FIXED BOBBIN FRICTION STIR WELDING OF MARINE GRADE ALUMINIUM

By

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To my late father Sued Abd Hamid which was there at the early stage of the studies, thank you for your motivation and encouragement, I miss you a lot.

To my wife Noor Rosida Arifin, my son Muhammad Izzuddin Hakim and my daughter Nur Aisyah Husna for your love, belief and patience.

To my mother Zainon Yg Mohd Yusoff and my siblings Mohd Shukri Hadafi, Norashikin and Nabilah Munirah for your continuous support.

A special thanks to my wife for her sacrifices, in helping me to support the family just in order to make us live comfortably while I’m focusing in my studies.

Without these would not have been this possible.
ABSTRACT

PROBLEM - The bobbin friction stir welding (BFSW) process has potential benefits for welding thin sheet aluminium alloy. The main benefits of friction stir welding over conventional thermal welding processes are minimisation of energy usage, no need for consumables, potential for good weld quality without porosity, no fumes, minimal adverse environmental effects (green), minimal waste (lean), and reduced threats to personal health and safety. The BFSW process has further advantages over conventional friction stir welding (CFSW) in the reduction of welding forces, faster welding, and less fixturing. It is especially attractive to industries that join thin sheet material, e.g. boat-building. The industrial need for this project arose from the desire to apply the technology at a ship manufacturing company, INCAT located in Hobart, Tasmania, Australia. However there are peculiar difficulties with the specific grade of material used in this industry, namely thin sheet aluminium Al6082-T6. Early efforts with a portable friction stir welding machine identified the process to have low repeatability and reproducibility, i.e. process-instability. There are a large number of process variables and situational factors that affect weld quality, and many of these are covert. This is also the reason for divergent recommendations in the literature for process settings. PURPOSE - The main purpose of this research was to identify covert variables and better understand their potentially adverse effects on weld quality. Therefore, this thesis investigated the hidden variables and their interactions. Developing this knowledge is a necessity for making reliable and repeatable welds for industrial application. APPROACH - An explorative approach that focused on the functional perspective was taken. An extensive empirical testing programme was undertaken to identify the variables and their effects. In the process a force platform and BFSW tools were designed and built. A variety of machine platforms were used, namely portable friction stir welding, manual milling machine and computer numerical control (CNC) milling machine. The trials were grouped into 14 test plans. These are tool shoulder gap, spindle and travel speed, tool features, machines, tool fixation, machinery, welding direction, plate size (width and dimension), support insulation, tool materials, substrate properties and fixation. For the welded plates besides visual inspection of the weld, current, force, and temperature were measured. The Fourier transform was used to analyse the frequency response of machines. Also the welded samples were tested to the maritime standards of Det Norske
Veritas (DNV). A number of relationships of causality were identified whereby certain variables affected weld quality. A model was developed to represent the proposed causality using the IDEF0 systems engineering method. **FINDINGS** - From these trials six main variables have been identified. These are tool features, spindle speed, travel speed, shoulder gap compression, machine variability, tool and substrate fixation. A rigid system is required for a consistent weld results. Under this condition, full pin features (threads and flats) need to be used to balance the adverse effects of individual features. It has been shown that fabricated bobbin tools with sharp edges can cause cuts and digging thus this feature should be avoided. Additionally, the substrate should have continuous interaction with the tool so the shoulder interference needs to be fixed and well-controlled. It is found that the compression generated by the shoulder towards the substrate helps material grabbing for better tool-substrate interaction. It is also shown that tool entry causes ejection of material and hence an enduring mass deficit, which manifests as a characteristic tunnel defect. The new explanation of the formation, origin and location of this defect has been explained. Material transportation mechanisms within the weld have been elucidated. It is also found that the role of the travel speed is not only to control heat generation but also for replacing the deficit material. Additionally, heat supplied to the weld depends not only on thickness, but also the width of the plate. Different types of machine cause an interaction in the material flow through their controller strategies. Jerking motion can occur at a slow travel speed, which also alters the way material is being transported. The Fourier transform (FFT) has been used to identify the characteristics of good and bad BFSW welds. This has the potential to be expanded for real-time process control. **IMPLICATIONS** - Tool deflection and positioning, material flow and availability are identified as affecting weld quality through stated mechanisms. The impact is even more severe when involving thin-plate aluminium. For the industry to successfully adopt this technology the process typically needs tight control of shoulder gap, tool strength and stiffness, feature fabrication, substrate and tool fixation. Additionally spindle and travel speed need to be adjusted not only based on the type of materials and thickness, but also the width, type of machine and method of tool entry. **ORIGINALITY** - New data are presented, which lead to new insights into the welding mechanics, production settings, material transportation and weld defects for BFSW on thin sheet material. The conventional idea that the welding
tool has a semi-steady interaction with the substrate is not supported. Instead the interaction is highly dynamic, and this materially affects the weld-quality, especially in the difficult-to-weld material under examination. Factors such as shoulder gap, tool and substrate fixation compliance and machine types emerge as variables that need to be given attention in the selection of process parameters. The causal relationships have been represented in a conceptual model using an IDEF0 system approach. This study has made several original contributions to the body of knowledge. First is the identification of previously hidden variables that effect weld formation for the fixed gap BFSW process. The second contribution is a new way of understanding the material transportation mechanics within the weld. This includes the flow around the pin in the plane of the weld, the vertical transportation of material up the pin, the formation of turbulent-like knit lines at the advancing side, and the formation of tunnel defects. Also included here is a new understanding of how material deficit arises at tool entry and exit, and from flash/chips, and how this contributes to the tunnel weld defect. In addition, new understandings of the role of feed rate have been identified. Related to the material transportation, the work has also identified the importance of an interference fit between the substrate and tool. A third contribution is the identification of the dynamic interaction between tool and substrate. This identifies the important role rigidity plays. Associated with this is the identification of frequency characteristics of the motors under load. The fourth contribution is identification of the specific process settings for the difficult-to-weld material of AL6082-T6. The fifth contribution is the development of a novel method of fabricating bobbin friction stir welding tools as embodied in a patent application.
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ACADEMIC CONTRIBUTION

