

Process optimization of rotary friction welding of Ti-6Al-4V alloy rods

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Abstract. This paper presents an investigation on the performance of rotary friction welded 25.4 mm diameter Ti-6Al-4V alloy rods. The process parameters used are friction and forging pressure, rotational speed, forging time and upset distance. The heating time was determined by the amount of friction pressure and rotational speed utilised. The final weld joints were examined for mechanical properties. The results revealed that friction welding process parameters have significant influence on the weld joint properties and weld joint integrity. The hardness and ultimate tensile properties of the weld joints varied with the variation in rotational speed and axial pressure. The tensile properties of the weld joints were higher than the parent material at lower rotational speed or higher axial pressure. The weld width was proportional to relative motion and inversely proportional to axial pressure.

1. Introduction

Joining of similar and dissimilar materials has always been a challenge in conventional welding processes. This challenge instigates because of deterioration in mechanical properties and change in the microstructure of the material at the weld joint. As a result, the weld joint becomes a point of failure during the transverse tensile test and the component loses trustworthiness for the critical applications. This challenge has always been a nightmare for fabricators even though many investigations and developments have been done to improve the efficiency of conventional welding processes, such as arc welding [1]. In many cases, deterioration of mechanical properties is a consequence of melting that happens at the weld interface as well as low temperature segregation caused by filler material during conventional welding processes [2-3].

Rotary friction welding (RFW), a solid-state welding process, is one of friction welding processes that maintains or have improved properties at the weld interface without the use of filler material. This is because this typical welding process occurs at a temperature below melting point of the parent material being joined therefore no melting occurs. On the other hand, since there is no filler material being utilized, the process eliminates defects associated with poor selection of filler material and undesirable effects of low temperature segregation [2-4]. RFW can be used to join many similar and dissimilar materials without any difficulties, even materials that were considered not weldable by the use of conventional methods or techniques.

RFW process consists of two joining workpieces, one placed at a stationary fixture and the other at a rotating fixture. The process is performed by rotating one part relative to the other along their common axis. This is done simultaneously with the application of axial pressure to enhance rubbing as a result of increased friction coefficient. The relative motion together with axial pressure increases interface temperature. This temperature is proportional to the axial pressure and inversely proportional to rotational speed [5-7]. When the interface temperature is high enough to induce plastic state, plasticized material at the interface is displaced out through the edges. This is a very important phase as all impurities are ejected out, leaving clean material from both workpieces. The final increased axial pressure is applied to permit consolidation after stopping relative motion. At this stage too, plasticized material is pushed out in a form of a flash. The weld interface is allowed to cool while consolidating. Finally, the axial pressure is quickly removed and the welding is complete. The weld joint formed consists of distinct weld zones as a result of microstructure variation [8-9]. Although this process produces a high-quality type of weld joint, there are major difficulties associated with poor selection of process parameters. Firstly, metal surfaces of workpieces are rough at atomic scale. Therefore, when low axial pressure is applied only fewer sections of the interface get into contact. Secondly, high axial pressure increases the number of contact surfaces, but oxides layer and occluded gas present in all metals under normal atmospheric conditions are encountered. On the other hand, higher relative motion or lower axial pressure increases the volume of material affected by heat, while lower relative motion or higher-pressure results in a visible physical deformation [1, 11-12]. However, these difficulties can be avoided if much attention is paid on the selection of process parameters based on the geometry of the workpieces and the properties of the material to be welded.

2. Welding Ti-6Al-4V under different conditions

Titanium grade 5 (Ti-6Al-4V) is one of material that is regarded difficult to weld using conventional welding processes. This is because this metal is highly reactive to the environment (air) at elevated temperatures. Therefore, much attention has to be paid on shielding to prevent defects associated with atmospheric gases. Rotary friction welding of Ti-6Al-4V has been performed widely under different process conditions or parameters. It has been reported that the variation in process parameters has a significant influence on the properties of friction welded Ti-6Al-4V. Poor selection of process parameters results in a weld joint with poor mechanical properties. Daldaard [7] reported that an increase in relative motion increases heat density, which in turn decreases friction coefficient resulting in a low heating rate. The research also reported that the heat density is inversely proportional to axial friction pressure. Dinaharan et al [3] reported that at higher rotational speed the coefficient of friction is lower resulting in longer heating time, high heat conductivity rate and later amount of material pushed out in a form of flash. Tolvanen [13] mentioned that cooling rate is the very important factor that determines the integrity and properties of component at the interface. The researcher also revealed that the cooling rate is proportional to pressure and inversely proportional to rotational speed.

