Development and Process Verification of a Linear Friction Welding Platform for Small Axis-Symmetrical Ti6Al4V Components

N T A Mohlala1, *, D G Hattingh1, * and W Rall1

1Nelson Mandela University, Department of Mechanical Engineering
*narishe.mohlala@mandela.ac.za
*danie.hattingh@mandela.ac.za

Abstract. This paper reports on the developments of a study done to establish the feasibility of implementing Linear Friction Welding (LFW) as a joining technique for small axis-symmetrical Ti6Al4V samples. This work will attempt to facilitate the manufacturing of high-integrity small near-net-shape components for aerospace, automotive and medical applications. LFW is a solid-state welding technique that utilises frictional heat generated by the rubbing of surfaces under an axially applied load, thereby forming a weld at temperatures below the beta transus point. The technique is advantageous as it has the potential to reduce defects normally associated with conventional welding of this material. This paper will describe the development of an experimental platform, which will facilitate the evaluation of the influence of selected process parameters and their influence on joint integrity. Process parameters that will form the basis of this study include axial load (weld interface force), consumed length (axial shortening), oscillating amplitude and frequency. Welds made on this platform will allow for the characterisation of the microstructural change across the weld zone or regions exhibiting grain refinement, linking this to the mechanical properties of the joint region. The study will create an understanding of how process parameters can be manipulated to achieve optimum joint properties or assist in eliminating weld defects. Knowledge generated will form the basis for developing a bench-top LFW research platform, with a reliable closed-loop response system that will aid in studying the effects of welding parameters on joint integrity of small titanium components.

1. Introduction

Joining and welding technologies remain fundamental to manufacturing and engineering, consequently the ability to form durable and strong connections between materials enables the fabrication of items that we rely on daily. Friction Welding (FW) is a solid state welding technology were welding takes place below the melting temperature of the material, this makes it a more attractive and practical joining technique for alloys that present difficulties to be joined by fusion welding [1]. Titanium alloys are alloys of choice for aerospace applications, cryogenics, automotive, bio-medical, petroleum and power generation; this due to their high specific strength, good fatigue, creep, fracture toughness properties and excellent strength to weight ratio [2]. Numerous FW techniques exist and include; rotary friction welding (RFW), friction stir welding (FSW), friction hydro pillar process (FHPP) and linear friction welding (LFW) with the last being of interest for welding symmetric and non-symmetric components. RFW has been a prevalent research field as opposed to LFW but it is limited to axi-symmetrical (rotational) welding. LFW is carried out by a relative reciprocating motion, in one plane of two components rubbing against each other under a certain pressure (10 - 200 MPa) at
a high linear oscillating motion (200 - 500 mm/s) [3]. LFW is predominantly used in blisk fabrication, therefore significant research has been done on developing the application for this technique, especially were welding takes place below the beta transus temperature (~ 980°C) of titanium [4]. Welding below the beta transus assist in alleviating welding defects which include; high thermal strain cycles, solidification segregation (macro-segregation) and micro-segregation), solidification cracking, contamination cracking, hydrogen embrittlement and sub-solidus (ductility dip) cracking porosity, which are inherent during fusion welding as a result of complex alloying and heat treatments [2] experienced during the manufacturing process of Ti6Al4V.

2. Literature Review

2.1. Background on LFW

The concept of LFW can be traced back to 1929, but proved doubtful because of difficulties in generating linear reciprocating motion at the time [5]. In the 1960’s, patents were presented on the linear reciprocating motion and not the friction welding process [6]. A purpose built electromechanical actuated LFW machine was commissioned in 1990 by The Weld Institute (TWI Ltd), which facilitated initial research and development aero-engine manufactures. This technology was initially initiated by the need to repair severely damaged blades and developments in near-net shape blisks manufacturing. Companies like Pratt & Whitney, MTU aero engines and Rolls Royce were assisted by these developments to commercialize production processes through LFW [1]. To date, Boeing Co. and United Technologies Corporation hold patents that protect certain applications and welding methods or tooling concepts of the process [8]. From literature, it appears that the fundamental principles of LFW are not patented.

