Optimisation of the rotary friction welding process of titanium alloy rods

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Abstract. This paper presents a study on the performance behaviour of friction welded titanium alloy rods. The Ti6Al4V alloy rods were friction welded with continuous-drive friction welding using different combinations of process parameters. The welding speed ranging from 1600 to 2700 RPM and the applied pressure ranging from 25 to 140 MPa were utilized for the welding process. The weld joints and the parent material were examined for microstructure characterisation, Vickers hardness and tensile properties. The microstructure of the weld joint revealed fine equiaxed grains with complete recrystallization. The presence of martensitic grains was obtained at process parameter combinations of low welding speed and high pressure. The tensile tests conducted revealed that the weld joints of low speed and high pressure had improved tensile properties when compared to that of the parent material. The ultimate tensile strength of 1040 MPa with the elongation of 26.5 % was obtained at a speed of 1900 RPM and 80 MPa pressure. The micro-hardness tests revealed an increase in hardness across all the weld zones when compared to the parent material, with the maximum hardness obtained at the weld nugget. Further study was conducted to evaluate the effect of parameters on the weld joint integrity.

1 Introduction

The use and the application of titanium alloys have increased worldwide and currently account for over 50 % of the total titanium usage worldwide [1]. This is due to the alloys having outstanding properties as compared to other materials and alloys in the same group. Titanium alloys have similar mechanical properties as steel alloys yet are approximately 45 % lower in specific gravity. These properties have brought about a wide range of applications that require a high level of reliability, corrosion resistance, and excellent performance in various conditions of applications such as in surgical and mechanical equipment, automotive industries, chemical plants, marine and aerospace industries, and biomedical body implants. In a wide range of engineering applications, titanium alloys have replaced a range of materials due to their ability to work continuously up to a temperature of 600 °C without the loss of mechanical properties, providing reliable components and prolonging the service life

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of many equipment [2, 3]. The availability of titanium alloys enables engineering designers and fabricators to use them for different forms of critical application, such as in orthopaedics and dental implants [4].

Ti6Al4V alloy is the most used titanium alloy. Its application in various industries has brought about positive changes in the serving life of many pieces of equipment and employees' injury rate due to failure of critical components. This is due to its excellent properties that enable the material to withstand various forms of demanding applications. Although Ti6Al4V alloy has outstanding mechanical properties and obvious economic advantages, the alloy is difficult to weld through conventional welding techniques [5, 6]. This is caused by the high embrittlement and high reactivity of Ti6Al4V when exposed to elevated temperatures. Such a challenge results in its weld joints having poor mechanical properties, and thus become the failure point during testing or application.

The friction welding technique has been the most economical and remarkable process in the welding of various materials including Ti6Al4V alloys. The technique produces the weld joints with improved properties and minimum volume fraction of defects [2, 7]. The friction welding process is a solid-state joining technique that produces the weld joint at a temperature below the solidus temperature of the parent material. The application of rotary friction welding (RFW) process (as one type of friction welding technique) in the joining of various materials has provided a better alternative to the conventional welding techniques with an ability to weld materials of different properties and those regarded as difficult to weld such as Ti6Al4V [2, 8]. Since the process is solid-state, many defects caused by the melting of the interface are not found, which acts as an added advantage over other fusion welding processes [9, 10]. RFW process was found by Bevington in 1891 after recognising that tubes can be welded by frictional heat generated when spinning them in different directions while applying axial pressure [11]. American Welding Society [12] further developed the process and formally defined the recommended practices for the welding industries. Over fifty years, TWI and the expertise have been at the forefront in the development of the process. Various experiments and tests have been conducted to improve the efficiency of the process [13].

Over the past decades, RFW has been gaining familiarity in various industrial applications for critical components. This is due to the process being the most economical, efficient, and successful welding technique in joining of hard materials, and its joints having excellent mechanical properties obtained from the recrystallized, fine grains in the weld zone [14, 15]. Although the process has been widely used in various industries, there have been limited studies that have focused and reported on the performance behaviour of rotary friction welded titanium alloys. Due to an increase in the use of titanium alloys worldwide and an increasing application of RFW process in the joining of various industrial components, the information on the performance behaviour of rotary friction welded titanium alloys has been in great demand. Therefore, this study aims to focus and report on the behaviour and the performance of rotary friction welded Ti6Al4V. The experimental method will be utilized to obtain different properties of the friction welded titanium alloy.

