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Design features for bobbin friction stir welding tools: Development of a conceptual model linking the underlying physics to the production process

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ABSTRACT

The effects of different pin features and dimensions of scrolled shoulder bobbin friction stir welding were tested for welding marine grade aluminium, Al6082-T6. Welds were created in longitudinal and transverse plate extrusion directions in thin plate aluminium clamped and supported at one side. Measured outcomes included visual inspection, plate distortion, mechanical properties, metallurgical examination, and hardness test. This study shows that tool features cannot be directly transferable from conventional friction stir welding technology without comprising process variables and tool part functionality. Process setting such as clamps, support arrangements, shoulder gap and welding direction create compression, vibration and heat distribution hence influence the weld quality. The best joint was produced by four flats tool pin followed by threaded tool pin with three flats. These findings were used to develop a conceptual theory representing the underlying physics of the friction stir welding process. The effects of pin features, specifically threads and flats, are identified. This model is useful for direct linking welding factors towards the expected consequences.

1. Introduction

Friction stir welding (FSW) is a solid state joining technique that was invented at The Welding Institute (TWI), United Kingdom in 1991. It is an alternative welding technology process to fusion welding. A defining characteristic of FSW is that the joint is created by a non-consumed cylindrical rotating tool, mechanically traversed through the materials. Frictional heat is generated between the wear-resistant welding tool shoulder and pin, and the material of the work-pieces. The frictional heat and surrounding temperature, causes the stirred materials to be softened and mixed [1]. The bonding is considered a solid state process, since the materials are not melted. However the grains are transformed and relocated. Material flows under the shoulder are similar to the forging process, while the material flows around the tool pin are like an extrusion process [2]. Weld quality in FSW is strongly affected by the tool geometry. This is because the tool has two important *functional consequences*: (1) to heat the workpiece and (2) contain and direct the plasticized workpiece material.

Benefits of FSW include less stringent process monitoring, lower energy consumption and potentially stronger welded joints. In addition to this, FSW does not require shielding gases, fillers, pre-weld preparation, or cleaning processes, and thereby is a more environmentally benign process.

While the principles of FSW are sufficiently well-established for application to industrial situations, there is still much to know about the welding process. In particular, the underlying physics and its effect on production processes are only partially understood [3–6]. This is due to the complex interaction of process variables which in turn affects the thermal (heat generation and temperature gradients), flow regimes and metallurgical changes at the grain level. This complex interaction is seen as the multi-physics interaction driven by the tool geometry and process settings. Consequently industrial applications tend to operate with a specific tool and process settings that have proved to work in only specific situation. There is missing of a better understanding of the operational boundaries and how the mechanical system related to the system performance to superior or inferior welds. At present, industry practitioners are forced to resort to continually create ad hoc solutions, resulting in non-optimal weld quality and performance. From the production perspective, weld quality is the primary output variable to be optimised. Some literature reviews state that weld quality is analogous for conventional and bobbin

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FSW [7,8] whilst on the other hand there are still several proponents that suggest weld quality is not comparable between two FSW methods. Results show bobbin friction stir welding (BFSW) to be better for medium and thick sections than for thin material [8–10], whereas other studies have achieved acceptable results for thin plate using bobbin tools [11,12]. The existing research in this field is characterised by a focus on the metallurgy issues [7,13–15], and the process perspective is under-represented. Tools, features-on-tools, and process variables have been researched, though in a piecemeal manner, and primarily for conventional friction stir welding (CFSW) [16] rather than BFSW. This makes it difficult to integrate the various studies into process models suitable for production engineering.

Although not initially apparent there are several large differences between CFSW and BFSW process in relation to the underlying physics. The first difference is the additional shoulder for BFSW. This additional shoulder has a major effect on the above *functional consequences*, through greater heat generation at the shoulder compared to the pin [6,17]. This then affects the readiness of the material to flow for a given process settings, hence affecting grain orientation and weld quality. Second, the BFSW process obviates the CFSW need for a support plate (anvil) at the bottom of the weld. In CFSW this support creates a cooling mechanism that causes non-uniform grain sizes developed in the welded area. Third, the BFSW tool rotates perpendicular to the plate to be welded. This creates uniform flow regimes. A more complex flow can be found if the tool is tilted which a common approach in CFSW processes. Thus process setting and variables are sensitive to the welding process, and elements of the underlying physics are also expected to differ.