The physics of the LFW process relies on heat generated by friction at the contact surfaces until a deformation-temperature is achieved which results in the formation of metallic bond[1]. The process has several phases as shown in Figure 1(a).

- Phase 1: Dry contact (no motion or oscillation).
- Phase 2: Dry friction with solid-to-solid contact, oscillation starts and axial load is applied. Initial flash forms but no coalescence between the components exists.
- Phase 3: A plasticized layer forms between the two components, while the oscillation frequency and axial load remain constant. Increased flash formation is observed accompanied by axial shortening (consumed length). Resulting in a formation of a fused flash indicating coalescence between the components.
- Phase 4: Rapid deceleration, oscillatory frequency reduced to zero and axial load increased consolidate weld (forging action).

![Figure 1](image-url)  
Figure 1. Schematic of the LFW process sequence and proposed process “Force Foot” print of LFW. The schematic illustration to the right of Figure 1 gives a proposed “Force Time” relationship for linear friction welding. The experimental work proposed for this platform includes the characterisation of a LFW “Force Foot Print” as was proposed by Hattingh et.al for friction stir welding in 2000 [15].

The joining by friction are divided in to four main stages, as original identified by Vairis and Frost [1].
• Stage 1: Heat generation by columbic friction between the rubbing surfaces. Asperity contact exists between the two surfaces, and as heat is generated, the asperities soften and deform, increasing the true area of contact between the two parts. (Columbic refers to friction generated by relative motion between bodies rubbing against each other)
• Stage 2: Transition stage, during which the true contact surface becomes 100% of the sample contact surface. This transition is accompanied by an increase in the force required to oscillate the parts. True area is the area revealed as the asperities are removed due to the oscillatory motion.
• Stage 3: Equilibrium, the shear force reaches a steady state value and the initial lengths of the joint components shortens through the generation of ash. The plastic zone gets progressively larger during this stage.
• Stage 4: Deceleration stage, the two specimen seize motion relative to each other and they are aligned. Depending on the application, additional forging pressure may be required.

2.2. Power input and modeling of LFW
The maximum rubbing velocity is determined by assuming sinusoidal motion of the oscillating work-piece, so the displacement, \( x \) can be approximated by (1)[8].

\[
x = \sin (\omega t)
\]  
(1)

Where \( \alpha \), is amplitude of oscillation and \( \omega \), is angular velocity which equates to \( 2\pi f \), \( f \) is the frequency of oscillation. Differentiating (1) with respect to time approximates the rubbing velocity of the oscillating specimen:

\[
\dot{x} = \alpha \omega \cos (\omega t)
\]  
(2)

Therefore, the maximum rubbing velocity:

\[
u = \alpha 2\pi f
\]  
(3)

In-plane force:

\[
F_p = \mu F_n
\]  
(4)

Where \( \mu \) is coefficient of friction and \( F_n \) is the axial load. The heat generated at the interface per cycle is estimated by \( Q_o \):

\[
Q_o = F_p \nu
\]  
(5)

The process parameters to be used in this study will be derived using a trial and error approach using parameters from industrial scale welds using guidelines from work done by McAndrew et al [6].

2.3. Aptness of Titanium to LFW
Materials that exhibit conducive high temperature properties especially compressive yield, shear strength and low thermal conductivity are well suited to LFW [1]. The low thermal conductivity allows for good retention of frictional heat generated as a result of high temperature mechanical properties where the heat generated is confined at the interface [1]. Heat generation at the interface is influenced by; frequency, amplitude and frictional pressure, therefore the synergy must be carefully controlled to achieve a uniform weld and a good welded joint [1]. Consequently making titanium alloys with their good high temperature mechanical properties and low thermal conductivity ideally suitable for this type of joining process. Mill annealed Ti6Al4V grade 5 samples will be utilized in this study.

