

A Comparison of Double Sided Friction Stir Welding in Air and Underwater for 6mm S275 Steel Plate

Philip Baillie, Stuart W. Campbell, Alexander M. Galloway, Stephen R. Cater, Norman A. McPherson

Abstract—This study compared the mechanical and microstructural properties produced during friction stir welding (FSW) of S275 structural steel in air and underwater. Post weld tests assessed the tensile strength, micro-hardness, distortion, Charpy impact toughness and fatigue performance in each case. The study showed that there was no significant difference in the strength, hardness or fatigue life of the air and underwater specimens. However, Charpy impact toughness was shown to decrease for the underwater specimens and was attributed to a lower degree of recrystallization caused by the higher rate of heat loss experienced when welding underwater. Reduced angular and longitudinal distortion was observed in the underwater welded plate compared to the plate welded in air.

Keywords—Charpy impact toughness, distortion, fatigue, friction stir welding (FSW), micro-hardness, underwater.

I. INTRODUCTION

FRICITION Stir Welding (FSW) is a thermo-mechanical process in which two metals are joined together in the solid state, to produce a high strength, high quality joint [1], [2]. Compared with conventional arc welding processes, there are a number of benefits including; low distortion, minimal chemical segregation and, enhanced hardness and strength due to grain refinement in the stir zone [3]-[6]. Although the process has reached a stage of technical maturity for the “light alloys”, its application to metals such as steel, nickel and titanium has been slower to develop due to the severe loads and temperatures the tool experiences during the welding process [7], [8]. Tool design and development of advanced materials for FSW of steel has therefore become a significant area of research in recent years, focusing specifically on improving tool lifespan [9]. Perrett et al. [10] investigated friction stir welding of industrial steels using two different tool materials; pcBN and a W-Re/cBN composite. In both cases, welds in excess of 40m were completed without tool probe failure or any signs of weld defects. In addition to this Sorensen [11] studied the wear and fracture sensitivity of three grades of pcBN tools and obtained a tool life of approximately 60m when welding structural steel. The welding parameters in FSW include; tool traverse speed, rotational speed, vertical force and traverse force. It has been reported that by varying these parameters, the microstructural and mechanical

properties can be precisely controlled, allowing for a repeatable, fully-autonomous joining process which produces almost defect free welds [12]. Fujii et al. [13] studied the effect of welding speed using three types of carbon steel; IF steel (ultra low-carbon steel), S12C (0.12wt.%C) and S35C (0.34wt.%C). In each case, the strength of the joint increased with increasing welding speed, with the exception of the S35C steel which peaked at 200mm/min. Hardness was also measured as a function of welding speed and the following results were obtained; the IF steel showed no significant gain in hardness, the S12C steel showed a linear increase in hardness and the S35C steel peaked again at 200mm/min. The results were explained by considering the relationship between the peak temperature and the A₁ or A₃ point on the iron-carbon phase diagram. When FSW is performed in the ferrite-austenite two-phase region, the microstructure is refined and the highest strength is achieved. Lakshminarayanan et al. [14] also reported increases in strength and hardness during FSW of 409M ferritic stainless steel, where the coarse ferrite grains in the base material were converted to a very fine duplex structure consisting of ferrite and martensite. To date, research into the subject of underwater FSW has been limited. Liu et al. [15] performed a study, which determined the effect of welding speed on the microstructures and mechanical properties produced when welding 2219 aluminium alloy underwater. The results showed a significant increase in the tensile strength of the underwater joint in comparison with arc welds in the same material, which was attributed to the increased cooling rate preventing the deterioration of strengthening precipitates. Given the increasing interest in FSW for subsea and shipbuilding applications, it is essential that further research be completed to assess the feasibility of underwater FSW for steels. The present study reports on the comparison between the mechanical and microstructural properties produced in S275 structural steel when friction stir welded in air and underwater.