The purpose of this research is to explore the dependencies whereby tool features and process settings affect output weld quality. The interest is in the functional perspective, rather than simply metallurgy per se. This paper specifically explores the tool-design part of this problem, with a particular focus on the tool pin features and production implications for bobbin tools.

2. Background research

The main mechanics involved in FSW are, as already identified, the thermal and flow dynamics, and the metallurgy. These form the dominant topics within the research literature. There are two types of flow occurring under the tool. These are known as pin-driven flow and shoulder-driven flow [18]. Both shoulder and pin affect material plastic flow and deformation [2,19]. In addition, the design of the tool is also known to affect the shape, size and location of any unfilled welds (defects) [20]. Therefore, in achieving a sound weld in FSW, the role and effect of the tool design need to be understood.

2.1. Conventional friction stir welding tools

Tool design has been an active area of research for single shoulder type CFSW tools [2,21]. The results can be categorised according to (1) pin features, (2) shoulder features and (3) tool dimensions. The known *functional consequences* of each are identified as follows.

Pin features: vertical motion can be introduced with cylindrical threaded pin feature [22], while flutes and flat faced features influence horizontal motion which helps in mixing the weld material [23,24]. A maximum of four flutes/faces is preferred as with additional flutes/faces provide little differences [25]. In addition, a tapered pin reduces torque and bending moment because of reduced swept volume during mixing [15].

Shoulder features: the primary design feature is the overall shape: flat, concave, or convex form. The concave design is common and is believed to provide a reservoir of material that feeds into the flow generated by the pin. Meanwhile for convex shapes the shoulder can be engaged with the workpiece at any location along the convex surface. This allows for a larger degree of flexibility in the contact area between the shoulder and workpiece [17,26–29]. Secondary features are also possible, the most common being a scrolled shoulder [17,25,26,28,30,31]. The intended purpose of this feature is to move material from the outer shoulder inwards. Edge fillet/chamfer features have also been used to reduce flash [31]. Each of the features can be combined in forming complex hybrid tools, some examples are contained within [19].

Tool dimensions: there are a number of heuristics that have emerged. For example, it is commonly stated that the pin diameter should be equal to the thickness of the materials to be welded, and pin length should be 0.2–0.3 mm shorter than the thickness of the material [20,22,23,32–35]. For the shoulder, the diameter should be three times the plate thickness [36].

2.2. Bobbin friction stir welding tools

The research described previously is for CFSW, the bobbin case has had much less research attention. While some of the underlying physics of CFSW is applicable to bobbin tools, this has not been demonstrated conclusively. Nor is it certain that the tool-features and process-settings are transferable, because of the fundamental differences in heat generation and flow characteristics. The notable works in this area are [12,15,30,37–39]. The implications, from these relatively small bodies of literatures, are that tool features have the following consequences:

a. A cylindrical pin with threaded features can produce a clear macrostructure boundary and higher bending strength. Alternatively three flats can be used.
b. A tapered tool pin with three flats enables a diameter reduction in the lower shoulder which then contributes low torque and bending moment.
c. When weld plates have high flatness variations, convex and scroll shoulder features can be useful.

A common design of BFSW is a cylindrical tapered threaded pin with three flats. Heuristics for tool dimensions are not directly transferrable from the CFSW case [39], because of the full pin penetration. Recommended process settings have been specified as follows: for thin aluminium (4–8 mm), spindle speeds of 450–600 rpm and travel speeds of 75–100 mm/min; for thicker material (about 25 mm) a spindle speed of 170–300 rpm and travel speed of 100–500 mm/min. However other variables e.g. dwell time, tool gap, support/clamp setting and plate condition, were not defined [12,15,37,39].

To the extent that thermal mechanisms dominate the welding process (which is a simplification, albeit a necessary one), the amount of heat generated is related to the spindle and travel speeds, but not solely to those variables. Other variables are tool geometry, features-on-tools, and other process settings. These should ideally be dealt with in an integrated way, though this is difficult to achieve because of the complexity of the interactions. It is therefore understandable that much of the research has approached these factors in a piecemeal manner.

There have been some attempts at unravelling the interactions of these multiple factors, though at present the results are limited in scope [17] and weld quality is not yet predictable [40].

2.3. Research aims

The gaps in the body of knowledge are as follows: (a) the underlying mechanics are poorly understood concerning the interactions