The following is a list of the outcomes that have been published/submitted/presented during the period of the doctoral study:

JOURNAL PAPER


- **M. K. Sued** and D. Pons, “Dynamic Interaction between machine, tool and substrate in bobbin friction stir welding” (*This paper has been submitted to a journal of manufacturing engineering*).

CONFERENCE/SYMPOSIUM PAPER


PATENT


SEMINARS/SHOWCASE/TALK


CHAPTER 1

INTRODUCTION

1.1 CONTEXT

Friction stir welding (FSW) as shown in Figure 1.1(a) is an emerging solid state joining technique that was invented at The Welding Institute (TWI) of United Kingdom in 1991. It represents an alternative welding technology process over fusion welding, e.g. Tungsten inert gas welding (TIG) and metal inert gas welding (MIG), Figure 1.1(b). These traditional joining techniques require close process monitoring, high energy consumption and labour involvement, and potentially provided poorer welded joints which require post processing work. This can be easily overcome by a FSW method. FSW also has the significant benefit of producing negligible fumes, no waste (slag), and no electromagnetic radiation (arc), and has thus sometimes been termed ‘green’ welding for its low environmental impact.

The technology has been relatively well developed for welding thick plates from one side. The most common application is to the joining of aluminium materials. However, it is still a specialised form of welding, and there are significant technological and process obstacles to be overcome for the wider adoption of FSW. There are particular issues regarding thin sheet material – which is a common joining situation in the fabrication industries- and certain types of materials. The reasons for the poor performance of FSW in these situations are poorly understood.

A typical industry that is a potential user of FSW technology is the shipbuilding industry. Many ships, such as fast ferries and light coast guard craft, are fabricated from aluminium for lightness. The material is in thin sheets and a large amount of welding is required. This having significant causes both financially and in terms of environmental impact. There is the potential for FSW technology to significantly improve these production aspects. Unfortunately, thin plate of a marine grade aluminium alloys is
particularly problematic to weld with a fixed bobbin tool of FSW. This is the problem to which this thesis is addressed.

The specific industrial impetus for this project came from a ship manufacturing company, INCAT located in Hobart, Tasmania, Australia. They build lightweight ships of various sizes for ferry operators, special service providers, and navies. One of INCAT’s world leading products is the Wave Piercing Catamaran, see Figure 1. INCAT has a dedicated 70,000 m² undercover production halls in Tasmania which can handle up to six vessels simultaneously in two dry-docks. This facility includes the ability to house construction of larger vessels of up to 112 metres in length [1]. To manufacture large and high performance ocean-going vessels requires high quality welding that complies with the strict maritime standards of Det Norske Veritas (DNV). At the same time, customer demands dictate short lead times and value for money. Due to these drivers, INCAT is constantly looking to develop and refine its fabrication and welding practices. They had a need to develop new tooling and welding procedures to achieve high weld quality at high deposition rates and at less cost and with less environmental impact.