II. EXPERIMENTAL WORK

S275 hot rolled structural steel was used in this study and was supplied in the form of plates measuring 2000 x 200 x 6mm (length x width x thickness).

The S275 steel plates were welded with no milling of their mating edges and no removal of the surface scale or primer. Double sided friction stir welds were created in both the air and underwater plates using the hybrid WRe-pcBN, Q70 (70 vol.%cBN) friction stir welding tool shown in Fig. 1.

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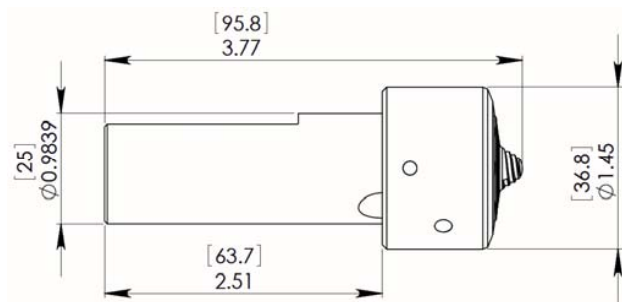


Fig. 1 Geometry of FSW tool

All welds were performed in the counter clockwise (CCW) direction by embedding the tool to a reference level of 4.8 mm below the surface from both sides, and a travel speed of 100 mm/min. In the case of the air welds, an argon gas shield was also used to prevent the welding zone and tool from oxidizing.

Post weld angular and longitudinal distortion was measured using optical distance sensor controlled using a LabVIEW program that scanned the workpiece according to a pre-defined grid pattern. Each plate was secured on four locating points, which were calibrated using the optical distance sensor to result in zero deformation at these locations, spaced 380 x 800 mm apart. It was also assumed that the plates were initially flat prior to the welding process. Distortion measurements were recorded in 10 mm increments in both the longitudinal and transverse directions.

III. RESULTS AND DISCUSSION

A. Distortion

The deformation profile for both the air and underwater FSW plates are shown in Fig. 2. A submerged arc welded (SAW) DH36 steel plate of the same dimension has been included to highlight the significant variation in distortion profile. All three plates show symmetrical distortion in the longitudinal direction. However, it is clear that the magnitude of distortion varies significantly between the FSW and the SAW plates. The underwater FSW plate exhibited the lowest distortion, with a deviation in the range of 5 to -1.5 mm from the zero reference-plane. The in air FSW plate showed a slightly larger deviation in the range of 25 to -5mm, while the SAW plate showed the largest deviation in the range of 110 to -20mm.

This can be explained by considering the difference in heat input between each of the welds. The heat input calculated by McPherson et al. [16] for the arc welded plate is 3.79 KJ/mm. The heat input for the FSW plates was calculated using (1) and (2) where f_1 is the process efficiency [17].

$$Power = \frac{2 \left(\frac{rev}{min} \right) (Spindle Torque)}{60} \quad (1)$$