2 Friction welding of Ti6Al4V

The welding of Ti6Al4V has been the biggest challenge for conventional welding processes. Although it can be welded, several challenges require special attention to make the welding process successful and further produce a high-quality weld joint. These challenges may be time-consuming and costly for the production of a single weld joint. For example, when Ti6Al4V is heated (welded) it tends to react with the environment, hence absorbing nitrogen and oxygen in the atmosphere. This causes weld oxidation, embrittlement, and discoloration that eventually deteriorates weld joint properties. Therefore, proper weld shielding is required

to isolate the welding process from the environment [2, 16]. Also, the fusion welds of Ti6Al4V alloy are susceptible to many forms of cracking, embrittlement through contaminations, and segregation [17]. Due to these challenges, various fabricators believe that the alloy is hard to weld.

RFW process has been the most efficient and cost-effective welding technique for the production of components of similar and dissimilar materials. Since the process involves rotation and application of pressure, much attention is paid to the selection of process parameters taking into consideration the geometry and the chemical properties of the materials to be joined. When Ti6Al4V is friction welded, the joining occurs below the solidus temperature. Defects and stresses caused by bulk melting do not occur [2, 18]. Embrittlement through contamination and segregation does not occur as well because the process is self-cleaning and filler-free [19, 20].

Numerous studies of friction welding of Ti-6Al4V have been conducted and various researchers have reported that the weld joint of the alloy had remarkable properties. These results were obtained with the use of suitable combinations of process parameters. Munchen [21] reported that friction welding of Ti6Al4v requires one to determine the friction characteristics of the joining material to be able to select the welding speed as the friction coefficient changes with rotational speed. Yates [19] conducted a study on friction welding of Ti6Al4V and the author reports that process parameters play a significant role in the properties of the weld joint. The author reported an increase in tensile strength and hardness when the pressure is increased or the speed is reduced [19]. Bohme et al [7] reported that the friction welding process produces weld joints with improved properties. The authors reported a maximum strength of 1026 MPa and a hardness of 385 HV [7]. Wisbey et al [22] reported an elongation of 15% and the strength of 1030 MPa on the friction welded titanium tubes. Threadgill [20] reported three distinct weld zone in friction welded titanium alloy. These zones are weld nugget (WN), heat affected zone (HAZ), and thermo-mechanically affected zone (TMAZ) [20]. Mashinini and Hattingh [23] found only the WN and HAZ in the friction welding of titanium plates. Although researchers reported different results in friction welding of titanium alloys, it is of great importance to further study the behaviour of friction welded Ti6Al4V in order to improve the efficiency of the process in titanium alloys and to further understand the evolution of different microstructures and properties of the friction welds.

3 Material and experimental procedure

3.1 Material

The material used in the experimental work is the commercially available titanium grade 5 (Ti6Al4V rods) of 25.4 mm diameter. The rods of Ti6Al4V were machined to a diameter of 12.5 mm and a length of 82.5 mm. The chemical composition of the workpiece was V (4 % wt), Al (6 % wt), Fe (0.25 % wt), H (0.015 % wt), C (0.01 % wt), N (0.02 % wt) and O (0.155 % wt). Before the welding process, the workpieces were cleaned to remove organic contaminants, such as grease and oil.

3.2 Experimental procedure

A continuous-drive friction welding machine, Process Development System (PDS), available at Nelson Mandela University was used. The machine has a maximum spindle speed of 10000 RPM, spindle torque of 200 Nm, and a vertical load output of 100 kN. The welding platform is illustrated in Fig. 1.

Fig. 1. The welding platform.

The combination of process parameters used to weld Ti6Al4V workpieces are shown in Table 1. The heating and breaking times of the process were obtained using the process cycle produced by each welding process. The range of pressures and rotational speeds were selected based on the preliminary welds analysis and the recommendations made by various authors.

