Development of a welding platform and tool for the study of weld and process parameters, during continuous friction stir welding of AA6082-T6 sheets

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Abstract. Bobbin tool friction stir welding is a relatively novel technology whose application, despite its benefits, is still limited due to unfamiliarity presented by less published literature. Advantages associated with the bobbin-tool technique lie imbedded in the resultant double-sided processed zone, of somewhat rectangular cross section, along the joint line. Currently, the joint integrity benefits are overshadowed by high setup costs associated with slightly more complex tool and platform designs of bobbin-tool friction stir welding. To largely exploit and optimise the technique, there is need for an in-depth understanding of interaction between welding parameters and response variables. This comprehension could assist with process optimisation, reproducibility, automation and possibly process economic feasibility. This paper proposes design considerations with regards to development of a continuous solid-state welding platform and tool, for instrumentation of process output variables. As an instance, upon tool and platform development, calibration and verification, data acquisition of weld forces developed during bobbin-tool friction stir welding, as a function of process time, can then be implemented to enable analysis. Feasibility of the proposed methodology is then left for evaluation in future work. Thus, analysis of weld forces can be facilitated by the design and development of an instrumented fixture and a bobbin friction stir welding tool, in joining AA6082-T6 aluminium plates.

1. Introduction
Friction Stir Welding (FSW), is a welding technique both invented and patented by The Weld Institute (TWI) in Britain, in the 1990s that involves the traversing of a rotating and wear-resistant weld tool along the weld interface of two metals [1, 2]. Dynamic contact friction between the tool and workpiece material and the resulting material plastic deformation, generate heat required to soften, stir and join the material, in solid state via a weld nugget. Material stirring, facilitated by the tool’s material mixing features, is done under the effect of a weld-consolidating forging force. Forging force continuously applied to the material by the welding machine spindle through the welding tool during welding, is counter-acted by the support given by a backing anvil or plate. A typical FSW tool consists of a pin, or probe, and either one shoulder in the case of conventional FSW (CFSW) or two shoulders in the case of self-reacting tool FSW (SRFSW). The latter FSW variant, SRFSW, is alternatively known as bobbin tool FSW (BFSW). Figure 1 illustrates these two approaches, along with the accompanying tool configurations.
Figure 1. Illustration of two FSW variants; (a) CFSW (b) BFSW. [3]

Owing to its simple tool design, CFSW remains dominant in both published literature and industrial applications. Sued MK and Pons DJ [4] report that CFSW is best suited to welding thicker materials and is associated with the potential of root flaws due to incomplete tool pin penetration. Unlike the conventional tool, the bobbin tool design is characteristically more complex, owing to the increased number of variables affecting weld quality, especially for thin materials [4]. Presently, less is understood about the complex nature of these relationships existing among the variables and resulting weld quality. Furthermore, a study carried by Sued MK et al. reveals that tool features and tool dimension heuristics are not directly transferrable from CFSW to BFSW, not without compromising process variables and tool part functionality [5]. Therefore, literature is yet to develop a model linking weld variables like weld speed and tool geometry to response variables like weld forces and the resulting weld quality. These limiting factors combined with additional set-up costs, commensurate with complex platform and tool design and development, consequently delay and discourage ready adoption of BFSW.

CFSW is generally associated with the potential of root flaws formation, unbalanced heat input and high process forces (vertical), requiring rigid workpiece support and clamping. Conversely, BFSW eliminates the net vertical forces along with the need of a backing plate at the weld interface. Process forces on fixtures and the FSW machine itself are reduced. Moreover, risks of root flaws and unbalanced weld distortions are eliminated. Balanced heat input profiles, higher peak temperatures and cooling rates are attainable, at a low heat input and an improved weld processing speed [6]. Finally, finer microstructure formed in the stir zone of BFSW samples, result in higher hardness values and slightly higher tensile strength. FSW in the past decades, has been successfully implemented in automotive, aerospace and shipbuilding industries. FSW has been attaining increasing application where non-ferrous metals have replaced steel as structural material, [1, 7]. This adoption of FSW as a preferred alternative with non-ferrous metals can be explained by the fact that, other welding techniques like MIG, TIG and spot welding, are either difficult or impossible to implement, for such metals. Despite the seemingly successful and widespread implementation of FSW, there remains a space for improvement, to further optimise process efficiency and fully exploit its benefits, using BFSW techniques. Focus of this paper forms a subsection of an ongoing project focused on automatic control of the continuous BFSW of long aluminium alloy sheets, as used in the marine industry. This is to be accomplished by making use of a short bed bolt-on extrusion feeder providing workpiece feed to a rotating spindle, using the TWI’s floating-bobbin tool concept and an FSW machine, as illustrated in Figure 5. The paper seeks to address the implementation of a system that enables analysis of variation of weld variables, especially separation forces, with process parameters; tool geometry, tool rotational and welding speed. Design considerations accompanying platform and tool development, for resistance to and instrumentation of weld forces, are examined.
2. Experimental Setup

