded steel clearly indicate defect free nugget/stir zone in both FSW and MMAW welded steel joints. No internal defects have been noticed or observed; however small undercut was observed for FSW welded steel of 24 mm thickness. Burr which is formed during FSW is responsible for reduction of thickness. If the reduction of thickness is in acceptable range, the burr formed during FSW can be removed by normal grinding operation.

The FSW welded joints consist of three regions as shown in **Fig. 2 (a)** namely the stir or nugget zone, thermomechanically affected zone (TMAZ) and heat affected zone (HAZ). The stir

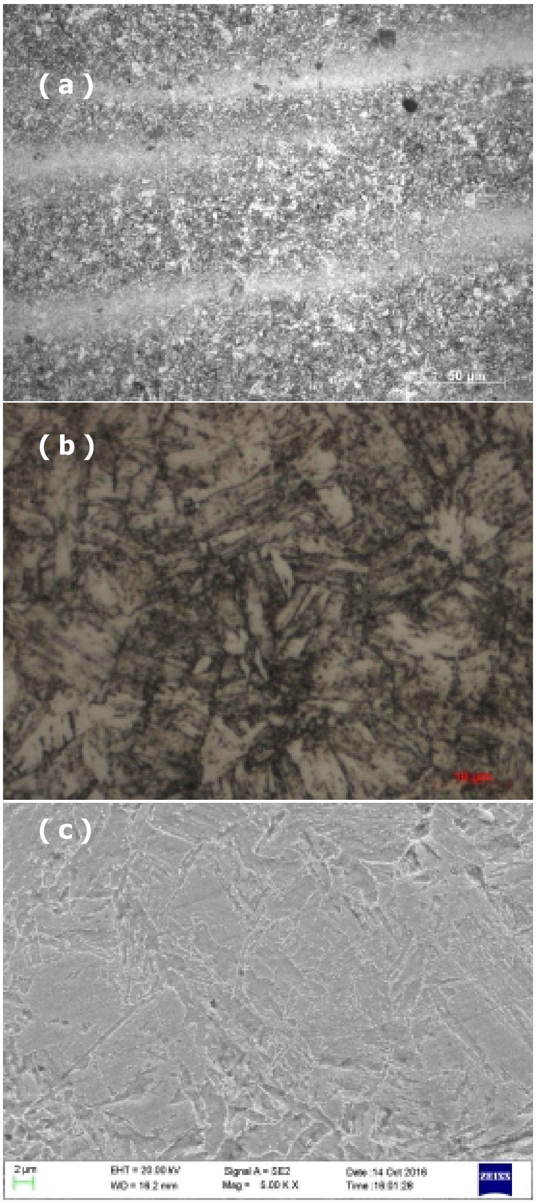

Fig. 1 : Optical and SEM microstructure of quenched and tempered HSLA steel at magnification of (a) 500X, (b) 2500X and (c) 3000X showing banded ferritic structure with iron carbide.

zone region is characterized by recrystallized grain formed by the interaction rotating pin of the tool and the region adjacent to stir zone is TMAZ. Basically TMAZ zone is the transition region between stir zone and TMAZ zone.

There is vast difference between the microstructure of welded FSW and MMAW weld nugget zone as the former is solid state welding technology and later is conventional liquid state welding process. As the resultant microstructure will govern the properties, therefore the microstructure was thoroughly

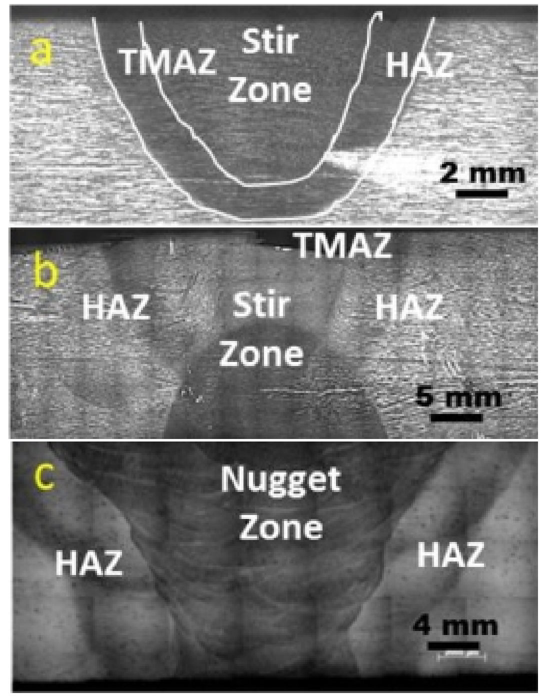

Fig. 2 : Mosaic macrostructure of welded steel (a) 8 mm-FSW, (b) 24 mm-FSW and (c) 24 mm-MMAW.

characterized. The microstructure of nugget/stir zone of FSW welded steel predominantly consists of widmanstätten ferrite which is grown on prior austenitic grain boundary with some martensitic regionsas shown in **Fig. 3 (a)** and **(b)**, whereas the microstructure of MMAW weld consist of allotriomorphic ferrite **(Fig. 3 (c))**.

