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The potential adaptation of stationary shoulder friction stir welding technology to steel

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ABSTRACT

Stationary shoulder friction stir welding is a newly developed technique currently used for joining plates of relatively soft metals at different angular planes. The process is not currently applicable to steel, hence the present study was developed to investigate the theoretical and technical viability of stationary shoulder technology in DH36 steel. Aluminium welds were produced using both conventional rotating shoulder and stationary shoulder friction stir welding techniques, and steel welds were produced using only conventional friction stir welding techniques. The effects of stationary shoulder technology on both the microstructural evolution and resultant mechanical properties of aluminium have been evaluated so that the likely effects on steel could be predicted. In the aluminium welds, the stationary shoulder technique results in a distinct transition between stirred and unstirred material, contrasting to the gradual change typically seen in conventional friction stir welds produced with a rotating shoulder. An investigation of weld properties produced in DH36 steel has demonstrated that if the stationary shoulder weld technique was used, the microstructure likely to be formed, would be dominated by a bainitic ferrite phase and so would exhibit hardness and tensile properties in excess of the parent material. It is predicted that if the same abrupt transition between unstirred and stirred material observed in aluminium occurred in steel, this would lead to crack initiation, followed by rapid propagation through the relatively brittle weld microstructure. Hence, these findings demonstrate that without further design and process improvements, stationary shoulder friction stir welding is unlikely to be applicable to steel.

1. Introduction

Friction stir welding (FSW) is a solid state joining process that develops a localised thermo-mechanically affected zone in the weld region [1]. The basic FSW process involves a specially designed, non-consumable, rotating cylindrical tool comprising a shoulder and a protruding pin that is of a length typically just less than the thickness to be welded [1–3]. The rotating tool is plunged downwards into the joint before being traversed along it. During the plunging phase of the process, the material is plasticised as a result of frictional heat generation [2]. However, temperatures are always maintained below the melting point, hence the solid state nature of the process [4]. The localised heating is facilitated in two ways; firstly as a result of friction between the rotating shoulder and the face of the work piece; and secondly, due to the visco-plastic dissipation of mechanical energy within the material [1,2,5]. As a result of the rotation and translation of the tool, the plasticised material is moved around it, from front to back, before being locally forged to form the welded joint [1–3].

The initial development of FSW focused on aluminium alloys, in particular those considered problematic when joined by conventional fusion welding processes [1,2]. In such alloys, the solid state nature of FSW leads to a number of benefits in terms of the mechanical and metallurgical properties of the resultant joint. For example, since there is no melting of material, the issues typically associated with solidification do not present a problem [1]. There cannot be solidification cracking, nor elemental segregation, hence the formation of brittle phases due to terminal eutectic type reactions does not occur. Since there is no molten weld pool, porosity due to gas trapped within it cannot occur [5]. In addition to the absence of these defects typically associated with fusion welding processes, friction stir welds have been documented to have excellent mechanical properties as well as demonstrating low levels of distortion and residual stress [1,5].

As the benefits of FSW have been reported, the technique has found application in various industries using a variety of different materials [5], including extensive use in the aerospace industry where the joining of light alloys which derive their mechanical

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properties from the precipitation of strengthening particles is crucial [6]. It is only in very recent years that this technology has been adapted to perhaps one of the most promising applications. the FSW of carbon and stainless steels [4]. FSW of steels has only been recently realised primarily as a result of issues in tooling material selection and development. The tool must exhibit high strength, wear resistance, fracture toughness and a resistance to chemical degradation all at the high temperatures associated with FSW [7–9]. Hence, finding a material which meets all of these requirements whilst producing industrially useful weld lengths has proved to be a significant engineering challenge, with studies being carried out into various ceramic options [7]. However, composite poly-crystalline Boron Nitride/Tungsten–Rhenium (pcBN/W–Re) tools are now becoming commercially available and facilitate FSW of steels [4].

FSW has found extensive use in the aerospace industry, where T-joints are a common geometry and are employed for the attachment of a structural stiffener to the main panel [6,10]. Both Fratini et al. [6] and Acerra et al. [10] utilised FSW technology to manufacture such a T-joint. This involved the pin of the FSW tool penetrating through the thickness of the skin and into the stringer. In addition, a specialised die was required to provide the localised forging of the plasticised material and hence the desired fillet radius. In both cases, the importance of the process parameters (tool rotation and traverse speed) were noted and macroscopic defects such as tunnelling were seen in the instances where these parameters were outside of optimum [6,10]. Furthermore, Acerra et al. [10] observed deleterious effects attributed to the coating applied to the materials. Moreover, Fratini et al. [6] conducted bend tests and deemed the behaviour to be unsatisfactory with cracking evident at "*very low values of bending angle*" [6].

