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Fatigue performance of friction stir welded marine grade steel

Helena Polezhayeva [a], Athanasios I. Toumpis [b,*], Alexander M. Galloway [b], Lars Molter [c], Bilal Ahmad [d], Michael E. Fitzpatrick [e]

[a] Independent Consultant, 78 New Road, Chilworth GU4 8LU, United Kingdom
[b] Department of Mechanical & Aerospace Engineering, University of Strathclyde, James Weir Building, 75 Montrose Street, Glasgow G1 1XJ, United Kingdom
[c] Center of Maritime Technologies e.V., Bramfelder Str. 164, D-22305 Hamburg, Germany
[d] Materials Engineering, Department of Engineering and Innovation, The Open University, Walton Hall, Milton Keynes MK7 6AA, United Kingdom
[e] Faculty of Engineering and Computing, Coventry University, Priory Street, Coventry CV1 5FB, United Kingdom

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ABSTRACT

An extensive study on the fatigue performance of friction stir welded DH36 steel was carried out. The main focus of this experimental testing programme was fatigue testing accompanied by tensile tests, geometry measurements, hardness and residual stress measurements, and fracture surface examination. The *S–N* curve for friction stir butt welded joints was generated and compared with the International Institute of Welding recommendations for conventional fusion butt welds. Friction stir welds of marine grade steel exceeded the relevant rules for fusion welding. This newly developed *S–N* curve is being proposed for use in the relevant fatigue assessment guidelines for friction stir welding of low alloy steel. Fracture surfaces were examined to investigate the fatigue failure mechanism, which was found to be affected by the processing features generated by the friction stir welding tool.

1. Introduction

Fatigue cracking in welded joints of structural components is a major cause of structural failure [1]. Therefore, most welded structures that are expected to experience fatigue loading are designed to satisfy fatigue strength requirements [2,3]. The cracks in conventional fusion welds are triggered by stress concentration due to changes of geometry, welding defects such as undercut, porosity, lack of fusion and cold laps, as well as residual stress, mechanical in-homogeneity and misalignments [3,4]. Satisfactory fatigue performance is achieved, among other means, by reduction in stress concentration of welded joints.

Friction stir welding (FSW) is an innovative welding technique which was patented by The Welding Institute and first introduced in 1991 [5]. Since its invention, the technique has mostly been used for aluminium alloys. Research has demonstrated the superior fatigue performance of FSW joints in aluminium as compared to those produced by fusion welding [6–8] due to significantly reduced stress concentration at a joint compared with fusion welding techniques.

A study [8] examined the influence of welding speed on fatigue strength of Al–Mg–Si alloy 6082. It was concluded that using a welding speed within the industrially accepted range has no major influence on the mechanical and fatigue properties of the FSW. However the fatigue performance of FSW was significantly improved at a very low welding speed, which is attributed to the increased thermal energy supplied to the weld per unit length. The results of fatigue testing of FSW were also compared with those for conventional arc-welding methods; MIG-pulse and TIG (Metal Inert Gas and Tungsten Inert Gas, respectively). The MIG-pulse and TIG welds showed lower static and fatigue strength than that of FSW. The effect of the welded surface finishing treatment on the fatigue behaviour of AA8090 FSW butt joints was studied by another publication [9] where the specimens subjected to surface finishing treatment demonstrated better fatigue performance as compared with the as-welded specimens.

The number of publications on the fatigue performance of FSW in low alloy steel is limited to those discussed herein. A study on FSW of DH36 steel was carried out to evaluate the mechanical properties (including fatigue strength) of the welds with a view to its possible application in the shipbuilding industry [10]. The researchers [10] investigated FSW of 4, 6 and 8 mm thick DH36 steel as compared with submerged arc welds. The conclusion was drawn on superior fatigue performance of FSW. It was also found that two FSW passes, one from either side, result in significant improvement in fatigue strength compared with that of single pass FSW [10]. Fatigue testing, tensile testing and hardness

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[*] Corresponding author. Tel.: +44 0141 574 5075.
E-mail address: athanasios.toumpis@strath.ac.uk (A.I. Toumpis).

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measurements were performed on double sided friction stir welds of S275 structural steel [11], where welding was carried out in air and underwater. It was shown that FSW carried out in air and underwater produced similar fatigue properties [11].

FSW of 4 mm thick GL-A36 steel was investigated with the purpose of evaluating the process for shipbuilding applications [12]. The fatigue resistance of parent material and FSW produced using various welding parameters, pre-welding conditions and tools were compared. The fatigue behaviour of FSW was similar to that of the parent material [12]. The fatigue properties of friction stir welded AISI 409 M grade ferritic stainless steel joints were studied elsewhere [13]. FSW demonstrated improved fatigue behaviour compared with the parent material, including crack propagation stage. This was attributed to the FSW dual phase, ferritic–martensitic microstructure, superior tensile properties and favourable residual stresses [13].