At present traditional welding methods are widely used across INCAT’s facility. By adopting a FSW technique, INCAT can potentially achieve their intention of reducing cost through minimum labour, material and production time as well as improving quality at similar or higher strength than the traditional joining method. The reasons being that because there are no requirements for shielding gases, fillers and additional preweld preparation or cleaning processes [2-4]. Moreover the technology is regarded as a green technology, which gives additional advantage to INCAT’s eco-operations intention.
1.2 CHARACTERISTICS OF FSW

A defining characteristic of the FSW process is that frictional heat is generated between the wear resistant non-consumable welding tool shoulder and pin (Figure 1. 3), and the material of the workpieces. Under idealized conditions, there are three sources of heat generated: (a) heat from the mechanical mixing process, (b) swirling based material flow and (c) surrounding temperature. These cause the stirred materials to be softened and mixed [8]. The bonding is considered a solid state process, since the materials are not melted. Material flows which occur underneath the tool shoulder are similar to a forging process while the material flows around the tool pin mimic an extrusion process [9].
The key benefits of friction stir welding can be categorised in three ways, Mishra and Ma [9], as shown in Table 1. Additional benefits besides those listed in Table 1 are that FSW has the capability of joining dissimilar materials and different weld thickness [10, 11]. All these benefits are highly attractive in the production engineering environment.

In the current research arena, which is largely directed at the development and practical advancement of the FSW technology, researchers have tended to categorise the technology based on the tool design [12-18]. As shown in Figure 1.3, there are two fundamental categories of tool, below which are numerous sub-categories that are influenced by a range of tool designs or features. A FSW process that involves the usage of a single sided shoulder (Figure 1.3(a)) is known as conventional friction stir welding (CFSW), and a process that uses a double sided shoulder (Figure 1.3(b)) is known as bobbin friction stir welding (BFSW) or self-reacting friction stir welding (SR-FSW) [17, 19, 20].

Table 1.1: The benefit of Friction Stir Welding processes [9].

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<tr>
<th>Metallurgical benefits</th>
<th>Environmental benefits</th>
<th>Energy benefits</th>
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<tr>
<td>1. Solid phase process</td>
<td>1. No shielding gas required.</td>
<td>1. Improved materials use (e.g. Joining different thickness) allows reduction in weight.</td>
</tr>
<tr>
<td>2. Low distortion of workpiece.</td>
<td>2. No surface cleaning required.</td>
<td>2. Only 2.5% of the laser welds energy needed for the FSW.</td>
</tr>
<tr>
<td>3. Good dimensional stability and repeatability.</td>
<td>3. Eliminate grinding wastes.</td>
<td>3. Decreased fuel consumption in light weight aircraft, automotive and ship applications.</td>
</tr>
<tr>
<td>5. Excellent metallurgical properties in the joint area.</td>
<td>5. Consumable materials saving, such as rugs, wire or any other gases.</td>
<td></td>
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<tr>
<td>6. Fine microstructure.</td>
<td></td>
<td></td>
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<tr>
<td>7. Absence of cracking.</td>
<td></td>
<td></td>
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<tr>
<td>8. Replace multiple parts joined by fasteners.</td>
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Regardless of this categorization, the tool serves two important functional consequences [21]: (1) to heat the workpiece; (2) contain and direct the plasticized workpiece material.

Due to the limited information currently available on the emerging BFSW process, the background studies of the process are developed largely based on the counterpart CFSW process.

### 1.3 CONVENTIONAL FRICTION STIRRING WELDING (CFSW)

At the initiation stage of the CFSW process, the rotating tool is plunged into the abutting edges of the workpieces to be joined, whereby the shoulder has intimate contact with the top surface of the material while the pin is fully submerged into the material, as shown in Figure 1.4. The tool heats and stirs the material from the advancing side (AS) to the retreating side (RS) while traversing through the material, creating a joint line at the rear of the tool (refer to Figure 1.4 (a)). A problem occurring with this process is that the plates to be joined require extensive clamping both in the vertical and horizontal directions to prevent them being separated by the high forces exerted by the CFSW tool. In addition, a rigidly supported plate (also known as backing plate or anvil) is used to counteract the vertical force, see Figure 1.4 (b). This arrangement slows setup time and limits the thickness of parts that can be welded by this process.
CHAPTER 1: INTRODUCTION

Figure 1. 4: FSW setup (a) The illustration of FSW process [9].
(b) Schematic diagram of material setup [22].