Recent developments in FSW tooling technology may provide an alternative method for producing such T-joints. As reported by Martin et al. [11], the use of a shaped stationary shoulder allows for the joining of plates which are at different angular planes and schematics of both conventional rotating shoulder and stationary shoulder techniques are shown in Fig. 1(a) and (b). This methodology does not result in the undercutting of the skin as reported by Acerra et al. [10]. As the shaped shoulder provides the localised forging of the plasticised material, it is reasonable to conclude that defects such as the ligaments noted by Steel et al. [12] are unlikely to be present. Stationary shoulder friction stir welding (SSFSW) does not inherently provide a fillet radius in a T-joint and thus from a loading perspective, the joint may be subject to significant stress concentration. Therefore, as reported by Martin et al. [11], a filler wire may be incorporated into the joint by forcing this additional plasticised material into the weld. However, there is no published research outside of that presented by Martin et al. [11] into the mechanical properties of the weld produced using SSFSW technology.

There is significant demand to adapt the FSW technology to carbon and stainless steels and it is therefore envisaged that there will soon be an increasing requirement for producing T-joints in steels. As discussed by Steel et al. [12], the shipbuilding industry would find significant application for such advancement in the attachment of longitudinal stiffeners to plate, where low distortion and minimal re-working is key and hence the FSW process would be ideally suited.

The adaptation of SSFSW technology to steel has not yet been achieved and its realisation is likely to be highly dependent upon the development of a tool capable of facilitating such a weld. Tool material selection for higher plasticisation temperature metals has been the subject of previous studies [4,9] and initially tool materials were categorised into either refractory metals (such as W–Re) or super abrasive tools (such as pcBN) [9]. In recent developments, manufacturers have combined these in the form of composite pcBN–WRe tools.

The problem envisaged for SSFSW of these higher temperature plasticisation materials (ferrous and nickel based alloys) is that without the presence of a shoulder, tool rotation speed will need to be higher in order to generate the same frictional heating that is required to sufficiently plasticise the material. It is predicted that this higher rotational speed will lead to increased wear and failure rates even in the pcBN–WRe tools. Hence, as discussed by Sorensen and Nelson [9] in the development of early W based tools, preheating of the tool or initial pilot hole drilling may be required.

If SSFSW is to be achieved for steel, and assuming that a tool capable of producing such a weld could be developed, it is important that the microstructural evolution and hence mechanical properties of the resultant weld are predicted and understood.

The aim of the present investigation is to determine if the transfer of SSFSW technology to steel would be technically viable, and to assess what would be the likely metallurgical features and hence mechanical properties resulting from the application of SSFSW to steel. In order to assess the transfer of stationary shoulder technology to steel, it was necessary to determine the characteristic effect

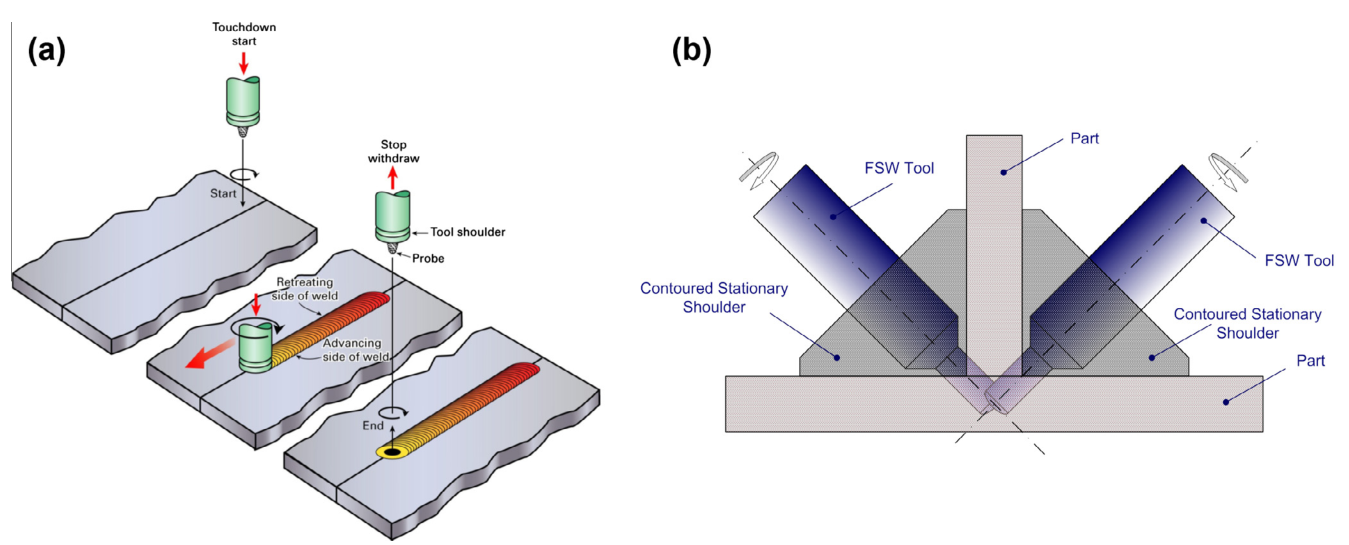

Fig. 1. Schematics showing: (a) conventional rotating shoulder, (b) stationary shoulder friction stir welding techniques. Image reproduced with permission from TWI.