Although other researchers believed that variation in process parameters have significant influence on the weld joint properties, Vill [14] believed that rotational speed is the least sensible process parameter and axial pressure does not have significant effect if it is not varied over a wide range. This was also supported by Yate [15] on the inertia friction welding of Ti-6Al-4V. However, Da Silver [1] and North [16] opposed this revealing that low relative motion reduce weld width therefore increases the tensile properties of weld joint. Munchen [17] reported that an increase in axial pressure reduces heat input, which results in higher cooling rate and hardness. Although researchers have different opinions regarding the effect of process parameters on the weld joint quality, it is important to understand the role of each process parameter in the production of weld joint.

The aim of this research study is to optimize the rotary friction welding process of Ti-6Al-4V under various conditions and to evaluate the effect of variation in process parameters. This was achieved by keeping certain process parameters constant while varying others.

3. Experimental procedure

3.1. Welding platform

The platform utilized for the welding of Ti-6Al-4V rods of 25.4 mm diameter was Process Development System (PDS) for friction welding process, located at Nelson Mandela University in Port Elizabeth, South Africa. The welding platform is fully automated with a computer interface that allows the switch between different process parameters and data collection.

3.2. Process parameters and Mechanical Testing

Rotational speeds of 1600, 1900, 2300 and 2700 rpm, and heating pressures of 25, 40, 60 and 80 MPa were utilized during rotary friction welding of Ti-6Al-4V rods, which was conducted on the laboratory under argon gas shielding. Forging time, forging pressure and upset distance were kept constant at 25 s, 95 MPa and 2 mm respectively. The heating and braking times were determined using process cycles recorded for each welding process. The range of heating pressures and rotational were selected based on the analyses of preliminary welds.

Tensile strength and micro-hardness were the tested mechanical properties on the welded specimens. The tests were performed on the welded samples and the parent material. The tensile test samples were prepared using ASTM E8/E8M-13a standard while hardness test samples were prepared using ASTM E92 standard. The tensile test speed of 2 mm/min and a pre-load of 2 MPa were used. The tensile testing was carried out at room temperature using Zwick/Roell Z250 tensile test machine, with the load capacity of 250 kN. Hardness testing was determined on the samples using Time Vickers micro-hardness tester. The hardness profile was performed at different locations of weld interface. The indentations were made over a distance of 10mm with a spacing of 0,5mm. The load of 300gf for a dwell time of 10 seconds was used.

4. Results and discussion

4.1. Process cycle

Figure 1 illustrates the rotary friction welding process cycle of Ti-6Al-4V that was recorded at a rotational speed of 1600 rpm and 40 MPa heating pressure. The different process parameters used as well as the responses are graphically represented against the welding time. The process is made out of three stages (as clearly marked with the letters in Figure 1) and these stages are heating stage - A, braking stage - B and forging stage - C. heating stage is divided into initial phase and constant heating phase.

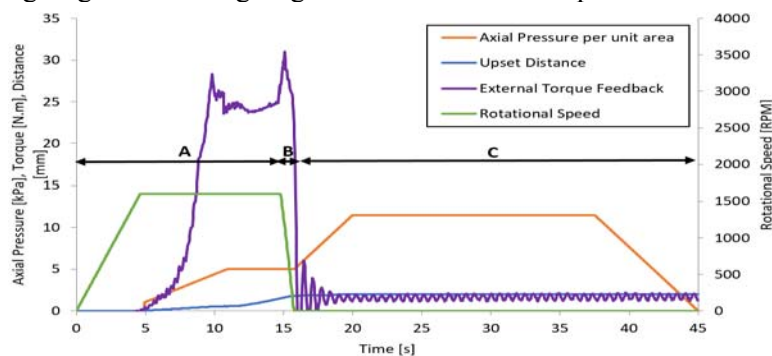


Figure 1. Process cycle obtained at 1600 rpm and 40 MPa

The pre-determined value of rotational speed (1600 rpm) was reached before the initial contact of the workpieces. This was done to reduce the friction coefficient at the initial contact. The predetermined value of heating pressure (40 MPa) was reached during the initial phase of the heating stage. This value was reached through a constant increment known as the ramp rate. The initial contact of workpieces causes a torque to increase and reach its first peak value. This was due to a higher friction coefficient as