2.1. Workpiece Material
Whilst almost any aluminium alloy can be used as substrate, AA6082-T6 plates 3mm thick were considered as base metal (BM), with workpiece dimensions of surface area of 110 mm x 400 mm each, in accordance with the ASTM B 557M-02a standard tensile testing sample sizes. Table 1 and Table 2 show respectively, the chemical composition and mechanical properties of the plates to be welded. AA6082-T6, being a high strength and light weight 6xxx series alloy, is often used for structural purposes. Its typical applications include highly stressed applications in trusses, bridges and transport systems. As such, high specific strength coupled by corrosion resistance [7], make AA6082-T6 preferable for marine applications.

| Elements | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
|----------|----|----|----|----|----|----|----|----|----|
| Base Metal | 0.92 | 0.445 | 0.05 | 0.61 | 0.75 | 0.05 | 0.142 | 0.065 | Bal |

Table 1. Chemical composition of AA6082-T6 (wt. %).

| Material | Yield Strength (MPa) | UTS (MPa) | Elongation (%) | HV (0.5 kg) |
|----------|----------------------|-----------|----------------|-------------|
| Base Metal | 255 | 318 | 9 | 95 |

Table 2. Mechanical properties of AA6082-T6.

2.2. BFSW tool development

2.2.1. Tool features. On the developed platform, to manufacture butt welds, bobbin tools were designed and developed. Tool configurations shown in Figure 2 and Figure 3 as Tool 1 and Tool 2, whose features and dimensions are displayed in Table 3 were adopted. Both tools feature scrolled bottom and upper shoulders and a 2.9 mm cylindrical, threaded and tri-flat probe. In consultation with existing literature [2, 5, 6, 8-12], effort was made to formulate an optimal bobbin tool design, to enhance the overall process efficiency and resulting butt weld quality. As an illustration, Casalino et al. [13] report that there is need for shoulder diameter optimisation, especially with regards to heat transfer and material flow. This is proposed due to the significant influence certain geometry features have on thermal cycles (peak temperature) and the required process power and torque. Thus, special tool features selected were recommended for better material mixing, essential for defect tolerant welds. Shoulder scrolls minimize flash formation and eliminate the tool tilt angle [12] whilst flats and threads promote material flow and circulation. Owing to tool (shoulders and probe) size limitations, Sued MK et al. assert that these special tool features, are difficult to fabricate and are rarely used in welding of thin materials [4]. In practice, when incorporated into design, additional costs are incurred. A case in point is the cost of fabrication, which rapidly escalates with the reduction of tool size and the complexity of features. K110 tool steel was selected as the bobbin tool material because of its good compressive strength, dimensional stability in heat treatment, adhesive and abrasive wear resistance, all necessary for high integrity welds.

| Tool | Shoulder diameter, D (mm) | Probe diameter, d (mm) | Probe thread pitch, p (mm) |
|------|---------------------------|------------------------|---------------------------|
| 1 (D₁, d₁, p₁) | 14 | 6 | 0.8 |
| 2 (D₂, d₂, p₂) | 17 | 8 | 0.8 |

Table 3. BFSW Tools 1 and 2 geometrical parameters.
2.2.2. Floating mechanism. The main components of the bobbin tool are as shown in Figure 3, a tool holder (sleeve) and the welding tool. The welding tool is attached to the tool holder, via a slot, a slot key and a floating mechanism. The floating mechanism comprises of two (compression and tension) mechanical springs, of identical compliance. The floating capability of the bobbin tool enables mechanical auto-alignment of tool with workpiece during welding, eliminating the need for accurate setup procedures and sophisticated force control systems [2]. Essentially, the floating feature ensures continuous contact between tool shoulders and the plate surfaces during welding. Misalignment could possibly cause the tearing away of the thin plate weld material or the excessive formation of flash.

2.3. Design of Experiments.
To facilitate data acquisition and analysis of process variables, in future work, welds will be done on a specialised PDS Rotary friction welding machine, in position-control mode, according to the test matrix shown in Table 4. Preliminary tests to establish the weldability window, with respect to weld quality and weld variables will be conducted first, to confirm the test matrix selected. Table 5 summarises control variables and corresponding magnitudes where applicable, to be used in these experiments. Table 3, Table 4 and Table 5, show that the main process variables considered in the tests would be (1) tool geometry, (2) weld speed and (3) tool rotary speed. It can also be noted from Table 4 and Table 5 that focus of the study would be limited to fast welds in a bid for process optimisation for industrial applications. Additionally, literature associates faster travel speeds with high integrity and reduced weld forces. Fast welds also naturally result in cold welding conditions and short processing times.
Table 4. Test matrix.

