A comparison between single sided friction stir welded and submerged arc welded DH36 steel thin plate

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Abstract

The adoption of the friction stir welding (FSW) process into the shipbuilding industry is being considered as a medium term issue. Currently the data on friction stir welded mild steels tends to be fragmented, with critical areas being short on specific data e.g. toughness.

The work described has been put in place to directly compare friction stir welded and submerged arc welded thin plate. The plate thicknesses used were 4, 6 and 8mm thick DH36 grade steel, which are commonly used in the construction of vessels such and destroyers, frigates corvettes and offshore patrol vessels.

Friction stir welding was carried out using the currently best established parameters for a single sided process and this was compared against Submerged Arc Welding (SAW) over the same thickness range.

Distortion was found to be lower in friction stir welded steel, but the 4mm thick was still showing significant distortion. No issues were identified with weld metal strength, and toughness at -20^{O}C was found to be comparable but more uniform across the weld area than with the submerged arc welded material.

Microstructural observations have been linked to hardness, toughness and fatigue test data. The fatigue data includes the observation of preferential crack initiation relative to the trailing/leading side of the welding process.

An assessment on the feasibility of the process in a shipbuilding environment will be included based on the data presented.

Keywords

Friction stir welding (FSW); toughness; fatigue, distortion

Introduction

Friction stir welding is being considered as a potential process to integrate into the shipbuilding industry. As a result there is a need to develop an understanding of what its specific strengths and weaknesses are related to commonly used shipbuilding steels. Currently one of the most common shipbuilding steel is Lloyds DH36 which is normally a carbon manganese niobium steel with a minimum yield strength of 360N/mm^2 and a minimum impact requirement of 36J at -20^{O}C. There is a publication (1) on this particular subject which concluded that there was a capability to produce single pass full penetration welds in 6.4mm thick steel plate. The steel used was not C-Mn-Nb but a C-Cr-Mo-V steel. Increasing the travel speed resulted in a progressive increase in weld metal hardness to a maximum level of 350, which is close the acceptable maximum. The all weld metal mechanical properties appeared to be acceptable with yield and tensile strengths well above the base plate. However, the elongation was below specification and was a function of the welding speed. There was no description of the toughness of the steel. On the basis of hardness and elongation it could be predicted that there was probably an issue in achieving the specification requirements. Another publication (2) alludes to a problem meeting the toughness requirements for DH36. However in that same publication (2), there appeared to be a potential to have better toughness when welding HSLA 65. The work did however show that lower distortion was produced from FSW processed material. An additional publication (3) from the same source highlighted the benefits of FSW as being, less need for fume extraction and lower distortion.

The area where FSW would be implemented in shipyard operations would be in a seam welding configuration which currently utilises submerged arc welding as the primary welding process. On the basis of this it was then seen to be obvious to compare FSW and SAW directly, and to ensure that toughness data was obtained for the DH36 steel being evaluated.

Three plate thicknesses were chosen for this work, namely 4, 6 and 8mm. For each thickness a friction stir welded and submerged arc welded joints were produced by joining overall plate dimensions of 400 x 2000mm. In each case the same parent plate was used for the two welding processes. The chemical analysis of each parent plate is shown in Table 1.

Table 1: Chemical composition of the parent plates, weld metal and also the heat input of the welds produced

Plate thickness		%C	%Si	%Mn	%P	%S	%Al	%Nb	%N	Heat input kJ/mm
8	Parent Plate	0.14	0.37	1.34	0.017	0.008	0.01	0.03	0.003	
	FSW weld area	0.15	0.38	1.35	0.016	0.008	0.01	0.03	0.003	3.23
	SAW weld area	0.11	0.46	1.5	0.018	0.008	<0.01	0.002	0.004	4.38
6	Parent Plate	0.11	0.37	1.48	0.014	0.004	0.02	0.02	0.002	
	FSW weld area	0.12	0.37	1.49	0.014	0.004	0.02	0.02	0.003	3.08
	SAW weld area	0.09	0.52	1.62	0.017	0.006	<0.01	0.01	0.003	3.79
4	Parent Plate	0.09	0.21	1.35	0.021	0.01	0.02	<0.01	0.002	
	FSW weld area	0.09	0.2	1.34	0.021	0.1	0.02	<0.01	0.002	2.68
	SAW weld area	0.08	0.55	1.67	0.022	0.009	0.02	<0.01	0.003	2.88

Welding

The difference in chemistry of the 4mm plate compared to the 6 and 8mm thick plate is related to the specific steel mill processing of the 4mm thick material.