$$Heat Input = f_1 \left(\frac{Power}{Travel rate} \right) \quad (2)$$

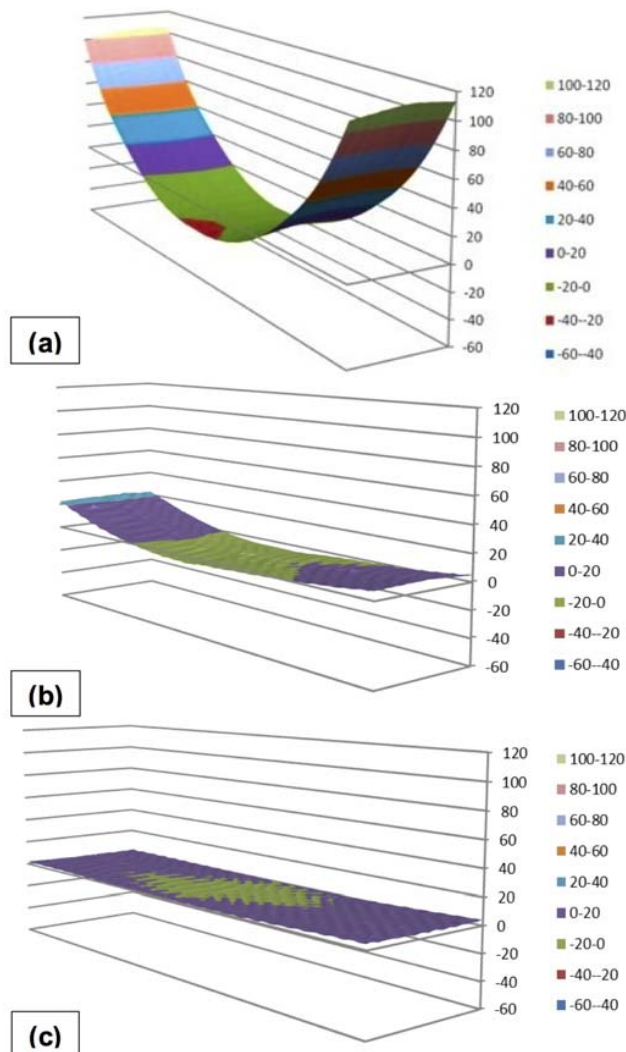


Fig. 2 Distortion profiles for (a) submerged arc welded DH36 steel, (b) air FSW plate, and (c) underwater FSW plate. Y-axis value indicates distortion from the zero-reference plane measured in mm

Heat input was calculated to be 3.01 and 4.29 KJ/mm for the air and underwater welded plates respectively. The additional heat input of 1.28 KJ/mm for the underwater plate is required to compensate for the high heat dissipation to the surrounding water, reducing thermal stress in the parent plate and subsequently reducing distortion.

The large variation between the distortion in the SAW and FSW plates could be attributed to two factors. Firstly, FSW plates are subjected to a higher degree of restraint during welding because of the large forces involved. These restraints eliminate movement during welding and hence reduce distortion. Secondly, the SAW process involves a phase change during welding from liquid to solid, whereas FSW is a solid-state process. This means that the magnitude of the thermal stresses will be larger for the SAW plate due to the volume change (longitudinal and transverse shrinkage)

experienced during solidification and subsequent cooling to room temperature.

B. Microstructure

The macro-etched image in Fig. 3 shows a full penetration weld from both sides with an interference zone of approximately 3.6 mm. The letters A, B and C represent the interference zone, thermo mechanically affected zone (TMAZ) and parent material respectively. The microstructure of each zone was analysed using an Olympus GX-51 microscope. The parent material shown in Fig. 4 has a microstructure of ferrite with pearlite located at the grain boundaries. The parent microstructure in both air and underwater FSW was identical. Within the TMAZ, Figs. 5 (a) and (b), it can be seen that the pearlite begins to degenerate in both cases. The ferrite grains within the air FSW plate (Fig. 5 (b)) are smaller, which was attributed to a slower cooling rate and hence a larger extent of dynamic recrystallization in comparison with the underwater FSW. The interference zone, Figs. 6 (a) and (b), shows significant grain refinement as a result of severe plastic deformation (SPD) and recrystallization. These factors, as well as the elevated temperatures the material experiences during FSW, resulted in the evolution of fine equiaxed grains. The interference zone consists of grains of ferrite with very fine particles of dispersed pearlite at the grain boundaries.