Note that the Z axis is taken as perpendicular to the substrate surface, X is in the direction of the weld progression, and Y is transverse to the weld line, as in the figure above.

1.4 BOBBIN FRICTION STIR WELDING (BFSW)

The bobbin friction stir welding (BFSW) tool has two shoulders with one shoulder on the top surface and the other on the bottom surface of the weld plate, with a pin fully contained inside the material. This reduces the requirements of extensive clamping and setup prior to welding. The reason is because the normal down force imposed by CFSW is reduced and the reactive forces within the weld are contained between the bobbin shoulders. There are three forms of bobbin tool; fixed bobbin, floating bobbin and adaptive bobbin [17, 23, 24]. The definitions of these variants are explained as follows:

- Fixed bobbin - The gaps are fixed between the two shoulders throughout the process and the normal Z-axis movement of the tool can be either fixed or controlled based on system capability (Figure 1. 5 (a)).

- Floating bobbin - The two shoulders have a fixed gap throughout the process and thus produce balanced forces in the Z-axis (Figure 1. 5 (b)). However, the tool floats in the Z direction throughout the process.

- Adaptive bobbin (AdAPT): The adaptive technique enables adjustment of the gap between the shoulders during the welding operation while the tool floats in the Z direction (Figure 1. 5 (c)).
When floating or adaptive bobbin tools are used, the Z forces should be near to zero. In addition to the above tool configurations, there are also discussions by TWI about the development of double driven bobbin (top shoulder and bottom shoulder driven) which can also include an adjustable shoulder gap. These developments along with many others are closely guarded due to the intellectual property (IP) potential.

According to the TWI [23], the industrial uptake of bobbin tool FSW has been limited by a perception that the equipment required to implement is complex and expensive. This includes concern on ease of the technology implementation. However, the most basic configuration of bobbin tool application can be implemented on most of the currently available CFSW facilities; especially the fixed bobbin format.

1.5 DOUBLE SHOULDER VERSUS SINGLE SHOULDER

High clamping forces and proper setup prior to welding is essential for CFSW. The examples of common defects that can be found in CFSW due to improper process setup are incomplete weld penetration and support plate contamination (refer to section 2.6: Defects in Friction Stir Welding). Furthermore, when lower temperatures are produced during the process, the material flow from the advancing tool edge to the retreating tool edge cannot always be completed, hence defects such as tunnel and kissing bonds are produced [8, 25].
To maintain a sufficiently high welding temperature, it is generally believed that high welding spindle speeds and slow travel speeds are required. Interestingly, the present work indicates that this is an unreliable assumption, at least in the BFSW case, as will be shown later. The conventional CFSW tools typically run at a travel speed of 150 mm/min and spindle speed reached 1000 rpm [9]. Meanwhile, for BFSW as in the [18] 300 mm/min and 300 rev/min rotational speed for welding AA6082-T6 Aluminium Alloy was used.

Welding setup and weld defects are found to be minimized or eliminated when the bobbin tooling is introduced. The reason is because the presence of the double shoulders reduces the clamping forces and generates enough heat for stirring and mixing the materials in the weld region. Beyond this, the additional advantages of the BFSW process are listed. This is based on the understanding that obtained from both processes through literatures, example in [8, 14, 17, 20, 25-28].

The BFSW advantages:
(a) Ease of fixturing.
(b) Elimination of incomplete/partial root penetration.
(c) Spindle speeds lower than conventional tools.
(d) Allows increased tool travel speed due to the heating from both shoulders (up to 500 mm/min; refer to Appendix A1).
(e) Requires no backing bar/plate.

On the other hand, BFSW joints are found to have lower mechanical properties, with bigger and more uniform grain size when compared to CFSW. The reason for the drawback was mainly because of the higher temperature input supplied by the rotating tool to the substrate. However there is limited literature available in this area. The disadvantages or functional perspective is not adequately discussed making the research opportunity wide open.

