The influence of rotational speed and pressure on the properties of rotary friction welded Titanium alloy (Ti-6Al-4V)

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Abstract

This paper presents an investigation of rotary friction welding of 25.4 mm diameter Ti-6Al-4V rods. The weld process parameters used for this research were rotational speed, axial pressure and forging time. Only relative speed and axial pressure were the varied parameters while the forging time was kept constant. The mechanical properties of the weld joints were analysed and characterized. The results showed that the rotational speed and friction pressure have significant influence on the tensile strength, microstructure and weld integrity. As rotational speed increased heating time also increased in the weld, as a result, greater volume of material was affected by heat resulting in a wider width of the weld joint. Fine microstructure resulted due to an increased rotational speed and frictional pressure respectively. The oxidation and discolouration of welds were also discussed.

Keywords: Rotary friction welding; process parameters; Ti-6Al-4V; microstructure; mechanical properties

1. Introduction

Titanium alloys are non-ferrous materials that can be welded by diverse types of welding techniques. Most of the welding processes that have been used in the past with success in joining of Titanium alloys were limited to conventional welding methods [1]. With developments in technology and joining technique, new methods were established including solid-state welding process [2]. Rotary friction welding (RFW) as one of solid-state welding process has been used with success in joining Titanium alloys for industries and in a wide range of experimental applications [3]. RFW is a welding technique invented and patented American Welding Society (AWS) [4]. RFW is a joining process that utilizes frictional heat generated from the rotating rod surface abutting with a non-rotating rod because of applied pressure axial to the welded rods. A frictional time is allowed to enable the surfaces to bond as the rotating member is stopped [5]. Fig. 1 illustrates the various steps for the welding process. It is expected that RFW process will continue to be used successfully and its applications will gain a wide range of use for Titanium and its alloys as more knowledge and understanding of the process is developed especially for Titanium and Titanium alloys specifically, Ti-6Al-4V alloy as it is the mostly used alloy [5].

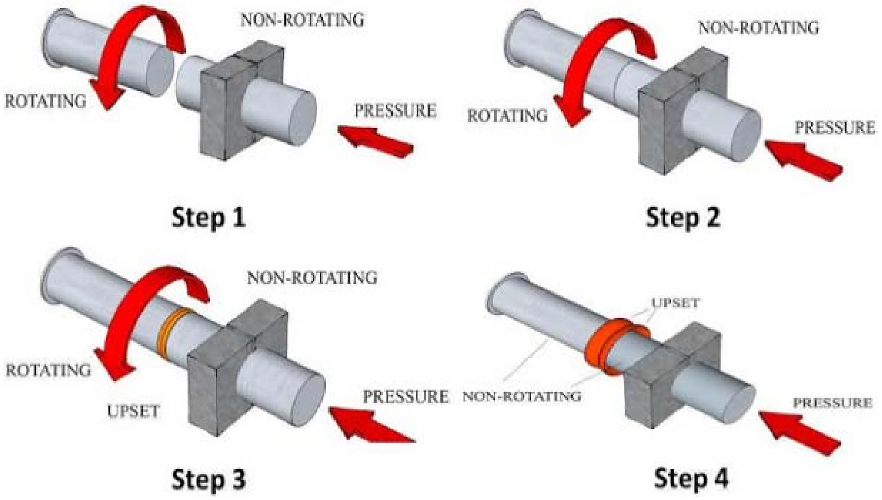

Fig. 1. Sequence of RFW process [6]

Titanium alloys have unique properties that makes the metal to be the best material for various applications [3, 7]. Titanium alloy components are mostly found where corrosion resistance and high strength properties are needed, such as in aerospace, marine application, chemical plants, medical applications and in the transportation sector [8, 9]. Titanium alloys have low density to high strength ratio that makes it ideal for high performance components [3, 7]. From the literature review, it was reported that it is possible to join dissimilar and similar metals with rotary friction welding technique. However, there are limited studies that have focused in welding of Titanium alloys by RFW. Therefore, the objective of this research was to join Titanium rods by rotary friction welding and present the change in microstructure and tensile properties of the weld joints in relation to parent material. RFW process is usually controlled by process parameters, which when engaged together significantly affect the joint quality. These process parameters are rotational speed (n), axial pressure (P_a), welding time (tw) and upset distance (s) [2]. However, researchers of friction welding process have reported different opinions on the influence of process parameters on the quality of the weld joints. da Silver [10] reported that rotational speed is the least sensible process parameter therefore can be varied over a wide range without influencing the weld quality [10]. Although Beloshapkin [11] said that forging pressure is not significant in RFW, it is important to have adequate axial pressure to prevent the occurrence of oxidation of the weld. This may result in a weld joint with voids and further discoloration [12]. Just like Yates [1] and da Silva [10] who suggested that the forging pressure should at least be twice the heating pressure for the formation of weld joint with no complications [10, 1]. Vill [13] reported that each material has optimum rotational speeds for friction welding process. If rotational speed is varied within the limits of optimum speeds, it does not have significant effect on the weld joint [13]. Beloshapkin et al [11] mentioned that the best quality of weld joint can be achieved when forging is not applied. Therefore, this explains that forging pressure is not significant in RFW process. They also reported that welding time is independent of workpieces diameter but depends on the properties of materials to be welded [11]. Palanivel et al [11] reported that rotational speed as well as axial pressure have almost the same influence on the weld joint quality.