| Tool | Speed, $v$ (mm/min) | Speed, $n$ (RPM) |
|------|----------------------|------------------|
|      |                      | 800              | 1200             | 1600             |
| 1    | 800                  | Test 11          | Test 12          | Test 13          |
| 1    | 1200                 | Test 14          | Test 15          | Test 16          |
| 1    | 1600                 | Test 17          | Test 18          | Test 19          |
| 2    | 800                  | Test 21          | Test 22          | Test 23          |
| 2    | 1200                 | Test 24          | Test 25          | Test 26          |
| 2    | 1600                 | Test 27          | Test 28          | Test 29          |

Table 5. Control variables.

| Variable                              | Value                       |
|---------------------------------------|-----------------------------|
| Workpiece material                    | AA6082-T6                   |
| Workpiece thickness                   | 3.0 mm                      |
| Workpiece curvature                   | 0.0 deg                     |
| Weld length                           | 400 mm                      |
| Weld condition                        | Cold, Fast                  |
| Dwell time                            | 5.0 s                       |
| Start-up parameters: Feed, Speed      | 1.75 mm/min, 1400 rpm       |
| Tool tilt angle                       | 0.0 deg                     |
| Tool pin flats, shoulder scrolls       | 3, 3                        |
| Pin thread depth                      | 1.0 mm                      |
| Pin thread pitch                      | 0.8 mm                      |
| Pin flat depth                        | 0.5 mm                      |
| Shoulder gap/pin length (@ 3.33% interference) | 2.9 mm |

2.4. BFSW Platform development

2.4.1. Design and Instrumentation. Due to the tool-workpiece interaction, transverse, longitudinal and axial mechanical forces are generated. In BFSW, the resultant axial force experienced by the spindle is approximately zero since equal and opposite axial forces contained between the two shoulders cancel out. Therefore, only longitudinal and transverse forces are expected to show a marked variation with process variables. A mild steel welding and Load-cell platform shown in Figure 4 was designed and developed to meet the various force measurement and clamping requirements during BFSW. One backing plate was mounted on linear guides, as the other was constrained, to effect a sliding contact between one backing plate and the common base plate. Done in a way that supports only infinitesimal movement whilst rigidly clamping the workpieces in place, the micro-strains generated during welding would be detected by three force transducers. Each of the three transducers were installed against the sliding backing plate, along the weld direction. Rigid clamping resists plate separation forces during welding, whose effects compromise weld quality and whose magnitudes can be measured and ascertained, under different welding conditions. Force transducers therefore, measure the transverse forces experienced by the clamping system on the platform, during welding. Transducers consist of full-bridge configuration gage installations of four active gages, two in compression and two in tension, during force detection. This configuration is more immune to apparent strain arising from temperature variations during welding. Each gage is connected as a resistor in the Wheatstone bridge circuit, registering any strain variation as voltage variation. The strain variation can then be mapped to the corresponding force variation, from calibration readings. Other accompanying weld forces, namely longitudinal and axial, can be measured by the PDS machine’s internal sensors.
2.4.2. **Data Acquisition.** Weld forces data acquisition can be provided for by the SoMat eDAQ field computer and the PDS machine’s data logging system. Calibration of the platform is achieved by an application of dead weight loads to the Figure 4 platform and noting corresponding gage strain readings.

3. **Discussions and conclusions**

Weld forces encountered in practice during FSW, are enormous enough to warrant concern. As a result, clamping forces to counteract them and arrest the undesirable effects of their development are necessary for every friction stir welding operation. For instance, separation forces must be resisted accordingly, to avoid compromising the weld quality through enlargement of the weld gap during welding. This often limits the implementation of continuous FSW, hence drastically reducing the efficiency and feasibility of the overall process. Sued MK et al. postulates that process settings such as clamps, support arrangements and shoulder gap create compression, vibrations and heat distributions, hence influence weld quality. For that reason, implementation of continuous FSW requires an address and investigation of weld forces and the complex relationships that exist among them, weld variables and weld quality, to enable efficient clamping and fixturing during welding. Such invaluable information would assist with process optimisation, automation and adaptive control. This observation is also concurred by Forcellese et al. [14]. An important consequence of these gains would be improved productivity through reduced processing and setup time. Other possible benefits would be improved weld quality and better process reproducibility. Additional benefits, particular to the methodology pursued and illustrated in Figure 5, may include easy handling of material before and after welding whereby rolls can be used for wrapping and storage of material. The developed platform and bobbin tool facilitate investigation into these issues.

Although less is known concerning the relationships governing variation of the weld forces and the weld quality with weld variables, artificial intelligence can be used to aid analysis and model such, making predictions possible. As data of this variation becomes available, implementation of continuous BFSW may be facilitated by use of derived control algorithms to control actuators providing workpiece feed and clamping. There yet remains many possibilities of process implementation and employment, to fully reap benefits of the FSW technology. It is the opinion of the authors that continuous bobbin friction stir welding presents a new methodology for achieving higher production rates for solid state butt welds and as such platform and tool development facilitating its investigation is necessary. BFSW process heuristics can also then be formulated, adding to the existing limited body of knowledge.
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