1.6 PROBLEM STATEMENT

The present work was motivated by two main issues. First is the industrial need to adapt the technology to the welding of marine grade aluminium. The second is a need to better
understand the underlying mechanics in the weld and how they affect the production processes. These details are explained as follows:

(a) INCAT, a shipbuilding company in Australia, intends to integrate BFSW into their production facilities to butt weld 20km in total length of wet deck panels for each large wave-piercing catamaran, from corrugated sections 11 meters in length. Currently, extruded 6082-T6 series marine grade aluminium alloy with thicknesses of 4 mm, 5 mm and 6 mm are welded using the fusion method for 2 minutes/meter which costs AU$7/meter, assuming that no post weld processing is required. In reality, the nature of the current process is such that it requires excessive post weld processing - grinding and sanding rework due to weld plate distortion and weld defects. Furthermore, when welding such long panels, the process needs to be stopped on occasion for system reconfiguration which leaves behind weld hole defects. These holes need to be filled later in the process. INCAT had started the trials with the BFSW process and found it difficult to achieve success, hence partnering with the university to better understand the production issues. The effects of interactions between BFSW welding parameters are complex and provide a significant production challenge. Once a deeper understanding has been gained, manufacturing engineers will be able to provide guidelines for the operators on executing good quality welds with low processing costs.

Friction stir welding using the fixed bobbin tool of this thin plate substrate is known to be particularly difficult: it has poor weldability. That creates a number of challenges. It also creates several opportunities. From a research perspective, there is an opportunity in that using a difficult process and alloy characteristic offer the prospects of being able to develop an understanding of the deeper mechanics of the welding process. From a practitioner perspective, there is a lot of welding to be done on say a ship, and the prospect of being able to do this with friction stir welding is highly attractive.

(b) There are three knowledge gaps with BFSW: (a) the underlying mechanics are poorly understood concerning the interactions of heat generation, temperature
distribution, material flow, and metallurgical changes, (b) there is no way of reliably linking tool features and process settings either to these deeper mechanics OR to the output weld quality, (c) bobbin FSW, which is necessary for the welding of thin plate, has a particularly lean research literature. Although not initially apparent there are several large differences between CFSW and BFSW in relation to the underlying physics. The first difference is the additional shoulder for BFSW. This has a major effect on the functional consequences, in that it results in greater heat input as most heat is generated at the tool shoulder rather than the pin [14, 29]. This then affects the readiness of the material to flow for a given process setting. Second, this additional shoulder alters the material flow, hence affecting grain orientation and weld quality, though the details are poorly understood. Thus the process setting and variables are sensitive to the tool features and elements of the underlying physics are also expected to differ.

In summary, there is a need to understand the causality whereby tools, tool features, process settings and other significant variables affect weld quality. One way of approaching this is to develop better models of the interaction that cover heat generation, material flow and process variables. Another is to take the production engineering approach of seeking to find relationships between the input variables that are controllable in the industrial setting, and the desired output variable of weld quality. The first approach is modelling, the second is empirical. The approach taken here is a combination of both.

1.7 RESEARCH OBJECTIVES AND SCOPE

Fixed bobbin FSW is perceived as a system that requires simple hardware that enables the opportunity to develop a portable unit. This attracts industry such as INCAT to adopt the process of replacing their fusion welding approached. While adaptive bobbin is believed to be flexible and better control, but the machinery is suspected to be costly due to the independent controller power head which require dedicated machinery that does not interest the company. In addition, INCAT objective is just to replace one of his processes which deal with long welding process of thin plate aluminium.
CHAPTER 1: INTRODUCTION

It is found later that, although BFSW in principle might be a better tool than CFSW to use in industry, investigations reported that the process is difficult. Because of this reason, the main purpose of this research was to optimise the BFSW process using a fixed bobbin tool. However, before the optimisation process through modelling or empirical studies can be done, the identification of the process variables, and their interactions, is of utmost importance. Developing this knowledge is a necessity for making reliable and repeatable welds.

The particular goal of this study is to link the casual parameters. These include machine types, tool fixation and rigidity, tool features, spindle speed, and travel speed. These variables need to be in control because their dynamic interaction with the process materially affects the weld-quality. The studies have focused on selected key combinations of these parameters with a focus on the functional perspective, rather than simply metallurgy per se.

The objectives of this research project were:

- To demonstrate the effect of machines, tool fixation, rigidity, tool features, spindle and travel speed towards weld formation.
- To explain and evaluate the BFSW process response.
- To develop a theoretical explanation of the failure mechanism of weld formation.
- To develop a conceptual model based on causality factors.
- To suggest guidelines to practitioners for welding material using BFSW process, especially thin plate aluminium.