Table 1. Combination of process parameters.

Weld Num- ber	Rotational speed [N] (RPM)	Friction Pressure (MPa)	Forging Pressure (MPa)	Forging Time (sec)
RFW1	1600	25	95	25
RFW2	1900	25	95	25
RFW3	2300	25	95	25
RFW4	2700	25	95	25
RFW5	1600	40	95	25
RFW6	1900	40	95	25
RFW7	2300	40	95	25
RFW8	2700	40	95	25
RFW9	1600	60	95	25
RFW10	1900	60	95	25
RFW11	2300	60	95	25
RFW12	2700	60	95	25
RFW13	1600	80	140	25
RFW14	1900	80	140	25
RFW15	2300	80	140	25
RFW16	2700	80	140	25

The characterisation of the weld joint microstructure was performed using an optical microscope. The samples were cut from the welded specimens using the electrical discharge machining (EDM), hot mounted in a PolyFast resin using CitoPress-1 mounting machine, wet grounded with progressively finer grades of silicon carbide emery paper using water to

lubricate and cool and polished with DiaPro Allegro diamond paste and Collodial silica of 9 and 0.04 μm grain size respectively. Finally, the samples were etched using Kroll's reagent for 30 seconds. The surfaces of the etched samples were then viewed using an Olympus SZX16 microscope.

The tensile testing process was performed at a laboratory temperature according to the ASTM E8/E8M-13a testing standard [24], using Zwick/Roell Z250 test machine. Both, the Parent material and welded samples, were tested using a pre-load of 2 MPa and a test speed of 0.002 m/min. The percentage elongation of the tensile test specimens was determined using the initial and final lengths. The microhardness testing was performed on the microstructure samples using the ASTM E92 - 82 hardness test method [25]. The tests were carried out using Time Vickers microhardness testers with a load of 0.3 kg force for a dwell time of 10 seconds. An indentation spacing of 0.5 mm over a length of 10 mm was performed on the samples.

4 Results and discussion

4.1 Process cycle response graph

Fig. 2 illustrates the process response graph that was obtained at a rotational speed of 1600 RPM and 40 MPa friction pressure. The process parameters are presented against the welding time. This process cycle has similarities to that reported by Yates [19] and Palanivel et al [26] in the friction welding of titanium alloys. The response graph is made out of four stages marked by letters A to D, where:

- A – Dry friction stage
- B – Friction stage
- C – Braking Stage, and
- D – Forging stage

The dry friction stage has the workpiece rotating in the air for about 5 seconds, while the speed increases to a predetermined value of 1600 RPM. The friction stage consists of initial contact and the heating phases. The initial contact of the workpieces caused the torque to reach its first peak, as shown in Fig. 2. This was caused by instant contact of stationary and rotating workpieces, and a high abrasion rate as a result of low temperature at the interface. As the friction stage progressed, the torque decreased with an increase in the interface temperature. Due to an increase in the interface temperature to maximum weld temperature and material self-cooling process, the torque dropped to some value considered to be an equilibrium value. The torque oscillated within the equilibrium value for the remainder of the friction stage. There was an axial shortening that was observed as the friction stage progressed. This was caused by the soft material being ejected in a form of flash as a part of the self-cleaning process (all oxides layers and impurities are ejected). The disengagement of the drive motor and the application of brakes at the braking stage, caused the torque to spike up once again and reach the maximum torque of the process. This was caused by the inertia of rotating components and an increase in rotational resistance.

Fig. 2. Process cycle response graph obtained at 1600 RPM and 40 MPa

The application of forging pressure of 95 MPa followed after the breaking stage to consolidate the weld joint before the interface material cools down. This resulted in a further increase in axial shortening to 2 mm. The forging pressure was maintained for 25 seconds to allow the weld joint to cool under pressure. In the end, the pressure was removed and the welding process was complete. The welding time recorded was 45 seconds, as shown in Fig. 2.

