Relationship between tool tilt angle, shoulder plunge depth and process energy input for pin-less friction stir welded thin Ti-6Al-4V sheets

A B Gili1, D G Hattingh1 and D Bernard1

1 Nelson Mandela University, Department Mechanical Engineering, Port Elizabeth, South Africa

E-Mail: s219227535@mandela.ac.za

Abstract. This paper reports on the initial process development towards evaluating pin-less friction stir welding as a feasible alternative joining technology for Ti-6Al-4V sheets. Initial research results were derived from “bead on plate” welds with a pin-less tool on 3 mm Ti-6Al-4V sheets to assist with decision making for joining 1 mm Ti-6Al-4V sheets. The study evaluates the shared influence of tool tilt angle and shoulder plunge depth on weld profile and process energy input for a pin-less tool. An experimental approach was followed, performing bead on plate welds with three tool tilt angles (0°, 1° and 2°) respectively at shoulder plunge depths from 0.15 mm to 0.25 mm in 0.05 mm increments. From critically evaluating the hardness profile and heat affected area below the tool shoulder, the shared influence of tool tilt angle and shoulder plunge depth could be analysed to give an indication of the best parameter combination for performing solid state welds on 1 mm Ti-6Al-4V sheet. Additionally, the thinning effect on the weld region was evaluated and compared to welds made with a pin. Future work will include quantifying surface residual stresses on the material and the relationship these stresses exhibits with the varying tool tilt and shoulder plunge depth. This work will assist in selecting weld parameter combination that will minimize tensile residual stresses in critical areas. Knowledge gained from this study forms the basis for the overall process development for joining 1 mm Ti-6Al-4V sheets by pin-less friction stir welding.

1. Introduction
The main considerations of the research projects revolve around evaluating the suitability of Friction Stir Welding (FSW), a solid-state joining technique for welding thin Ti-6Al-4V sheets. Ti-6Al-4V is a material of choice where high strength to weight ratio is desirable. FSW is a proven approach for joining, especially for Aluminium. However, the FSW of high strength, high melting point materials has proven to be more complex as tool wear becomes more prevalent [1]. Wear driven by geometrical changes of the tool has a direct influence on process energy input and material flow, effecting weld integrity. Despite these challenges the joining of Titanium, by means of this solid-state welding technique, stays attractive due to superior mechanical properties, good corrosion resistance and its ability to perform well under elevated temperatures.

The crystal structure of titanium is a close packed hexagonal crystal structure (HCP). Alloying titanium for example with aluminium, vanadium, copper, zirconium, etc. the structure can be manipulated in forming α, β and mixed α-β Ti [2]. These structures have specific applications, however a mixed α-β structure is
regard as metallurgical more stable owing to the presences of α-β stabilizers making this type of titanium (e.g. Ti-6Al-4V) more versatile and extensively popular for engineering applications. The alpha titanium grades like pure titanium don’t exhibit ductile-brittle transformation making the grades suitable for cryogenic applications. The beta titanium grades contain predominantly beta stabilisers with small amount of alpha stabilizers which increase biocompatibility [2]. Although titanium can be joint by a number of conventional fusion techniques like gas metal-, tungsten-arc, plasma and laser beam welding, these techniques present process control complications pertaining to the increase material reactivity with oxygen, hydrogen, nitrogen at the associated high welding temperatures potentially contributing to embrittlement of the welded joint.

Solid state joining (FSW), developed by Wayne Thomas [1] in the early 1990s presented an alternative solution to these inherent reactivity challenges of fusion welding, as for FSW the material is welded below the β-transus temperature of the parent material. Performing welds below the β-transus temperature with gas present in the melting pool limits effects associated with metallurgical transformation at elevated temperatures. Also, the reduction in thermal cooling cycle in FSW as a result of welding at a lower temperature reduces residual stresses in the weld region and limits the distortion [2]. Pin-less FSW is similar to conventional FSW in all ways except that the welding tool in pin-less FSW consist of a shoulder only. The tool is rotated and forced against the surface of the material to produce frictional heat at the contact area. The frictional heat plasticises (softens) the material, allowing it to be mixed by the stirring action of the pin-less tool shoulder, thereby creating a bond between the abutting sheets without reaching melting temperature of the base metal. Reported by Mashinini et al.[3] in a comparative study of friction stir and laser beam welded Ti-6Al-4V sheets, LBW experienced high tensile residual stresses in the centre of the nugget zone compared to those experienced in FSW which are more evenly distributed across the stir zone. From this same study it was reported that highest residual stress, during FSW were recorded under high transverse speed. Mashinini et al.[3] also reported hardness values for FSW which indicated higher values for the weld zone compared to the base material. However some studies indicate the minimum hardness values within the heat affected zone (HAZ) [4] and others reported the stir zone (SZ) to have the lowest values in hardness [5, 6] with hardness decreasing with an increase in rotational speed.