The FSW plates were welded at The Welding Institute (TWI) in Sheffield, UK. Prior to welding the plate edges were milled to give a tight fit and the paint primer was removed in a 20mm region from either side of the weld centreline. As this welding was to be done in a single pass, a nickel alloy backing plate was used on the root side of the welding jig to prevent any adhesion of the root to the backing strip. Welding was carried out using a polycrystalline cubic boron nitride (PCBN) tool and the leading and trailing edges of the weld were identified. An argon gas shield was also used, more to protect the tool rather than the surface area of the welded region.

In the case of the SAW, the plates were brought together with no additional edge preparation and with no gap. Welding was carried out from two sides for each plate thickness. The SAW samples were seen as being indicative of the current process, and were produced to act as the comparator.

Looking at the data in Table 1 it can be seen that the FSW welds had an apparently lower heat input compared to the SAW. Traditional calculations were used to determine the SAW heat input, but the FSW heat input was based on the equation shown below:

$$\text{Heat input} = \varepsilon 2\pi r T / 1000v$$

Where:
ε = dimensionless factor indicative of process efficiency
r = rotational speed (revs/min)
T = average steady state spindle torque (Nm)
v = transverse speed (mm/min)

Testing

The following tests/techniques were carried out for the overall evaluation:

- Distortion measurements
- Weld metal chemical analysis
- Cross weld tensile strength
- Weld centreline Charpy toughness testing at -20°C
- Weld Charpy toughness at 2, 4 and 6mm from the weld centreline on each side of the weld at -20°C
- Vickers hardness mapping using a 1kg load
- Metallography
- Fatigue testing

Distortion measurements of the FSW showed a very pronounced improvement for each thickness against the SAW comparator plates. However, there was still significant distortion on the 4mm thick FSW plate. This is shown in Fig.

1(a-f), which was generated from a laser scanning system and assumed the plates were initially flat.

The weld metal chemical analysis along with the parent plate chemical analysis is shown in Table 1. The most obvious features here are the virtually identical analysis of the parent plate and FSW weld metal. This is not surprising as it is an autogenous non melting joining process. Compared to FSW, the SAW weld metal showed the obvious effects of the welding wire chemistry, particularly in the manganese and silicon contents. Considering the high dilution aspects of the process, there is still a very significant effect of the wire.

Cross weld metal tensile testing of FSW and SAW produced parent plate fractures in all cases, showing the weld metal tensile strength to be above that of the parent plate.