The single pass stir zone microstructure of FSW conducted at 700 rpm and 60 mm/min traverse speed contained large prior austenite grains that have transformed into a ferrite, Widmanstattan ferrite/bainite and martensite (marked by circle) and shown in **Fig. 4 (a)**. However two pass FSW was performed for joining 24 mm thick steel and welded from both the sides and the overlap stir zone microstructure was analyzed. The amount of ferrite contained in the stir zone of first pass was found to be greater than the second pass. The widmanstätten ferrite/bainite lathe spacing is also found be greater in first pass as compared to the overlapped region. This may be attributed to the higher amount of stress and strain experienced in the overlap stir zone of the weld. The most important point to observe is the presence of undesirable martensite phase in the microstructure (marked by circle in **Fig. 4**). The TMAZ region of the weld for 8 and 12 mm doesn't possess shear band, however shear band was observed for two pass 24 mm steel as confirmed by **Fig. 5**. The microstructure of the TMAZ contains refined ferrite grains with dispersed

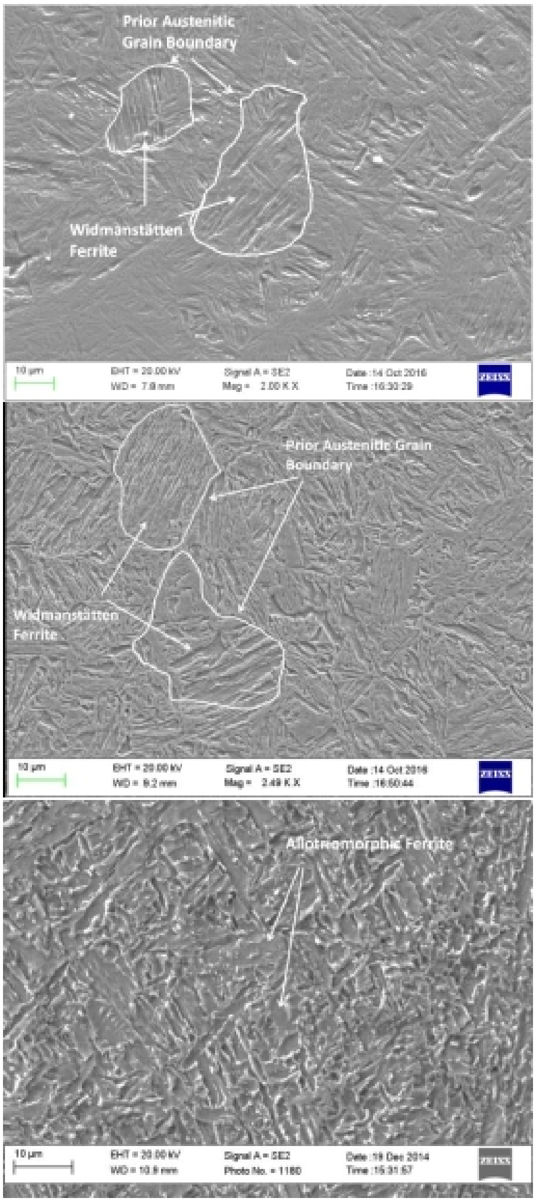

Fig. 3 : SEM microstructure of FSW and MMAW welded nugget/stir zone of (a) 24 mm steel, (b) 8 mm steel and (c) 24 mm steel showing prior austenite grain boundary, widmanstätten ferrite and allotriomorphic ferrite.

colonies of iron carbide as shown in **Fig. 5 (c)**. The grain size of ferrite in the TMAZ was greatly reduced as compared to base metal.

The tensile test on the transverse specimens leads to failure on the base metal side and thus indicates that the weld is stronger than the base metal. For FSW of 8 mm, 12 mm, and 24 mm and MMAW steel joints the yields strength was found to 762 ± 10, 758 ± 8, 748 ± 10 and 692 ± 4 MPa respectively. The ultimate

Fig. 4 : Optical microstructure of FSW welded nugget/ stir zone of (a) 8 mm steel and (b) overlap stir zone in 24 mm steel showing widmanstätten ferrite, α-ferrite and martensite.

tensile strength was found to be 892 ± 8, 878 ± 10, 875 ± 10 and 774 ± 4 MPa on FSW 8, 12, 24 mm steel and MMAW 24 mm steel respectively. The percentage elongation was in the range of 15-17% for FSW joints, however the MMAW joint show much more elongation of 22%. The charpy impact properties of the FSW joints showed lower average value of 52 ± 5 J, as compared to MMAW joint showing 72 ± 4 J. The microstructure obtained in the stir zone was also correlated with the hardness value obtained for stir zone and HAZ. The FSW stir zone and TMAZ show hardening due thermal and mechanical condition imposed by FSW process and this effect is even more pronounced in the steel which more susceptible to quenching. The hardness of 440 ± 12 Hv was recorded for the FSW stir zone, while it was 314 ± 8 Hv for MMAW weld. The hardness values were found to be same for the advancing and retreating side, however the overlap stir zone shows 445 ± 8 Hv hardness in two pass weld. The reason for the increase of the hardness is attributed higher stress and strain experienced during FSW as well as formation of martensite in the stir zone. The quenched and tempered grades of steels are more susceptible and