LFW can be used for a wide variety of materials, including certain aluminides and metal composites with low temperature mechanical properties and high thermal conductivity. However, high input processes forces are generally required to achieve sufficient heat to produce sound welds [13].
Alpha alloys exhibit creep resistance superior to β alloys subsequently they are preferred for high temperature applications [12, 14]. The absence of a ductile-to-brittle transitions, a feature of β alloys, makes α alloys suitable for cryogenic applications. Beta alloys have excellent harden-ability, and respond readily to heat treatment. Solution treatment is the common thermal treatment followed by aging. Titanium alloys exhibit a high chemical affinity for oxygen, which increases with an increase in temperature, coupled to a growth in surface oxide layer [3]. Temperatures exceeding 500°C, result in reduced oxidation resistance of titanium at a greater rate and the alloy is highly vulnerable to embrittlement by O, N and H as they dissolve interstitially in titanium [3]. LFW of titanium should be done in total vacuum or inert environments. For the purposes of this study argon (Ar) will be the inert gas of choice. Good shielding improves the weld integrity of the joint, 200 ppm is the desired amount of O₂ remaining in your medium to achieve optimal welded joints [9].

3. Linear Friction Welding Platform Development

3.1. Platform Design Methodology and Process Variables

The design of this Linear Friction Welding (LFW) platform required the identification of key process variables (constraints) fundamental to LFW, these include; generating oscillatory motion, ramp up time and deceleration. Hence, an evaluation was done to determine the feasibility of using existing equipment to satisfy the above mentioned process parameters, where the platform will be attached or adapted during operation. The Zwick and Instron fatigue platforms were the two cyclic platforms at the Department of Mechanical Engineering considered as base equipment for integration of the LFW research platform. The type of dynamic motion of interest, in this case, is controlled cyclic loading from a frequency and displacement point of view. With further investigations into available platforms, it was realized that the Instron platform was the best suited from a process control point a view as it inherently provided precise control during the ramp-up and deceleration cycles. Consequently, the developed platform was designed with a view of attaching it to the Intron platform.

The main features of the Instron that dictated the adaption of the welding platform was the top and bottom jaw configuration, with the later been attached to the actuator that generates oscillating motion during fatigue tests, dictating how the platform is going to drive the oscillatory component. With this in mind the top jaws was envisaged to support the axial load applied on the non-oscillatory component as discussed as in section 2.1. The maximum travelling distance between the two jaws was of particular importance as it determined the maximum height of the platform, while facilitating the adaptation of the platform while maintaining functionality.

3.2. Process Parameters and Control

The welding platform has to meet the process parameters of LFW which includes the following; axial load, consumed length (axial shortening), oscillating frequency, oscillating amplitude and forging force. LFW is a self-regulating process from an interface temperature point of view, therefore a precise control and monitoring of the process during welding is fundamental to ensure that repeatable and defect free weld can be produced.

3.3. Axial Load and Forging Force

A constant axial load is required on the non-oscillatory component before deceleration (stage 4), consequently a load cell is required to continuously measure the applied axial load throughout the process. The load cell will translate the applied axial load via a control loop to relay the measured signal to the servomotor in an effort to control the applied load. Load control is essential during welding as the material at the interface undergoes a repeated heating, plasticise and collapse cycle, resulting in the components inability to support the initially applied axial load continuously. Hence, the term self-regulatory, as this process continues until the applied load stabilizes or exhibits minute fluctuations. Which will be a clear indication of steady state and coalescence between the components is achieved.
Due to the complicated design of the non-oscillatory chuck, an off-the-shelf load cell was not available to fit into this chuck. Therefore, a load cell was designed to meet the requirements of this stage and overcome platforms space constraints by using strain gauges. Altair *Hypermesh* was used to ensure that the deformation is linear and increase the sensitivity of the load cell as depicted in Figure 2(a).