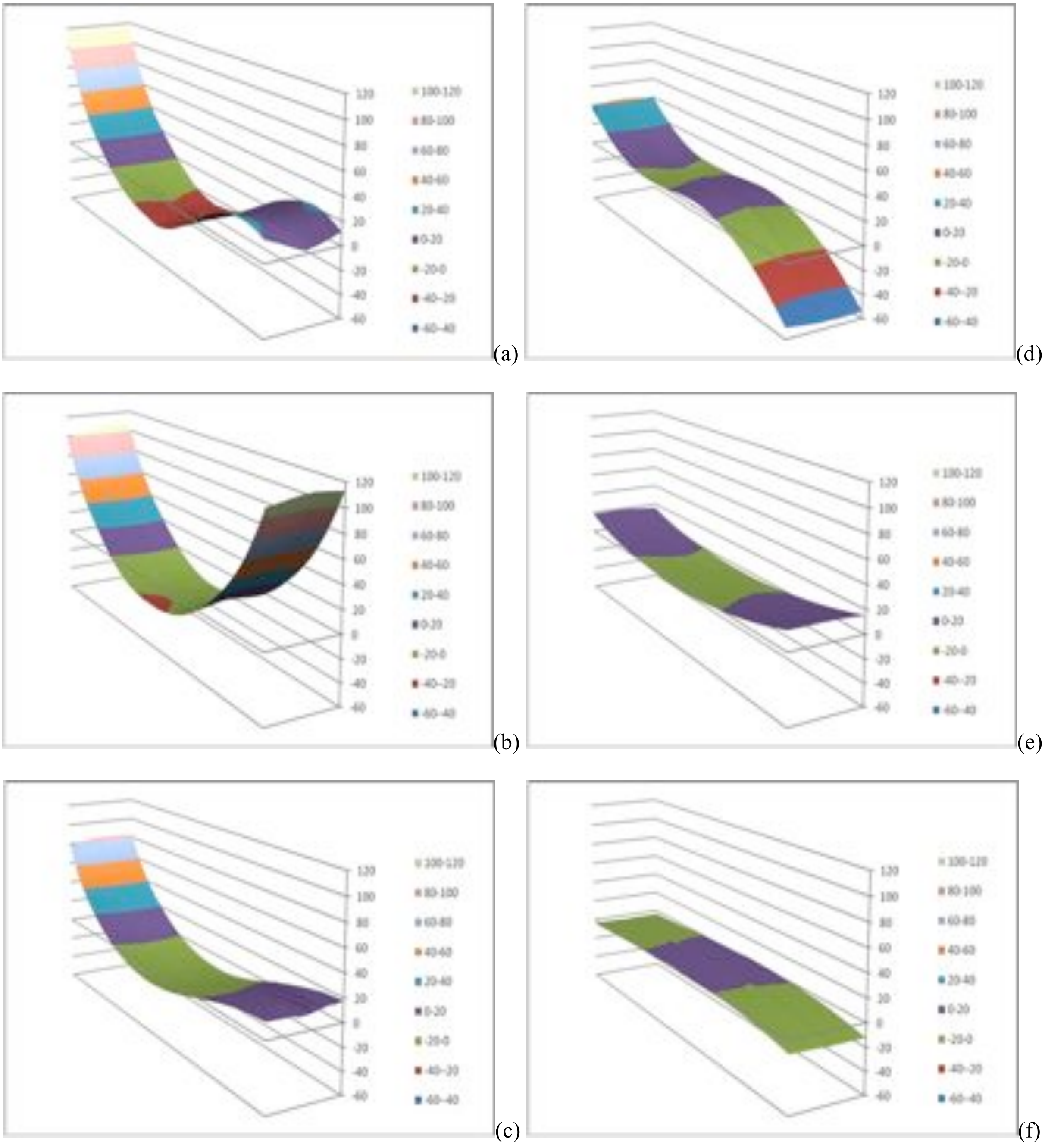


Fig. 1: Distortion plots of each weld with FSW showing better overall profiles ((a) 4mm SAW, (b) 6mm SAW, (c) 8mm SAW, (d) 4mm FSW, (e) 6mm FSW and (f) 8mm FSW)

Toughness was one of the most significant areas of this evaluation, as the data in the literature (1,2) was not particularly conclusive and was pointing to a possible problem area for FSW material.

