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Development of a process envelope for friction stir welding of DH36 steel – A step change

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ABSTRACT

Friction stir welding of steel presents an array of advantages across many industrial sectors compared to conventional fusion welding techniques. However, the fundamental knowledge of the friction stir welding process in relation to steel remains relatively limited. A microstructure and property evaluation of friction stir welded low alloy steel grade DH36 plate, commonly used in ship and marine applications has been undertaken. In this comprehensive study, plates of 2000 × 200 × 6 mm were butt welded together at varying rotational and traverse speeds. Samples were examined microscopically and by transverse tensile tests. In addition, the work was complemented by Charpy impact testing and microhardness testing in various regions of the weld. The study examined a wide range of process parameters; from this, a preliminary process parameter envelope has been developed and initial process parameter sets established that produce commercially attractive excellent quality welds through a substantial increase in the conventionally recognised weld traverse speed.

1. Introduction

Friction stir welding (FSW), invented by Thomas [1] in December 1991, is a solid state joining process in which a constantly rotating, cylindrical-shouldered tool with a profiled probe is traversed at a constant rate along the joint between two clamped pieces of butted material. The probe is slightly shorter than the weld depth required, with the tool shoulder riding along the top of the work piece surface. The material is thermo-mechanically worked and heated high enough for plastic deformation to occur but well below its melting point. The basic concept of the process is shown in Fig. 1.

Frictional heat is generated between the tool and the work pieces. This heat, along with that produced by the mechanical mixing process and the adiabatic shearing within the material causes the stirred materials to soften without melting. As the tool is moved forward, a special profile on the probe forces plasticised material to the rear where clamping force assists in a forged consolidation of the weld. This process of the tool traversing along the weld line in a plasticised tubular shaft of metal results in severe solid state deformation involving dynamic recrystallization of the base material. FSW is a very complex multi-physics process incorporating mechanical and thermal processing of the material, considerable plastic deformation and high levels of flow stress; it is a process analogous to forging rather than casting which more closely resembles the conditions observed during conventional fusion welding.

FSW is currently being extensively employed in aluminium joining applications [2] but there is significant interest by many industrial sectors in transferring the process and its advantages to steel. Preliminary studies have demonstrated the feasibility of FSW of steel [3,4], while others have shown that there are several positive effects on the properties of friction stir welded steel plates such as considerable grain refinement, excellent fatigue properties and minimised distortion [5,6].

The current study is focusing on FSW of steel grade DH36, a low alloy steel utilised in the European shipbuilding industry among other sectors. For FSW of steel to become economically and technically viable for introduction in the shipbuilding industry, it should evolve into a process competitive with conventional fusion welding methods. In the shipbuilding sector, this requirement is translated into high welding speeds (in millimetres per minute) which produce welded joints of acceptable quality. Therefore, an optimisation study is a fundamental step towards this direction; that is, a study concerned with establishing the limits of the process (the

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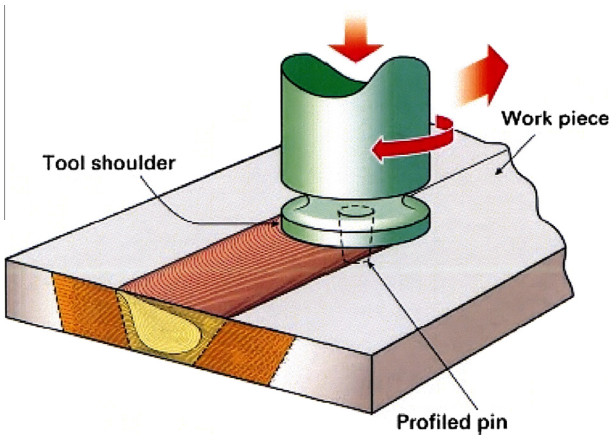

Fig. 1. The basic concept of friction stir welding.

process envelope) in terms of the two more significant parameters which can be directly controlled, tool traverse speed and tool rotational speed.

There are limited studies thus far for FSW of structural steel in the relevant technical literature, particularly for high welding speeds. In a well cited study from 2003, Reynolds et al. [4] examine friction stir single sided welds of hot rolled, 6.4 mm thick DH36 steel, produced by four different welding speeds in an inert gas environment, to assess the relationship between varying weld parameters and resultant weld properties. They [4] observe a bainitic and martensitic microstructure in the bulk of the thermo-mechanically affected zone (weld nugget) of the fast weld (450 mm/min). However, only this weld's microstructural features are reported therefore no comparison can be made to the intermediate and slower welds. The hardness of all welds demonstrates a continuous increase from parent material to nugget, with a variation of approximately 190 HV up to the peak hardness of the fast weld. The tensile tests reveal significant overmatching of all welds; longitudinal tensile tests show that the yield strength of all welds is higher than the parent material's ultimate tensile strength (UTS), and this is attributed to the weld nugget microstructure being very different from the original ferrite/pearlite microstructure. In all, weld hardness and strength is seen to increase with increasing welding speed. The effect of increasing rotational speed on weld properties is not considered in this study [4].

