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Systematic investigation of the fatigue performance of a friction stir welded low alloy steel

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ABSTRACT

A comprehensive fatigue performance assessment of friction stir welded DH36 steel has been undertaken to address the relevant knowledge gap for this process on low alloy steel. A detailed set of experimental procedures specific to friction stir welding has been put forward, and the consequent study extensively examined the weld microstructure and hardness in support of the tensile and fatigue testing. The effect of varying welding parameters was also investigated. Microstructural observations have been correlated to the weldments' fatigue behaviour. The typical fatigue performance of friction stir welded steel plates has been established, exhibiting fatigue lives well above the weld detail class of the International Institute of Welding even for tests at 90% of yield strength, irrespective of minor instances of surface breaking flaws which have been identified. An understanding of the manner in which these flaws impact on the fatigue performance has been established, concluding that surface breaking irregularities such as these produced by the tool shoulder's features on the weld top surface can be the dominant factor for crack initiation under fatigue loading.

1. Introduction

There has been a growing number of studies demonstrating the feasibility of friction stir welding (FSW) of steel, producing defect-free welds, examining the microstructure and resultant mechanical properties of the welds, and concluding on the beneficial impact of this solid state joining process on the properties of welded steel components [1–8]. One representative publication [4] implements an extensive examination of FSW of DH36 steel in which an initial set of welding parameters that expand on the commonly applied welding speeds is developed through microstructural characterisation and mechanical property testing, and an understanding of the link between the complex metallurgical system that FSW of steel produces and the consequent mechanical properties is established; the higher strength and hardness of the welds is attributed to the greatly refined microstructure [4].

There remains however one important mechanical property of steel friction stir welds, fatigue, which requires to be investigated and reported. Fatigue of metals is a particularly significant property for numerous applications such as aerospace and marine [7], and is considered to be the most important failure mechanism for steels. It is commonly quoted for example that fatigue is responsible for almost 90% of all mechanical service failures [9]. In welded components, the weld itself contains process related flaws from which cracks can rapidly propagate. Thus, welding has been demonstrated as an undermining factor to the mechanical properties of such components; specifically under cyclic loading, welds are generally the dominant detail for fracture [10], also characterised as the critical design factor in shipbuilding [7]. In fusion welding, solidification cracking, i.e. minor inner cracks which can act as crack propagation sites during fatigue loads are considered unacceptable by international standards, hence need to be avoided [10]. Undercuts and lack of weld penetration are other examples of intolerable defects which are widely reported as highly detrimental features in terms of fatigue life [11]. Therefore, fatigue life of welded components is commonly much reduced when compared to components that are un welded. The efforts in extending the fatigue life of components are primarily concentrated on improvements in design [12]. International rules have been developed to implement specifications in the design of structural details, thus reducing the applied stresses particularly by minimising possible stress concentration regions [13].

The research on FSW of aluminium and other low melting point metals is quite extensive, with the process achieving a level of maturity [6]. It has been demonstrated that FSW is a viable option

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for welding aluminium alloys, for example in automotive, rail and aerospace applications where welded components need to operate in extreme conditions therefore high fatigue strength is a fundamental requirement [14], also allowing for the successful joining of Al-alloys that cannot be welded with conventional fusion methods [15]. Many publications on FSW of aluminium examine the weldments' fatigue strength; indicatively, Ericsson and Sandstrom [16] investigate the effect of varying welding speed on the fatigue performance of friction stir butt welded high strength Al6082 and compare this to MIG and TIG fusion welding. The fatigue strength of FSW is found to be practically unaffected by speed increasing within the industrially acceptable range, and FSW exhibit higher fatigue lives than the two examined fusion welding methods in the same stress range [16]. Other studies assess the process's defect tolerance and fatigue behaviour with regard to the weld root flaw [17] and the post welding top surface finishing [14]. Kadlec et al. [17] evaluate the effect of the weld root flaw ("kissing bond") on the FSW fatigue performance of a high strength aluminium alloy and attempt a quantitative analysis concerning this flaw's length. A critical weld root flaw length of approx. 300 μm is established; the welds' fatigue performance is seen to significantly decrease when a longer flaw is detected, hence becoming an unacceptable defect [17].