Tooling material and tool wear presents a challenge in the joining of alloys such as titanium by FSW. The characteristics of the tool material must include the ability to retain its strength and resist wearing while operating at elevated temperatures (+1000°C Titanium). Special tooling material such as Tungsten (cp-W), Tungsten Rhenium (W-Re), Tungsten cobalt (WC-Co), Lanthanated Tungsten (W–La2O3), Polycrystalline Cubic Boron Nitride (PCBN) etc. are needed to join high melting temperature alloys. Some of the aforementioned tool material have been reported by various authors [7-14] on FSW of Ti-6Al-4V of different thicknesses.

This study will evaluate the shared influence of tool tilt angle and shoulder plunge depth on weld heat effected profile and process energy input for a lanthanated tungsten (W–1%La2O3) pin-less tool on a 3 mm Ti-6Al-4V sheet. This data is expected to inform the further develop of the process towards evaluating the feasibility of using pin-less tools for friction stir welding for joining 1 mm Ti-6Al-4V sheets. The use of a pin-less tool has originally gained consideration in pin-less friction spot welding [15-18] with few studies reporting pin-less friction stir welding as a joining technique for thin aluminium sheet. A number of studies evaluated the relationship between the tool shoulder and pin and the relationship of this combination to material thickness. The current understanding shows that tool pin is prominent for FSW of material thickness above 3 mm and as material get thinner the role of the pin becomes less prominent than the shoulder from a mixing and process energy input point of view, however the opposite is also true in that as the material thickness increase the shoulder become less prominent and the pin become important from both mixing and process energy input, this phenomenon lead to the development of “Stationary Shoulder” FSW. Additionally, with tool wear [19]being one of the associated difficulties for friction stir welding of high-strength/melting point alloys, risk of accelerated pin wear is a reality
which result in tool geometry change as the weld progress, effecting process energy input and material flow which could adversely affect weld integrity.

2. Experimental Procedure

Bead on plate welds in the rolling direction were performed on mill annealed 3mm thick Ti-6Al-4V square coupons with dimensions of 110 mm x 110 mm. Chemical composition (wt%) of the actual coupons are as shown in Table 1. A flat featureless shoulder pin-less tool, 14 mm diameter was manufactured from lanthanated tungsten alloy (W-1%La2O3) and used to implement bead on plate welds on the I-STIR Process Development System platform developed by MTS Corporation (MTS I-STIR PDS). Backing plate manufactured from Haynes 230 alloy was used during welding as it retains its strength and resists oxidation at operating temperatures up to 1149°C, making it well suited for FSW for high temperature alloys such as Ti-6Al-4V.

![Figure 1. Pin-less friction stir welding illustration](image-url)

The only two parameters varied for the purpose of this study were tool tilt angle (0°, 1° and 2°) and tool plunge depth (0.15 mm, 0.2 mm and 0.25 mm). The definition of tilt angle and plunge depth is visually illustrated in Figure 1. Bead on plate welds were produced at all plunge depths for each selected tilt angle producing a total of 9 welds (W12, W13, W14, W15, W16, W17, W19, W20 and W21 respectively) also listed in Table 4. These welds were all made at a constant rotational speed of 950 rev/min, transverse speed of 55 mm/min and a dwell time of 3 seconds in position control. Argon was used as a shielding gas for all the welds. For metallographic and micro hardness analysis specimens were extracted in the stable zone of each plate perpendicular to the tool transverse direction by water jet cutting so as to induce no heat on the specimens. The specimens were mounted, followed by mechanical polishing and were then etched with Kroll’s reagent. The metallographic evaluation was performed through optical microscopy. Microhardness was performed on the Micro Vickers tester (Future Tech FM–700).

| Elements | Al | V   | Fe | C   | N   | O   | Ti   |
|----------|----|-----|----|-----|-----|-----|------|
| wt%      | 6.25 | 4.04 | 0.19 | 0.018 | 0.008 | 0.18 | Balance |

3. Results and discussions

3.1 Weld surface appearance

Table 2 shows the top weld seam appearance of the bead on plate welds on Ti-6Al-4V sheet 3 mm thickness. Varying degree of discoloration was observed on the weld surface, an indication of surface oxidation as the titanium react with oxygen at elevated temperatures despite shielding with Argon. Flash...
formation were more prominent at welds made at 0° tilt angle and generally decrease with an increase in tool tilt angle. However, an increase in shoulder plunge depth resulted in an increase in flash formation at all tilt angles. In this scenario the material is not contained beneath the tool shoulder as is the case when a tilt angle is increased but is rather expelled as flash around the tool. With W14 and W21 ridges were formed on the weld surface resulting in a poor surface finish. Welds accomplished at 0.2 mm plunge depth exhibited a smooth appearance over the entire weld length. Uneven profile for the first 10-30 mm of the weld length can be attributed to a number of events such as the 3 seconds dwell time which was insufficient for the tool to generate enough frictional heat before it starts to transverse, also platform stability during the weld initiation stage, resulting in discarding the first 30 mm of the weld for all the tests performed. Tool exit position presented a shiny smooth surface with no pin hole that requires run off plate as compared to tools characterized with a pin.