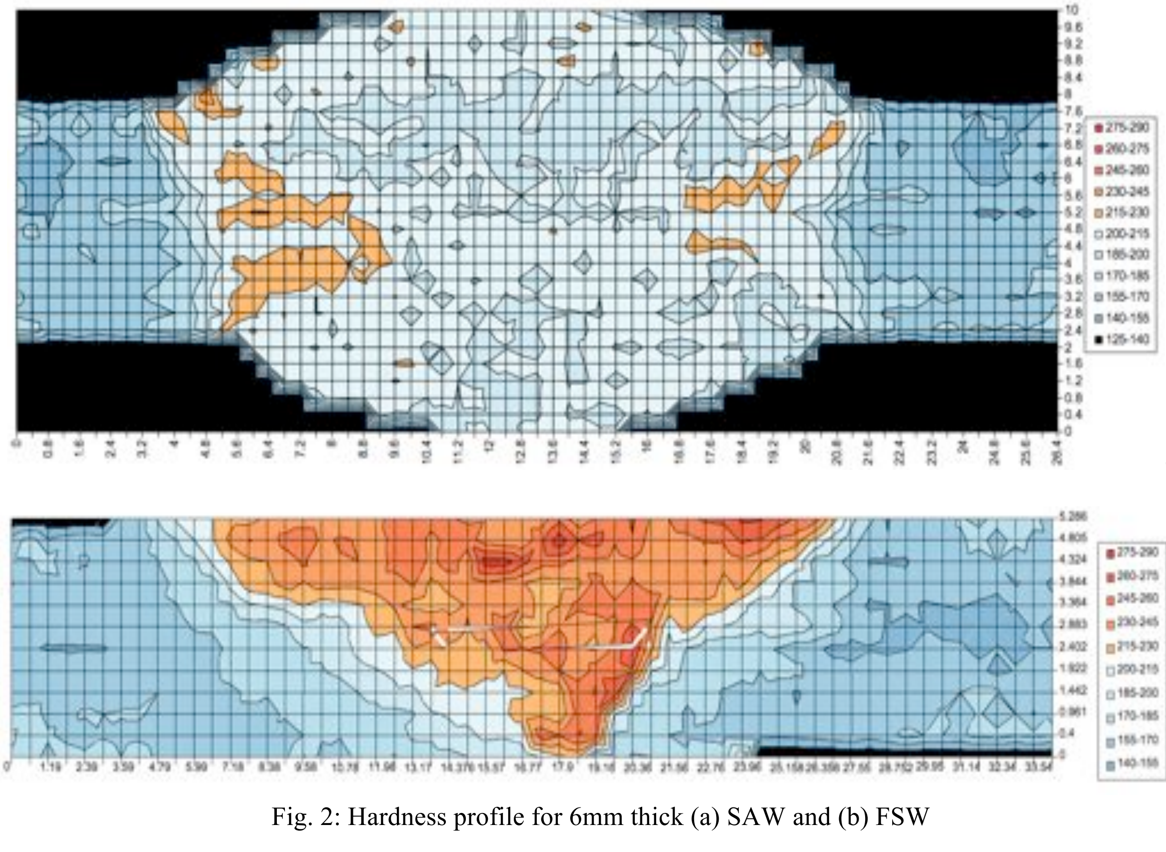
The Charpy testing was carried out on sub size specimens. However to make the data more comparable, conversion factors were used to produce a 10x10mm equivalent value. For the 7.5x10mm samples the conversion factor was 8/7, and for the 5x10mm sample the factor 3/2. There is no defined factor for the 2.5x10mm sample and an arbitrary figure of 2 was used. The toughness data is shown in Table 2.

In all cases of the FSW material the toughness was seen to be satisfactory, and there was no consistent leading/ trailing side difference. Between the FSW and SAW samples there were no significant differences either, for the purpose of this evaluation.

Vickers hardness mapping was carried out on an automated system and the data was converted to produce a 2D visualisation of the overall weld area. It was found that a 1kg load was the optimum to create this output. Initially 5kg was used but found not to be acceptable in terms of image generation. Overall the results were acceptable and there was no evidence of high figures reported elsewhere (1). An example of the 6mm SAW weld is shown in Fig. 2(a) and the 6mm FSW is shown in Fig. 2(b). Overall the FSW weld is harder, but not at a level that would cause concern.

Table 2: Toughness results for FSW and SAW welds (L – leading side for FSW and T – trailing side for FSW)

Plate thickness (mm)		Weld Metal CL	+2mmL	+4mmL	+6mmL	+2mmT	+4mmT	+6mmT
8	FSW weld area	69.6	69.2	45.7	50.3	65	44.5	48
	SAW weld area	62	71	51	38.5	126	45.5	34.3
6	FSW weld area	116	79.5	51	111	85.5	72	132
	SAW weld area	93	94.5	94.5	114	46.5	69	118.5
4	FSW weld area	61	66	62	58	64	58	56
	SAW weld area	46	60	56	72	62	60	60