a result of low temperature on the joining surfaces. As the heating stage progressed, the interface temperature increased resulting in a decrease in friction coefficient, which in turn caused a sudden decrease in torque to some extent, as shown in Figure 1. The interface temperature was inversely proportional to the coefficient of friction and rotational speed. This was backed up by Dalgaard [7] on the Linear Friction Welding (LFW) of Titanium alloys. The torque decreased further to some extent that was considered as an equilibrium torque as the heating stage progressed further. This may be correlated to a high temperature being reached at the interface causing a further decrease in the wear rate and friction coefficient. This may also be linked to the interface material getting softer and pushed out because of heat and pressure. The torque oscillated along its equilibrium value for a short period and gradually increased at a minimum gradient through the remainder of the constant heating stage. This was due to the variation of interface temperature as a result of self-cooling process of Ti-6Al-4V. In addition, an increase axial shortening was observed throughout the constant heating phase. This was linked to interface material being soft and pushed out as a result of relative motion and applied pressure. The braking stage was reached at the end of heating stage. At the braking stage, the drive motor was dis-engaged and brakes were applied. This was done to eliminate the relative motion before consolidation. The torque value increased yet again and reached its second peak value that was the maximum torque of the welding cycle. This was caused by an increase in rotation resistance. Additionally, an increase in axial pressure to a pre-determined forging pressure resulted in a rapid increase in axial shortening. This was achieved by pushing more soft material out in the form of a flash. A forging pressure of 95 MPa was applied at the end of braking stage to the stationary workpieces. This resulted in a further increase of axial shortening to a pre-set value of 2 mm. Forging pressure was maintained at a pre-determined value for a period of 20 seconds to allow consolidation and self-cooling of material affected by the heat. At the end of forging stage, pressure was quickly removed and Ti-6Al-4V weld joint was formed. Similar process cycle was obtained by Palanival et al [3] during friction welding of Titanium tubes.

4.2. Effect of process parameters on Ti-6Al-4V weld joint

Rotational speed is one of the sensitive process parameters in rotary friction welding of Titanium alloys. It has an extensive influence on the weld joint quality if it is varied over a wide range. The efficiency of RFW is improved by using a relatively low rotational speed, as shown in Table 1. The observation on friction welded Ti-6Al-4V revealed that the shearing effect at the weld interface was replaced by polishing action at a higher rotational speed. This was attributed to a minimum coefficient of friction at a higher rotational speed resulting in a low heating rate that allows for higher heat propagation rate along workpieces axially. Lower heating rate prolonged heating time, which in turn caused heat loss resulting in a greater amount of energy being used for welding process. In addition, the weld joint produced at higher rotational speed had wider width as a result of heat dissipation. The tensile and hardness tests revealed that the weld joints of higher rotational speed were weaker while those of low rotational speed were improved. This was concluded after having failure points within the weld zone for high speed (as shown in Figure 2a) and outside of the weld joint for lower rotational speed (as shown in Figure 2b). This was attributed to the minimum temperature gradient as a result of higher heat dissipation rate. Higher rotational speed demotes the cooling rate, wide weld width and hence reduces mechanical properties of the weld joint.

Table 1. Tensile and hardness test results at different speeds and pressure

	Rotational Speed (rpm)				Axial Pressure (MPa)				Parent material
	1600	1900	2300	2700	25	40	60	80	
Tensile Strength (MPa)	1035	1033	1030	1024	1022	1022	1031	1034	1030
Micro Hardness (HV)	375.9	372.3	370.8	365.0	346.5	351.6	359.2	360.2	336

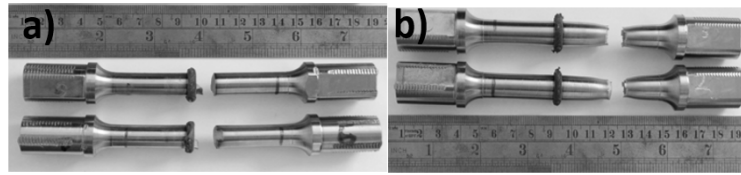


Figure 2. Typical tensile specimen failure positions at: a) high and b) low rotational speeds.