Table 2. Surface appearance of welds made at different tool tilt angle and tool plunge depth.

| PD   | Tilt Angle 0° | Tilt Angle 1° | Tilt Angle 2° |
|------|---------------|---------------|---------------|
| 0.15 mm | W17           | W12           | W21           |
| 0.2 mm  | W15           | W13           | W20           |
| 0.25 mm | W16           | W14           | W19           |

3.2 Weld Macrographs
Cross-sections of the welds showed a symmetrical shape on the stir zone about the weld centerline. The macrographs are characterized by stir zone (SZ), a narrow heat affected zone (HAZ) and base material (BM) as shown by a representative sample in Figure 2. With titanium having a low thermal conductivity the formation of heat affected zone becomes very narrow and less distinct in titanium FS Welds [20]. Stir zone depth was measured at the center of the stir zone along the centerline at the interface between SZ and HAZ.

Table 3 shows the weld cross-section perpendicular to the welding direction of Ti-6Al-4V pin-less friction stir welded sheets under different tool tilt angle and tool plunge depth. After metallographic preparation the samples revealed weld stir zone depths close to 1 mm, with weld W17 (0° tilt and 0.15 mm plunge) recording the lowest stir zone depth (0.83 mm) as indicated in Table 4. Very little overall sheet thinning was observed across the welded samples except for a parameter combination of 1° tool tilt angle and 0.25 mm shoulder plunge depth (W14) revealing irregular thinning along the advancing side (AS) and retreating side (RS).
Table 3. Weld Macrographs at different tilt angles and plunge depths

| PD  | Tilt Angle 0° | Tilt Angle 1° | Tilt Angle 2° |
|-----|---------------|---------------|---------------|
| 0.15 mm | RS W17 AS | RS W12 AS | RS W21 AS |
| 0.2 mm  | RS W15 AS   | RS W13 AS   | RS W20 AS   |
| 0.25 mm | RS W16 AS   | RS W14 AS   | RS W19 AS   |

3.3 Weld Process data
The MTS I-Stir PDS platform is equipped with transducers to record the process response during welding. The variables include spindle torque, tool downforce. The typical force and torque response are presented in Figure 3.

![Figure 3](image)

Figure 3. Typical force and torque response as measured along the weld length.

The reported torque value in Table 4 was calculated from the average torque value occurring in the stable zone of the weld, coinciding with the position where the macrograph samples were removed. The torque and force response, stir zone depth, process energy input (determined from the reported torque) is shown in Table 4.
Table 4. Weld matrix, process data and average process energy input calculated

| Weld | Weld Variables | Response Variables | Measured Effects |
|------|----------------|--------------------|------------------|
|      | Tilt angle(°)  | Plunge depth(mm)   | Torque (Nm)      | Forge Force (kN) | Process Energy Input (J/mm) | Stir Zone Depth (mm) |
| W17  | 0              | 0.15               | 10.869           | 2.267            | 1116.54                      | 0.83                |
| W15  | 0              | 0.2                | 11.51            | 2.976            | 1220.707                     | 0.97                |
| W16  | 0              | 0.25               | 14.145           | 3.081            | 1284.726                     | 1.63                |
| W12  | 1              | 0.15               | 12.178           | 2.915            | 1338.98                      | 1.42                |
| W13  | 1              | 0.2                | 11.741           | 2.564            | 1299.917                     | 1.01                |
| W14  | 1              | 0.25               | 11.279           | 2.472            | 1239.153                     | 0.92                |
| W21  | 2              | 0.15               | 13.032           | 2.375            | 998.2669                     | 1.12                |
| W20  | 2              | 0.2                | 12.638           | 1.836            | 1247.834                     | 2                   |
| W19  | 2              | 0.25               | 12.463           | 2.968            | 1204.431                     | 1.51                |