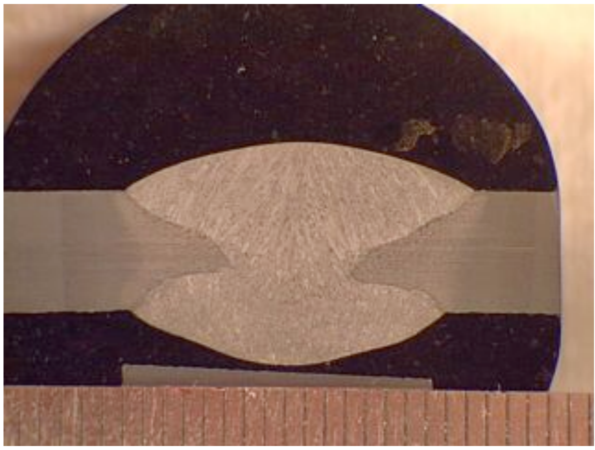
(a)

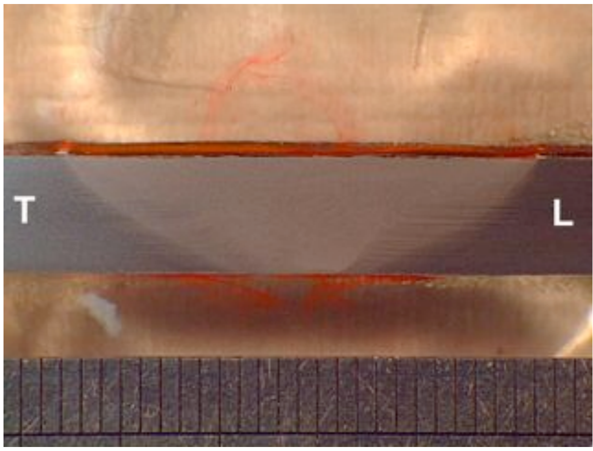
(b)

Fig. 2: Hardness profile for 6mm thick (a) SAW and (b) FSW

Metallography was confined to macro and optical microscopy In the macroetched samples in Fig. 3(b) there was only very slight evidence in some samples of the swirl zones which have been reported elsewhere (1).

In the FSW samples the parent plate was seen as a banded ferrite pearlite microstructure and this showed evidence of pearlite degeneration in the outer HAZ, but still maintaining evidence of banding. The microstructure in the main weld region was a very fine acicular ferrite and with possibly some bainite present. The uniformity of the FSW microstructure and the phases is reflected in the hardness data shown in Fig. 2(b).

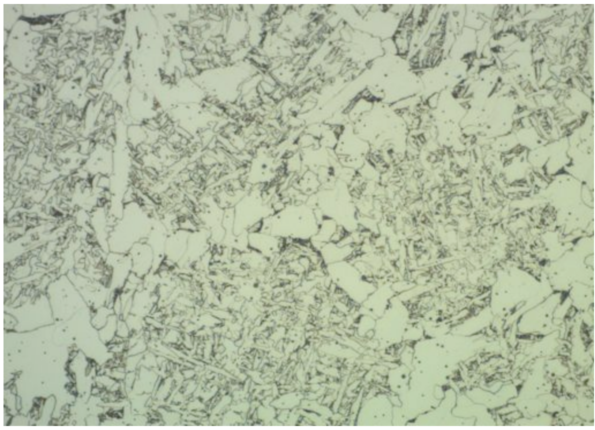

(a)

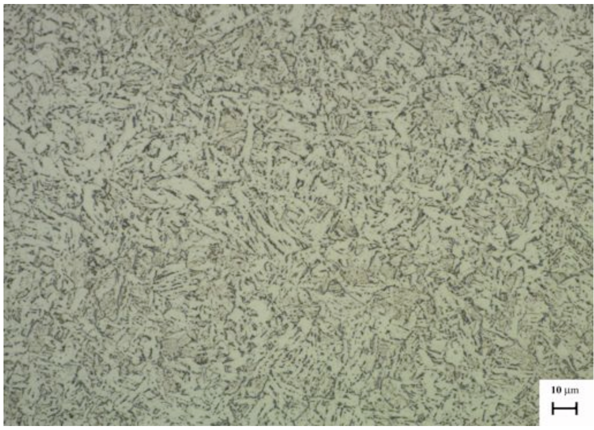


(b)

Fig. 3: (a) Macroetched SAW showing double sided weld, and (b) Macroetched FSW showing no significant swirl features (T – trailing edge and L – leading edge)

The micrographs shown in Fig. 4(a) and (b) are typical of the areas in each sample. The stir zone in the FSW material has been classed as acicular ferrite whereas the SAW is a combination of pro-eutectoid ferrite and a coarser acicular ferrite.