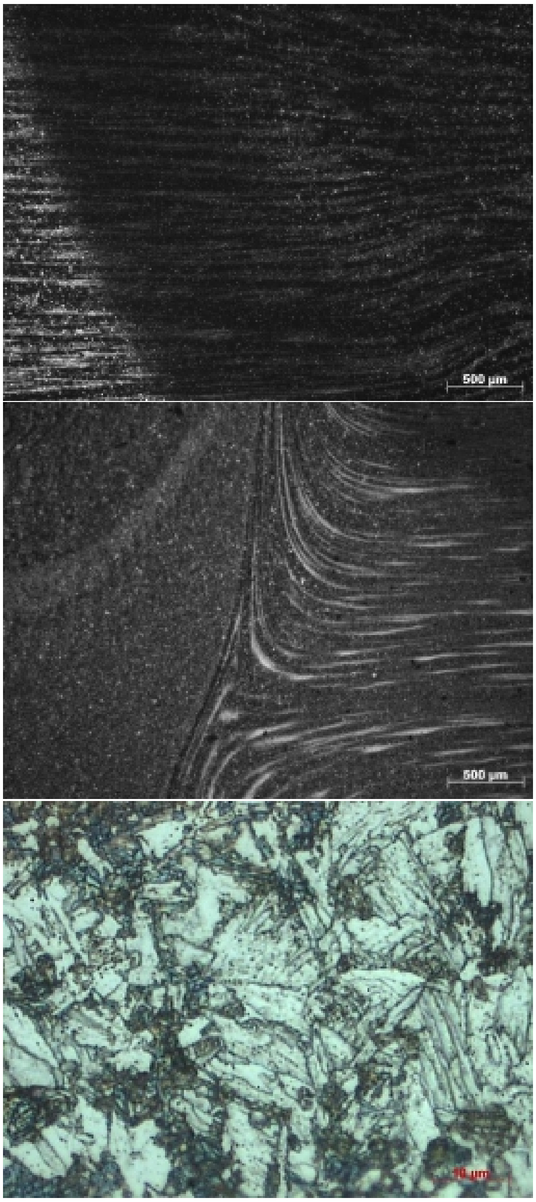

Fig. 5 : Optical microstructure of FSW welded TMAZ zone of (a) 8 mm steel, (b) overlap stir zone in 24 mm steel and (c) at 2500X.

sensitive to the quenching and hence getting desired properties and microstructure is of further investigation.

4.0 CONCLUSIONS

Preliminary investigation on quenched and tempered grade of HSLA steel with different thickness of 8 mm, 12 mm and 24 mm were performed in order to confirm the applicability of the innovative FSW process for the shipbuilding applications. The main outcome of the investigation is as:

- The NDT testing of the joints confirms defect free joints can be obtained by FSW.
- The microstructure in the stir zone consists of bainite/ widmanstatten ferrite along with undesirable martensite.
- The higher hardness, lower impact and elongation value indicate the presence of brittle phase in the microstructure. However, more investigation is required to fully understand the microstructure formation particularly in the high strength sensitive grade steel.
- The MMAW weld is showing better toughness and ductility as compared to FSW welded joints.

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REFERENCES

[1] Shinoda T and Takegami H (2005); Development of FSW process for steel assembly to shipbuilding and offshore structure, Proc. 15th Int. Offshore and Polar Eng. Conf., Seoul, pp.19-24.

[2] Show BK, Veerababu R, Balamuralikrishnan R and Malakondaiah G, (2010), Effect of vanadium and titanium modification on the microstructure and mechanical properties of a microalloyed HSLA steel, Materials Science and Engineering A, 527, pp. 1595–1604.

[3] Rai R, De A, Bhadeshia HKDK and Debroy TT (2011); Review: friction stir welding tools, Science and Technology of Welding and Joining, 16(4), pp. 325-342.

[4] Thompson B and Babu SS (2010), Tool degradation dharacterization in the friction stir welding of hard metals, Edison Welding Institute, 89, pp. 21-26.

[5] Ragu Nathan S, Malarvizhi S, Balasubramanian V and Rao AG (2016), Failure analysis of tungsten based tool materials used in friction stir welding of high strength low alloy steels Engineering Failure Analysis, 66, pp. 88–98.

[6] Ragu Nathan S, Malarvizhi S, Balasubramanian V and Rao AG (2015), Effect of welding processes on mechanical and microstructural characteristics of high strength low alloy naval grade steel joints, Defence Technology, 11, pp.308–317.