Although material property data are gradually being generated for FSW of high melting point alloys, the process has been slow to transfer to steel due to the more extreme conditions, mainly high flow stress and temperature, which are developed [6]. The relevant publications evaluating its behaviour in fatigue loading are very few [7] and seemingly small scale investigations. A comprehensive study [5] evaluating the technical potential of FSW as a shipbuilding welding process in comparison to submerged arc welding (SAW), a well-established technique in the shipbuilding sector, reports on an acicular shaped ferrite microstructure in the thermo-mechanically affected zone (TMAZ), consistent over the mid-thickness of all FSW samples, and a finer unspecified structure seemingly increasing with decreasing plate thickness. SAW samples present a typical acicular ferrite microstructure defined around proeutectoid ferrite grains. The study concludes that FSW of DH36 steel is feasible and moreover carries significant improvement in the mechanical properties of the welded components; specifically, the fatigue testing programme demonstrates that FSW samples exhibit better fatigue performance than the SAW samples of equivalent thickness. Impact toughness levels for FSW and SAW samples are noted to be similar and within classification society impact requirements. Further, analysis of the chemical composition of all welds reveals that SAW produces considerably different composition than the parent material (PM) due to the addition of filler material, whilst FSW results in no chemical segregation of the PM [5]. A further publication from the same research group compares double sided FSW of S275 structural steel in air and underwater in terms of the developed microstructure and resultant mechanical properties [6]. It is detailed that the TMAZ in both cases comprises refined ferrite grains produced by dynamic recrystallisation (DRX), smaller in air welding where slower cooling rate is expected, and dissociated pearlite. Fatigue testing (revealing comparable fatigue strength for air and underwater welds), tensile testing, and hardness measurements show that underwater FSW, an indispensable application for the marine sector, is not detrimental to the welds' mechanical properties apart from decreased impact toughness [6].

High quality welds of steel grade A36 are produced with pcBN and Tantalum-based FSW tools in a study assessing the mechanical properties and particularly the welds' fatigue performance with a focus on the shipbuilding sector [7]. Virtually no deterioration of the PM properties due to FSW is observed; tensile testing of the welds produced with the Ta-fabricated tool reveals higher yield strength (YS) than the corresponding of the pcBN tool. The fatigue lives of both groups of welds have not declined compared to the PM behaviour, with the Tantalum tool welded samples performing slightly better. The latter is attributed to the improved efficiency of this type of tool linked with suitably optimised welding parameters delivering an even hardness distribution throughout the weld zone [7]. On the relevant subject of fatigue crack growth rate, Pandey and Gupta [8] investigate friction stir butt welds of 3 mm thick mild steel. The weld YS is seen to be moderately increased compared to the PM but the elongation to fracture is reduced, due to the harder weld zone. It is concluded that the fatigue crack growth rates for FSW and PM are almost identical when using stress ratio (R) of 0.1, whereas the PM crack growth rate is higher for $R = 0.2$ [8].

A study on the FSW of AISI 409M ferritic stainless steel researches the welds' fatigue behaviour with regard to the PM properties [18]. FSW is seen to transform the original coarse PM grains into a refined ferrite/martensite banded structure of significantly higher hardness. The resultant dual phase microstructure is responsible for an improvement in the fatigue life compared to the PM; notably, friction stir welded samples present higher fatigue lives than the base material and improved resistance to crack propagation [18]. Despite being quite comprehensive, the examination of only 300 mm long welds at a noticeably slow welding speed (90 mm/min) weakens this study's merit. It is worthy of note that fusion welding reduces the desirable mechanical properties (ductility, toughness, etc.) of this alloy because of significant grain growth, whereas FSW can prevent these issues and achieve high quality welds by developing a highly refined microstructure; this represents an infrequently discussed positive effect of FSW [18].

Due to the significance of a solid understanding of the fatigue behaviour in supporting the acceptance of the process on steel within a wider industrial environment, the considerable potential of FSW in delivering high fatigue performance welds as concluded in the above discussed publications, and the lack of pertinent studies on low alloy steel, a detailed and extensive fatigue testing programme of steel grade DH36 FSW is undertaken. This original programme assesses the welds' fatigue behaviour by testing samples in constant amplitude uniaxial tensile loading, generating the *S–N* (stress-life) curve and comparing to international rules, also characterising the weld microstructure and analysing the fatigue samples' fracture surfaces; the experimental procedures and findings are reported herein.

2. Experimental procedures

There are no internationally accepted standards for the testing and assessment of welded components under fatigue [7], apart from guidelines. The lack of such standards is even more evident with regards to investigating the FSW of steel [18], a novel process. Thus, this study has formulated and observed a new standard operating procedure, i.e. a comprehensive set of guidelines for the fatigue assessment of FSW of steel. This allows for a fully compliant fatigue testing programme to be performed, and the various experimental stages are described below.

2.1. Material and welding details

The material under examination is steel grade DH36 with the nominal chemical composition presented in Table 1 (as supplied

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