(a)



(b)

Fig. 4: (a) SAW microstructure showing proeutectoid ferrite and acicular ferrite, and (b) FSW microstructure which appears to be almost completely fine acicular ferrite

No data appears in the literature on the fatigue performance of FSW carbon steel material. The data shown in Fig. 5, shows that compared to the SAW samples the fatigue performance was superior. This was the same under low stress or high stress conditions. There was a view that the shoulder area shown in Fig. 3(b) would create a fatigue crack growth initiation site. This has been the case in some instances, but the initiation potential is less than the cap to parent plate junction on the SAW samples.

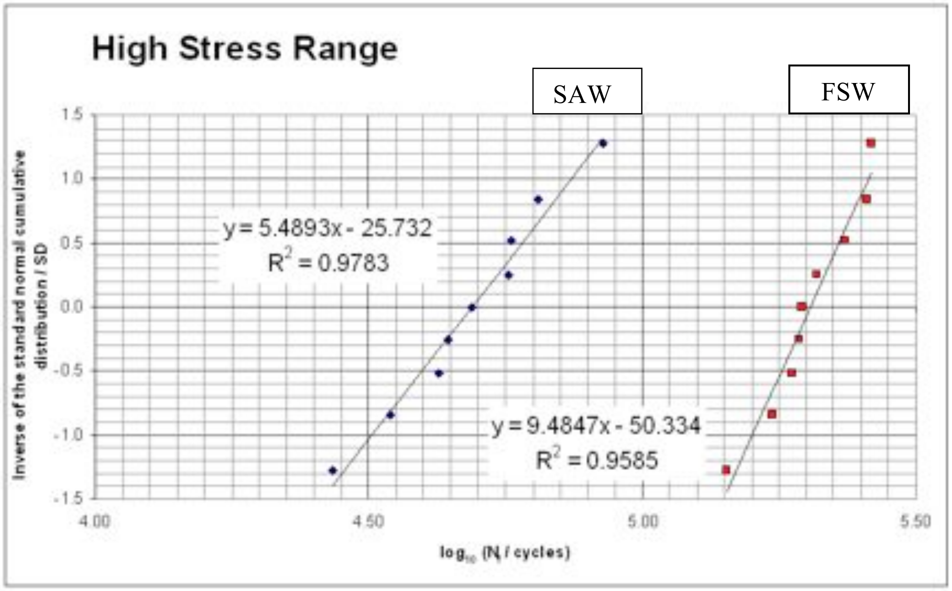


Fig.5 Fatigue testing results in the high stress range testing group

Discussion

The overall outcome of this study showed that FSW was a viable welding option to replace SAW when the parent plate was DH36 grade steel, and that there were no significant property issues. In fact, the FSW material performed better in a number of areas, particularly distortion reduction and enhanced fatigue properties.

However, at this stage of the friction stir welding process development there is a significant challenge in terms of process costs. This currently centres around the tool. It is quite clear that the issues related to tools become more challenging as the melting point of the material increases. In the case of structural carbon steel, the optimised tool material has not been arrived at. At present the tool cost contribution to one metre of weld would be about £100 ($150). This clearly does not outweigh the benefits to be obtained in the areas of distortion and fatigue. However, it is clear that although the cost of thev tool may not come down the lifetime of the tool will be extended, and in this manner the cost /metre will decrease.

Conclusions

From the data generated in this study, it is quite clear technologically that FSW is a superior process to the conventional SAW process.

The issues related to toughness by previous studies have been shown not to be of concern, from this study.

Fatigue performance is superior to SAW material.

The challenge to the FSW process is to develop a process that will economically challenge the SAW process, perhaps using the value added aspects of reduced distortion and superior fatigue performance.

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