The marine and offshore industries face demands for increased service lives of offshore structures, so this makes FSW of steel a very promising technique as it allows to reduce local stress concentration therefore improve fatigue performance. Still, in order to offer steel FSW to industry as an alternative to fusion welding, the existing knowledge gap on the fatigue behaviour of steel FSW must be addressed. The current research advances the scientific understanding of steel FSW by developing novel *S–N* curve parameters with respect to low alloy steel for marine applications. For this purpose, an extensive industrial scale testing programme was undertaken, including fatigue and tensile testing, hardness and residual stress measurements, and examination of fracture surfaces. The latter is performed to relate the fatigue failure to the FSW microstructure and investigate the mechanism for crack initiation and propagation. The *S–N* curve for FSW in low alloy steel was constructed and compared to IIW recommendations [3] and the effect of longitudinal and transverse residual stresses has been assessed.

2. Experimental programme

2.1. Material and welding details

The test specimens were produced from 6 mm thick marine grade DH36 steel. This particular steel grade is widely used in ship structures, especially in stiffened panels. The chemical composition of DH36 as provided by the steel manufacturer is given in Table 1. The minimum acceptable mechanical properties for DH36 steel of thicknesses $\leqslant$50 mm according to Lloyd's Register rules [14] are outlined in Table 2.

Steel plates of 2000 mm × 200 mm × 6 mm were butt welded using a MegaStir Q70 pcBN-WRe tool for steel with scrolled shoulder (dia. 36.8 mm) and stepped spiral probe (5.7 mm length). FSW was performed at varying traverse and rotational speeds as indicated in Table 3. Each combination of traverse and rotational speed from Table 3 will further be referred to as 'slow', 'intermediate' and 'fast' welding speed. The welding speed combinations were selected as representative of a previous research [15].

Metallographic examination of the welds produced using slow, intermediate and fast speed has been discussed previously [16]. It was demonstrated that slow speed welding delivers a homogeneous microstructure with significant grain refinement in comparison to the parent material [16].

Table 1
Chemical composition of 6 mm thick DH36 steel (wt%).

C	Si	Mn	P	S	Al	Nb	N
0.11	0.37	1.48	0.014	0.004	0.02	0.02	0.002

Table 2
Minimum acceptable mechanical properties of 6 mm thick DH36 steel [14].

Grade	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Charpy V-notch impact tests Average energy at −20 °C (J)	
				Longitudinal	Transverse
DH36	355	490–620	21	34	24

Table 3
Welding parameter sets.

Welding speed group	Slow	Intermediate	Fast
Traverse speed (mm/min)	100	250	500
Rotational speed (rpm)	200	300	700

2.2. Specimens

The specimens for fatigue and tensile tests were transversely machined from welded plates. The shape and dimensions of the specimens are shown in Fig. 1.

The specimen sides were polished up to a surface finish of 0.2 μm R_a or better, according to the applicable British Standards [17] to avoid fatigue crack initiation from the machining marks. To ensure that the required surface roughness was achieved, surface roughness measurements were performed using a Mitutoyo system. The top and bottom surfaces of the specimens (where the top surface is the tool contact surface) were left in the as-welded condition, and a subsequent assessment of the linear and angular misalignment (distortion) showed that these were negligible.

Three specimens per weld speed were subjected to tensile testing in order to identify the yield strength (YS) of the weldments. The average YS value for the intermediate weld speed was 382 MPa; this value was used to calculate the applied loads for fatigue testing.

2.3. Hardness measurements

A homogeneous hardness distribution in welds is important from a fatigue point of view as abrupt changes in hardness produce a material notch [18]. Average hardness values were measured in FSW sections for each of the slow, intermediate and fast welds. The positions for measurements representative of the weld zone are given in Fig. 2. The measurements were taken using a Mitutoyo hardness tester by applying a load of 200 gf.

The hardness measurements for the three weld speeds are presented in Fig. 3, where the values are supplied as an average of two measurements per position marked in Fig. 2. In all relevant figures, AD and RT correspond to the advancing and retreating side of the weld respectively, whereas HAZ is the heat affected zone and TMAZ is the thermo-mechanically affected zone. As seen from Fig. 3, the steel that is affected by the welding process is harder than the parent material. In addition, the hardness of the weld is increased with increasing welding speed. This can be attributed to the increasing cooling rate which causes the development of harder phases such as bainite. Microstructural examination [15,16] has discussed the rise in bainite content with each speed increment.

2.4. Residual stress measurements

The sample for residual stress measurements was transversely machined from a welded plate of 6 mm thickness. Fig. 4 shows