![Figure 2. Load cell and non-oscillatory chuck](image)

**Figure 2.** Load cell and non-oscillatory chuck

Figure 2 (b) shows the load cell and non-oscillatory chuck prior to and after assembly, a T-rossetes with three measuring grids as depicted in Figure 1. This design was in particularly guided by space restriction on the load cells face and non-oscillatory chuck prior to assembly.

3.4. Consumed length (Axial Shortening)
The consumed length is of particular interest because it can be related to the observed flash between the components, which aids with expelling surface contamination during plasticisation (stage 2) of the welding process, therefore ensuring a clean weld fusion zone (oxide free).

4. Discussions
Figure 3 depicts the LFW research platform for small sample developed after considering the above mentioned process variables and parameters. The top and bottom clamps will be mounted in the jaws of the Instron from where the cyclic motion will be introduced via the Instron actuator. The servo-motor will be used to drive the non-oscillatory chuck. The servo-motor will apply the required torque to maintain a constant axial load during the welding process. Trapezoidal nut and lead screw were used to connect the servo-motor to the non-oscillatory chuck with the aid of the coupling. The trapezoidal nut is mounted on the non-oscillatory chuck housing to ensure that the servomotor can slide forward and backwards, ensuring that the above mentioned fundamentals of LFW are satisfied.

![Figure 3. Linear Friction Welding Platform](image)

**Figure 3.** Linear Friction Welding Platform

**References**
[1] Bhamji I, Preuss M, Threadgill P, and Addison A, Solid state joining of metals by linear friction welding: a literature review. Materials Science and Technology, 27(1):2-12, 2011.
[2] Cengel Y. A and Ghajar A. Heat and mass transfer (a practical approach, SI version). McGraw-
Hill Education, 2011.

[3] Donachie M. J, Titanium: a technical guide. ASM international, 2000.

[4] Javadi Y, Akhlaghi M, and Najafabadi M A. Using finite element and ultrasonic method to evaluate welding longitudinal residual stress through the thickness in austenitic stainless steel plates. Materials & Design, 45:628-642, 2013.

[5] Maurya R and Kauzlarich J, Bonding apparatus (friction welding by reciprocal motion. Patent nos. US3420428-A, DE1552871-A, CA844858-A, 1969.

[6] Midling O and Grong. A process model for friction welding of Al Mg Si alloys and Al SiC metal matrix composites, haz temperature and strain rate distribution. Acta Metallurgical et Materialia, 42(5):1595-1609, 1994.

[7] Nunn M. Aero engine improvements through linear friction welding. In 1st International Conference on Innovation and Integration in Aerospace Sciences, pages 4-5. CEIA, Queen's University Belfast Northern Ireland, UK, 2005.

[8] Shtrikman M. Linear friction welding. Welding international, 24(7):563-569, 2010.

[9] Tsikayi D. S. Friction Hydro Pillar Riveting Process of Ti-6Al-4V Titanium Sheet. PhD thesis, Nelson Mandela Metropolitan University, 2015.

[10] Vairis A and Frost M. Modelling the linear friction welding of titanium blocks. Materials Science and Engineering: A, 292(1):8-17, 2000.

[11] Vill V. I. Friction welding of metals, volume 1. American Welding Society; trade distributor: Reinhold Pub. Co., 1962.

[12] A. H. Volume. 2: Properties and selection: Nonferrous alloys and special-purpose materials. ASM international, pages 1770-1886, 1990.

[13] Wanjara P and Jahazi M. Linear friction welding of Ti-6Al-4V: processing, microstructure, and mechanical-property inter-relationships. Metallurgical and Materials Transactions A, 36(8):2149-2164, 2005.

[14] Welsch G, Boyer R, and Collings E. Materials properties handbook: titanium alloys. ASM international, 1993.

[15] Hattingh D, Blignault C, Van Niekerk T, and James M. Characterization of the influences of FSW tool geometry on welding forces and weld tensile strength using an instrumented tool. Journal of Materials Processing Technology, 203(1-3):46-57, 2008.