4.2 Microstructure of the weld joints

The material’s microstructure is a significant element that determines the mechanical behaviour of the component in any form of application. The microstructure Ti6Al4V used for this research study is shown in Fig. 3. The alpha grains (light) are interspersed within the transformed beta (dark). In some regions of the microstructure, coarse acicular alpha grains were observed. This type of microstructure can be linked to different processes of Ti6Al4V processing that give the material its unique properties and allow Aluminium and Vanadium stabilizers to diffuse through the structure.

Fig. 3. Microstructure of Ti6Al4V

The microstructure of friction welded Ti6Al4V revealed 3 distinct weld zones namely, weld nugget (WN), thermo-mechanically affected zone (TMAZ), and the heat-affected zone (HAZ). These weld zones were identified based on the variation of the microstructure of the centre of the weld to the Parent material. Fig. 4 illustrates the weld zones of the Ti6Al4V weld joint.

Fig. 4. Distinct weld zones of Ti6Al4V weld joint

The microstructure of the WN revealed fine equiaxed alpha grains within a matrix of Widmanstatten beta grains, as shown in Fig. 5. This was linked to complete recrystallization that occurred as a result of the temperature elevating beyond beta-transus temperature. A basket-weave microstructure with fine acicula alpha particles was also observed at the WN and may be linked to cooling from an extreme temperature, as shown in Fig. 5. Mashinini et al [3] and Munchen [21] reported similar results in their studies on friction welding of Ti6Al4V. Also, very fine ‘needle-like’ martensitic grains were observed at weld joints of low energy input, as shown in Fig. 5. This was attributed to the heating and cooling processes in a short period as a result of a high-temperature gradient. The use of low welding speed and/or high friction pressure results in the production of the WN microstructure with very fine grains and a high volume fraction of martensitic grains.

Fig. 5. WN Microstructure

The microstructure of the TMAZ is almost similar to that of the WN because the region gets exposed to extreme temperatures that may result in recrystallization, as shown in Fig. 6. In most cases, it is very difficult to identify and distinguish this region from the WN as its existence is negligibly small in friction welded titanium alloys, resulting in other researchers treating it as part of the WN. However, it is very important to understand and clarify the evolution of this weld zone as it may be a point of poor mechanical properties. As observed, the region contains very fine equiaxed alpha grains with a very small volume fraction of martensitic grains, as shown in Fig. 6. This may be linked to the region being exposed to extreme temperature even though it is not physically involved in the joining process.

Fig. 6. TMAZ microstructure

The microstructure of a HAZ was observed to have elongated equiaxed grains aligned in a flow pattern, as shown in Fig. 7. This was linked to the rotational nature of FRW and the high heat flow rate as this was more visible on weld joints of high heat input, i.e., high welding speed and/or low friction pressure. The volume fraction of beta grains was higher than that of the parent material due to the exposure to elevated temperatures. The same observation was reported by My Nu et al [2] when friction welding titanium alloy.

Fig. 7. HAZ Microstructure

4.3 Mechanical properties of welded Ti6Al4V

Table 2. illustrates the tensile test results of weld joints obtained at different process parameters. The tensile test of the parent material revealed the Ultimate Tensile Strength (UTS) of 1026 MPa, the Yield Strength (YS) of 950 MPa, and the elongation of 18 %. The tensile tests conducted on the friction welded Ti6Al4V specimens revealed that the specimens produced at speeds of 1600 and 2700 RPM, and friction pressure of 25 MPa (RFW1 and RFW4) had poor tensile properties. This was concluded after obtaining the failure points within the weld zone, as shown in Fig. 8A. Such results were linked to the use of low friction pressure that may have demoted the rate of heat generation, the inter-atomic bond at the interface, and the efficiency of the self-cleaning process, resulting in the presence of weld defects. The YS, UTS, and the elongation of these specimens were almost equivalent to that of the parent material.