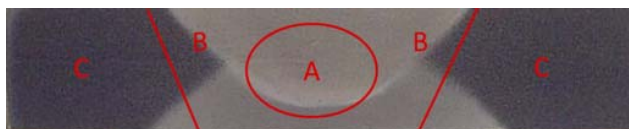


Fig. 3 Macrostructure of the double-sided FSW

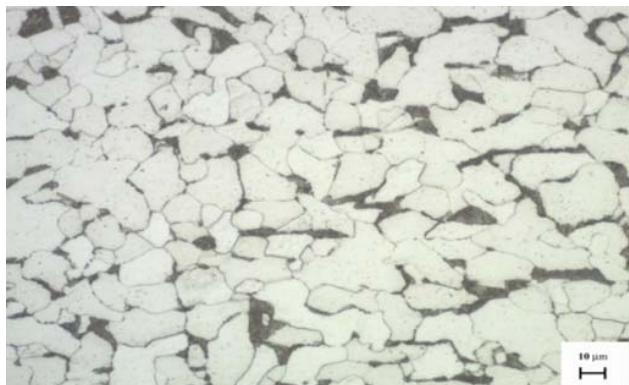


Fig. 4 Parent Material



Fig. 5 TMAZ of (a) underwater FSW plate and (b) air FSW plate

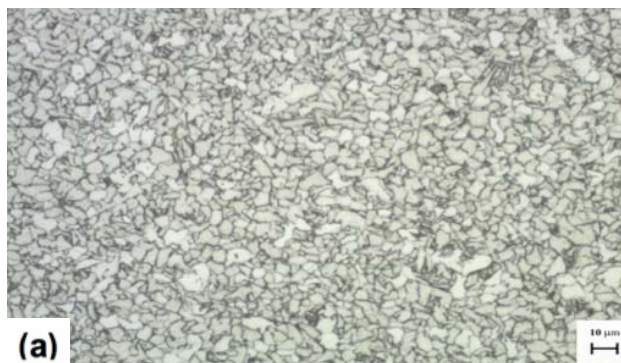


Fig. 6 Interference zone of (a) underwater FSW plate and (b) air FSW Plate

C. Mechanical Properties

1) Tensile Strength

Transverse and longitudinal tensile tests, fabricated in accordance with BN EN ISO 4136: 2011, were performed to assess the strength of the welded joints (three in each direction for both air and underwater FSW). In all cases the transverse samples failed in the parent material, highlighting the superior strength of the weld metal. As such, there was no significant variation in the air and underwater transverse specimens. The longitudinal tensile tests produced results considerably higher mean average yield strength and ultimate tensile strength (UTS) (475 and 577 MPa respectively) than the transverse tensile tests that failed in the parent material (353 and 509 MPa respectively), equating to an improvement of 25.68 and 11.79% for the yield and UTS respectively. This enhanced strength within the weld metal attributed to the microstructure and grain refinement experienced in the interface zone.

2) Micro-Hardness

Micro-hardness was measured in accordance with BS EN ISO 6507-1: 2005 using a Mitutoyo MVK-G1 hardness tester. No significant variation in hardness between air and underwater FSW was observed. The micro-hardness did increase in the weld zone but not to a level that would cause any concern.

3) Charpy Impact Toughness

Charpy impact toughness was assessed according to BS EN ISO 148-1: 2010 using a scaling factor of 1.5 to compensate for the non-standard specimen dimension (10 x 6 mm due to plate thickness). The specimens (three for each location) were machined perpendicular to the weld centreline with notch positions -6, -4, -2, 0, +2, +4, +6 mm from the weld centre. Charpy impact toughness, tested at 20, -20 and -40 °C, is shown in Tables I and II. It can be observed that the Charpy impact toughness is significantly reduced for the underwater FSW, attributed to the faster cooling rate, which prevents the material from fully recrystallizing.