Further work [5] on the same grade of steel, DH36, extends the mechanical properties assessment of friction stir welded plates, also examining three different thicknesses (4, 6, and 8 mm) and comparing to submerged arc welded (SAW) plates of same thickness, in order to evaluate the potential of FSW as a shipbuilding welding process. McPherson et al. [5] observe an acicular shaped ferrite microstructure in the thermo-mechanically affected zone, consistent over the mid-thickness of all weld samples, and a finer unspecified structure seemingly increasing with decreasing plate thickness. The parent material is seen to consist of bands of ferrite and pearlite, as expected for rolled steel plates. Variations in hardness distribution are considered minor and certainly not expected to produce adverse effects. Likewise, impact toughness levels for FSW and SAW samples at −20 °C are reported to be similar and within classification society impact requirements. The focus of this study [5] is shifted towards the previously mentioned mechanical properties therefore the welds' tensile behaviour is not discussed in detail; all transverse tensile samples however fractured in the parent material. In conclusion, this study [5] supports sufficiently the argument for the capability of FSW to match shipbuilding requirements.

Ghosh et al. [7] study the friction stir lap welding of thin plates of high strength martensitic M190 steel by optical microscopy, tensile lap shear testing and micro-hardness testing. Their objective is to optimise the FSW of M190 steel in the automotive industry by assessing the resultant microstructure and mechanical properties produced by ten different sets of welding parameters, 600–1200 rpm rotational speed and 51–203 mm/min traverse speed, also applying forced air cooling. The researchers [7] find that with increasing traverse and rotational speed, the microstructure of the weld nugget becomes predominantly martensitic due to very high cooling rate. Bainite is seen to appear and gradually increase with the same rotational speed but slower traverse speeds, hence marginally lower cooling rates. They conclude that the temperature of the inner heat affected zone exceeded the steel's lower transformation temperature (A_1) during welding, thus austenite transformed into ferrite and pearlite during cooling. Still, the outer heat affected zone temperature remains below A_1 therefore exhibiting tempered martensite because of the martensitic parent material and the amount of heat dissipating through this region. The results of the tensile shear tests show that all samples fractured in the vicinity of the inner heat affected zone that seems to be the weakest region due to its ferrite-pearlite microstructure. Ghosh et al. [7] however do not proceed in developing new sets of parameters which will improve the mechanical properties of the weld zone, consequently weakening their case for an optimisation study.

In an investigation into the possible use of FSW as an alternative to electric resistance welding of API X100 grade high strength linepipe steel, Cho et al. [8] examine its microstructural evolution during friction stir butt welding after significant prior preparation of the plates. Their work is mainly focused on the grain structure development in a single set of process parameters, 127 mm/min and 450 rpm, using optical microscopy, scanning electron microscopy with electron backscatter diffraction and transmission electron microscopy. Starting from the parent material microstructure of dual phase ferrite and bainite, the thermo-mechanically affected zone is reported as having a very fine, homogeneous microstructure while the stir zone is acicular shaped bainitic ferrite rich. The former is attributed to continuous dynamic recrystallization, while the latter occurs because of the particular to this region austenite to ferrite phase transformation under high cooling rate and high strain. Possible heterogeneity of the weld is not discussed however as the microstructural assessment is concentrating only on the retreating side of the weld zone. The micro-hardness measurements [8] show that stir zone hardness is significantly higher than all other regions, mainly due to its developed microstructure. No other mechanical properties of the weld are presented.

There are many relevant optimisation studies for FSW of aluminium alloys including modelling, statistical analysis or experimental work [9–13], but most seem rather small scale projects when compared to the present work, and therefore cannot be transferred into FSW of steel. For example, Kumar and Kumar [10] attempt to optimise the FSW of two dissimilar aluminium alloys with regard to tensile properties and hardness of the weld, with no commentary on the microstructural evolution of the thermo-mechanically affected zone. They [10] also explore the effect of each parameter (rotational speed, tool tilt and type of tool pin) on these properties by percentage contribution, as derived from their statistical analysis. Kumar and Kumar [10] employ the Taguchi method to direct their analysis but this approach leads them to experimentally examine only nine sets of parameters; in fact, traverse speed, although highly significant, is not one of these parameters. Hence their conclusions are vague and limited.

Ghosh et al. [13] investigate the FSW process on two dissimilar aluminium alloys for optimised strength and formability by developing appropriate sets of parameters (rotational speed and traverse speed). They conclude [13] that components welded at