Table 2. Tensile test results

Weld Num-ber	Rotational speed [N] (RPM)	Friction Pressure (MPa)	Ultimate Tensile Strength	Yield Strength	Strain (%)
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			[UTS] (MPa)	[YS] (MPa)	
PM			1026	950	18.26
RFW1	1600	25	1029	948	19.87
RFW2	1900	25	1030	951	22.48
RFW3	2300	25	1029	949	22.06
RFW4	2700	25	1026	951	17.73
RFW5	1600	40	1033	947	22.64
RFW6	1900	40	1032	945	24.90
RFW7	2300	40	1036	952	25.34
RFW8	2700	40	1032	946	25.88
RFW9	1600	60	1036	950	25.12
RFW10	1900	60	1037	952	24.08
RFW11	2300	60	1036	947	25.52
RFW12	2700	60	1037	944	26.00
RFW13	1600	80	1038	953	24.73
RFW14	1900	80	1040	948	26.68
RFW15	2300	80	1038	950	26.36
RFW16	2700	80	1035	946	27.32

Fig. 8. Tensile test specimens

The weld joints made at 40, 60, and 80 MPa friction pressures respectively had the failure point away from the weld zone, as shown in Fig. 8B. This revealed that their weld joints had improved tensile properties compared to the parent material. This is attributed to the recrystallized fine equiaxed grains obtained in the weld joints. This was also linked to narrower weld joints achieved as a result of increased friction pressure resulting in low energy input for the process. The maximum UTS of 1040 MPa and the elongation of 26,68 % were achieved at the specimens welded with 1900 RPM rotational speed and 80 MPa (RFW14) friction pressure. Yates [19] and Da Silva [8] reported similar results in their studies.

Fig. 9 illustrates the micro-hardness results obtained at weld joints of 1900 RPM and 80 MPa. The hardness was tested in the outer, middle, and inner diameters of the weld joints. The results revealed an increase in the hardness properties from the HAZ to the WN. The maximum hardness of 376 HV0.5 Ti6Al4V was obtained at the WN, as shown in Fig. 9. This was attributed to the very fine grains achieved at this zone. Other weld joints obtained at different process parameters revealed an increase in the hardness properties on the HAZ, TMAZ, and WN. Such behaviour was linked to the heating and cooling processes that occurred and the fine grains observed. Similar results were reported by Dalgaard [27] in friction welding of titanium alloys.

Fig. 9. Micro-hardness test graph

4.4 The effect of speed and pressure on the mechanical properties of friction welded Ti6Al4V

Fig. 10 presents the effect of varying speed and pressure on the tensile and hardness properties of the welded specimens. Rotational speed and friction pressure are the primary and sensitive process parameters of the RFW process. The main function of the speed is to generate the relative motion to enhance heat generation, while the function of friction pressure is to maintain intimate contact of the surfaces, prevent oxidation and enhance consolidation [16]. Fig. 10A and B present the effect of varying speed on the UTS and hardness of welded Ti6Al4V. The results revealed that an increase in rotational speed decreases the UTS and hardness properties. This may be linked to a reduced friction coefficient at high-speed resulting in a low rate of heat generation, and thus wider weld width. Therefore, rotational speed has an inverse proportionality to the UTS and hardness.

Fig. 10. The effect of speed and pressure on the weld joint properties

Fig. 10C and D illustrate the effect of varying friction pressure on the UTS and hardness of welded Ti6Al4V. The results revealed that the increase in friction pressure increases the UTS and hardness properties of the weld joints. This can be linked to a high heat generation rate at high pressure, promoting recrystallization at the weld interface. The weld joints of high friction pressure were observed to have very fine grains which may be the reason for high UTS and hardness. Friction pressure is directly proportional to the UTS and hardness

properties of the weld joint. Friction pressure and welding speed do not have a significant effect on the weld joint properties if varied within the optimum pressure and speed respectively.

5 Conclusion

Titanium alloy Ti6Al4V was successfully welded with the RFW process. The weld joint microstructures achieved had three distinct weld zones. The WN had fine equiaxed alpha grains within the transformed beta grains. The martensitic alpha grains appeared well on the weld joints produced at high friction pressure and low rotational speed. The use of very high or low speed with low friction pressure increases the probability of obtaining welds with poor tensile properties. The maximum UTS, strain, and hardness were achieved at welds of 1900 RPM speed and 80 MPa pressure. Speed and pressure had no significant impact on the weld joint properties when were varied with the optimum range.

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