TABLE I
CHARPY IMPACT TOUGHNESS (AIR WELD) ABSORBED ENERGY (J)

Temp. (°C)	CL	+2mm (R)	+4mm (R)	+6mm (R)	+2mm (A)	+4mm (A)	+6mm (A)
20	127.5	124.5	81	106.5	144	123	106.5
-20	135	124.5	124.5	93	105	64.5	45
-40	99	115.5	54	37.5	117	135	48

TABLE II
CHARPY IMPACT TOUGHNESS (UNDERWATER WELD) ABSORBED ENERGY (J)

Temp. (°C)	CL	+2mm (R)	+4mm (R)	+6mm (R)	+2mm (A)	+4mm (A)	+6mm (A)
20	64.5	102	81	123	87	45	72
-20	82.5	114	114	37.5	63	79.5	130.5
-40	90	64.5	69	19.5	79.5	124.5	126

4) Fatigue

Low cycle fatigue testing was performed at a stress level of 90% of the measured yield strength. The mean average cycles to failure for the air and underwater specimens being 301K

and 745K cycles respectively. Although the ratio of these two mean values may be considerable in absolute terms, there is almost no difference between the longest and shortest lives within each set of results as shown in Tables III and IV.

TABLE III
LOW CYCLE FATIGUE DATA (AIR WELD)

Maximum Stress (N/mm ²)	Minimum Stress (N/mm ²)	Cycles to Failure
311.19	22.93	470K
311.91	28.31	312K
314.67	31.01	187K

TABLE IV
LOW CYCLE FATIGUE DATA (UNDERWATER WELD)

Maximum Stress (N/mm ²)	Minimum Stress (N/mm ²)	Cycles to Failure
314.40	30.84	907K
315.49	32.43	469K
315.37	31.64	969K

To assess the significance of the results, a statistical analysis was performed [18]. The test showed that if the two populations had identical properties there would be a 6.4% probability of obtaining an apparent difference greater than that seen in the experiments. This is marginally higher than the benchmark figure of 5% that would be required before making any claim that the results were significantly different. Comparing the log-normal distributions shown in Fig. 7 (a) it can be seen that there is no significant difference in the fatigue performance of the air and underwater welds. This is further confirmed by considering the pooled data in Fig. 7 (b). If there were two distinct populations (i.e. fatigue life), the graph in Fig. 7 (b) would show some variation from linearity.

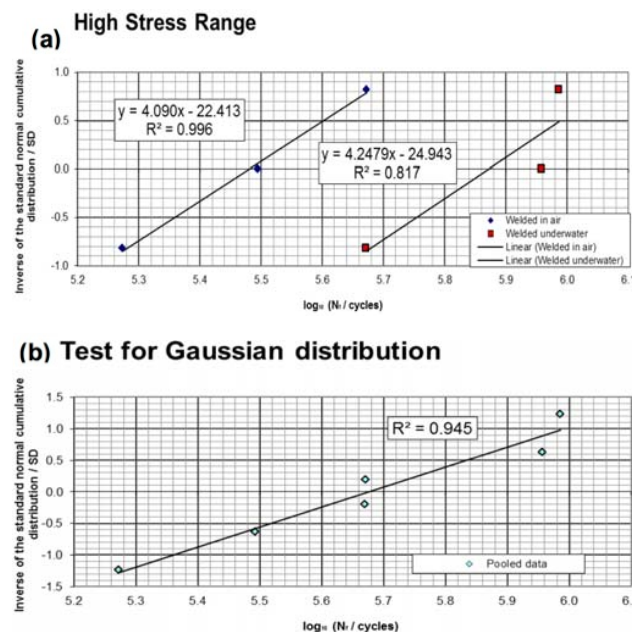


Fig. 7 (a) Log-normal distribution, and (b) pooled data, for the air and underwater FSW specimens

IV. CONCLUSIONS

This study has shown that FSW can be successfully completed underwater for S275 structural steel without any adverse effects to the strength, hardness or fatigue life of the material. Charpy impact toughness was however shown to decrease for the underwater weld and has been attributed to the lower degree of recrystallization caused by the faster cooling rate when welding underwater.

It is proposed that the faster cooling rate produces a weld that has high strength and hardness (compared to the base material), but low ductility, meaning that it is more brittle in nature.

It was also shown that underwater FSW has benefits compared to SAW and FSW in air. This was apparent in the distortion results where it was shown that FSW underwater significantly reduces angular and longitudinal distortion in the work piece.

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