Another sensitive process parameter is the axial pressure. It regulates the weld joint temperature gradient, friction power required and upsetting. Axial pressure can be varied over a wide range depending on the materials properties as well as the geometry of workpieces to be welded. The main function of axial pressure is to maintain intimate contact of the surfaces, preventing oxidation and enhancing consolidation. When low axial pressure is applied fewer sections of the interface get in contact. This prolongs welding time, increases weld defect possibilities and promotes heat propagation along the workpieces consequently, larger volume of material gets heated and a large weld joint is produced. The mechanical properties of weld joints of light axial pressure exhibit poor mechanical properties, as shown in Table 1. This is caused by lack of bonding and weld defects present within the weld joint. Therefore, the weld joint becomes a point of failure during tensile test of welded specimens, as shown in Figure 2a). Low axial pressure reduces shortening rate, increases heat propagation rate, increases weld defects and increases weld width.

4.3. Results and characterisation of weld joint.

The analyses of welded Ti-6Al-4V samples revealed a change in microstructure across the weld joint. The weld nugget (WN), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) were three distinct weld zones that were obtained during microstructure characterization. The same results were reported by Dalgaard [7]. A basket-weave microstructure with complete recrystallization was obtained at WN, as shown in Figure 3a). The refined alpha grains were well distributed within transformed beta grains. This was caused by recrystallization occurred as a result of temperature elevating beyond beta-transus temperature. Cooling from the temperature above beta transus resulted in very fine acicular grains within the WN. In addition, very fine martensitic alpha grains were more visible at the weld joints produced at lower rotational speed and higher axial pressure. This was due to the faster heating and cooling rate as a result of high temperature gradient between weld joint and cold base material. The microstructure of TMAZ is almost similar to that of WN. This is because this region is exposed to extreme temperature for a short period of time, therefore allowing partial dynamic recovery, although it is not physically active on the welding process. This region contains very fine grains with the presence of acicular alpha grains, as a result of extreme temperature exposure, which may have resulted in recrystallization, as shown in Figure 3b). Furthermore, the microstructure of the HAZ contains visible alpha grains within the fully transformed beta phase. The grains of this region were elongated and arranged in a radial flow pattern, as shown in Figure 3c). This may be attributed to the nature of RFW and heat propagation, which may have caused a loss of torsional stiffness at this location.

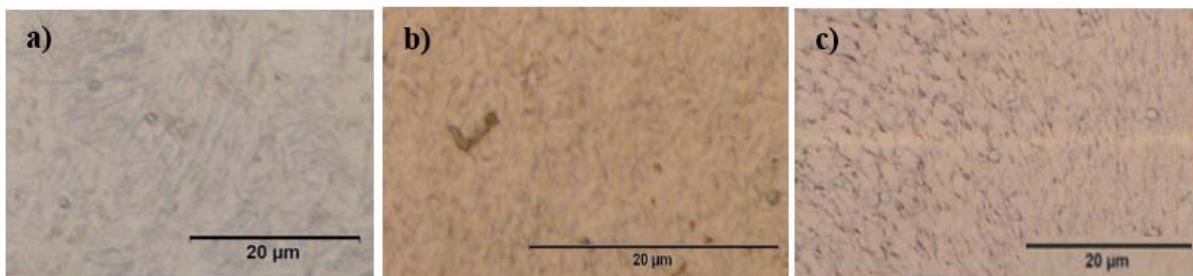


Figure 3. Microstructure of WN a), TMAZ b) and HAZ c)

5. Conclusion

Titanium rods of 25.4 mm diameter were successfully welded at different rotational speeds and axial pressures. The results revealed that axial pressure and rotational speed had significant influence on the quality of the weld joint and weld integrity. The increase in rotational speed reduced the mechanical properties of the weld joint as a result of reduced friction coefficient. Rotational speed was proportional to weld width and inversely proportional to welding time. The weld joint obtained had typical weld zones in friction processing: weld nugget, thermo-mechanically affected zone and heat affected zone. The weld nugget has basket-weave microstructure with very fine acicular grains.

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