Figure 4. Effects of tool plunge depth on process energy input

The relationship between the process energy input and tool plunge depth is presented in Figure 4 for each tool tilt angle. Due to interaction between the tool shoulder and the plasticised material contact forces are developed during the process and the amount of energy required to overcome these forces is defined as process energy input. There was a general trend observed at 1° and 2° tilt angles, with the process energy decreasing with increasing plunge depth but vice versa for 0° tilt angle. The effect of not having a tilt angle (0°) on the tool results in a build-up of plasticised material in front of the tool, effecting the flow and consolidation below the tool shoulder. This resistance of material in front of the tool result
in an increase in process energy input and not necessarily in increase heat input. A negative linear relationship was observed for both the welds done at 1° and 2° tilt angles. The driving factors for a negative linear relationship could be the increased contact surface with increased plunge (increase frictional area) which led to a larger volume of material softening, thereby decreasing the required process energy input. There was no significant variation between two welds done at the same plunge depth and different tilt angles (1° and 2°) which further substantiates that tilt angle has an insignificant influence on the process energy when performing pin-less FSW at constant parameters. Further work still needs to be done which will help to explain the above observations. The highest process energy input was required with 0.25 mm plunge depth for 0° tilt. 

Figure 5. Tool plunge depth as a function of stir zone depth and process energy input for (a) 0°, (b) 1° and (c) 2° tool tilt angle.

The stir zone depth was measured from the weld micrographs, and the relationship between the stir zone depth and plunge depth is shown in Figure 5. To assist with interpretation and comparison the process energy input was added to Figure 5. The general observations is that 0° and to a lesser extent 2° tilt angle achieved greater stir zone depth as the plunge depth was increased. The rapid increase in stir zone depth at 2°, 0.2 mm plunge cannot be explained currently and is considered as an anomaly associated with the specific position in the weld. At 1° tilt angle we observed an associated decrease in stir zone depth with increased plunge depth. This phenomenon needs further investigation as an increase in tool plunge depth should increase the tool shoulder contact area with the material, resulting in an increase in frictional heat
generated by the shoulder action. Possible explanation lies in the large volume of flash expelled at these parameters.

3.4 Hardness profile

Figure 6 shows micro Vickers hardness profile which was performed with a 500 g load for 15 s. Indents at a pitch of 0.5 mm were made along a line 0.7 mm below and parallel to the top surface of the weld.

Within the weld region the hardness profiles were fairly similar for all the welds tested, and there were no observable dependence on either tilt angle or plunge depth. The hardness in the stir zone increased from approximately 310 Hv in the parent material, to 345 Hv in the stir zone. This increase in hardness is consistent with published literature and is driven by the refined grain in the dynamically recrystallized stir zone. Variation in hardness was observed on the retreating and the advancing side of the base material, however, the variation falls within the hardness range of the base material. However a risk was identified that the samples prepared did not extend beyond the heat affected zone of the sheet on the advancing side of the weld, this could also be a contributing factor for the off-set in hardness data on the advancing side if compared to that of the retreating side. For comparison purposes the hardness was also measured 0.7 mm and 1.5 mm beneath the top surface of the parent material in an attempt to explain the large variation in hardness data. Important to note that for the parent plate the hardness at a depth of 0.7 mm ranged from 300 HV to 333 HV (average 313 HV) and at mid-thickness the ranged from 301 HV to 315 HV (average 306 HV), revealing a larger scatter in data closer to the surface.

![Figure 6. Effects of tool tilt angle and tool plunge depth on microhardness of FSW Ti-6Al-4V 3mm sheets](image)

4. Conclusion

Lanthanated tungsten tool was used to perform successful bead on plate welds on 3mm Ti-6Al-4V sheets and the shared influence of various tool tilt angle and tool plunge depth on the weld profile was evaluated through macrostructure, process energy input analysis and microhardness. The conclusions to the study are summarized as follows.

- From the macrograph it could be determine that most of the selected parameter combinations resulted in a stir effected depth of more than 1 mm (except W17). This 1 mm minimum stir depth becomes an important observation for transferring this data to 1 mm thick sheet. The highest stir zone depth (2 mm) was achieve at 2° tilt and 0.2 mm plunge. Form evaluating all data and visual appearance W13 looks to be a very good weld, this will however need more evaluation.
• Process energy input and plunge depth showed a negative linear relationship (reduce process energy) for welds performed at 1° and 2° tilt angles. The driving factors for this relationship can possibly be contributed to an increase in plunge depth, which results in an increase in tool contact area. This increase in contact area generates a larger volume of plasticised material and a reduced effect of “dry friction” which will be more prominent at low plunge depth with low tilt angles.
• There was no significant variation between two welds done at the same plunge depth and different tilt angles (1° and 2°) which at this stage are indicative that for the considered tilt angles, changes in process energy input will be minimal when performing pin-less FSW at constant parameters.
• The lowest hardness values were recorded in the base material and the highest hardness in the stir zone. No significant variation was observed with neither a change in tilt angle nor plunge depth.

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