As rotational speed increases or axial pressure decreases, the properties of the weld joint reduces. This was mentioned by Beloshapkin et al. [11] on their study. Although researchers have different views regarding the effect of parameters on the weld joint, it is of great significant to comprehend the importance of these process parameters in a formation of a high-quality weld joint. Investigating an influence of process parameters using Titanium alloy Ti-6Al-4V is important for both engineering and scientific perspective. Firstly, the use of Ti-6Al-4V has increase worldwide and currently accounts for 50% of the total usage of Titanium in the world over [14]. Secondly, RFW process has been used as an alternative joining process to be a replacement of conventional welding techniques for cylindrical components of Ti-6Al-4V. This process has been suggested to be a quick and efficient welding process, and since the process does not require any filler material, it removes the influence of low temperature segregation and prevent possibilities of weld oxidation and porosity [15, 16]. Due to a nature of RFW process, it is important to understand the procedure of process parameter selection for the production of high strength welds. Poor selection of parameters can lead to a weld joint with poor mechanical properties and thus become a point of failure during static and dynamic testing [12, 17].

2. Experiment procedure

2.1 Welding platform

Commercially available Ti-6Al-4Valloy rods of 25.4 mm diameter were used for this study. The rods were welded with continuous-drive friction welding process. The welding platform utilized for joining the Titanium rods was Process Development System (PDS) for friction welding process that is based at Nelson Mandela University in Port Elizabeth South Africa. The platform is fully automated with a computer interface that allows for the entering of input process parameters and the recorded data collection. With this unique platform, perfect weld joints are achieved through the engagement and collaboration of different process parameters. Such input parameters include axial pressures (friction and forging), rotational speed, upset distance as well as rotational speed. Fixtures to clamp the stationary and rotating rod were designed to hold securely the workpieces in a vertical position, and to have a perfect alignment between joining parts. Fig. 2 illustrates the arrangement of the fixture and the workpieces. In addition, holders were designed with the gap screws that assist in preventing slippages during welding. Shielding gas was supplied to the transparent shielding shroud through tubes (as seen in Fig. 2) to prevent oxidation and further discoloration of the weld joint. The argon gas occupied the bottom half of the glass, as it has greater density than air.

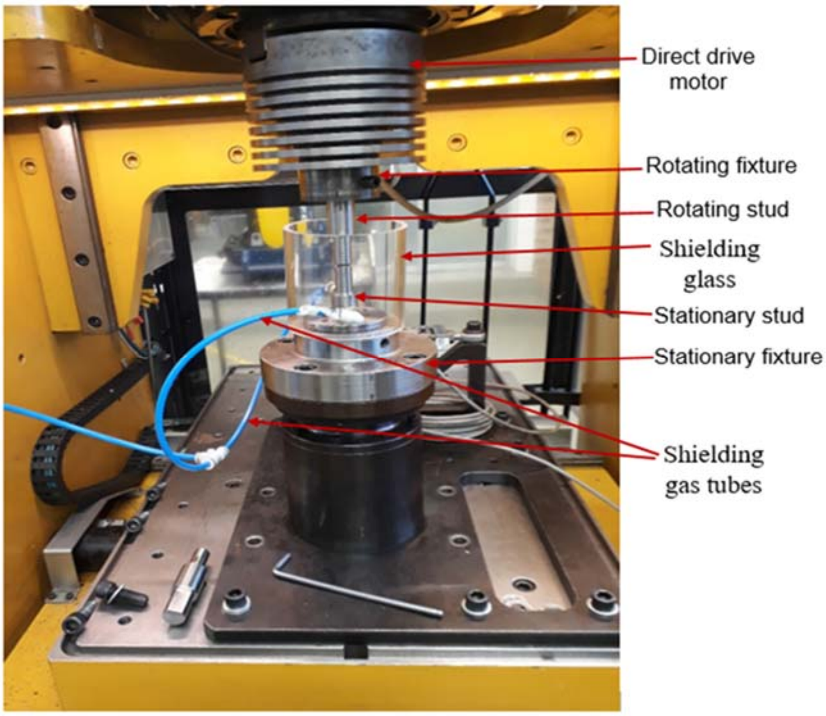

Fig. 2. Welding platform

2.2 Process parameters

Titanium alloy rods were welded at rotational speeds of 1600 rpm, 1900 rpm and 2300 rpm. Frictional pressures used were 40 MPa and 60 MPa. A forging pressure of 100 MPa and forging time of 25 s were used and kept constant. An upset distance (S) was calculated based on the final (L_f) and initial (L_i) lengths of the specimens, according to the following expression.

$$s = L_i - L_f \qquad \text{Eq. 1}$$

The range of rotational speeds as well as frictional pressures were chosen based on the visual examination of the flash formation and distortion of the welds from preliminary welding. Similarly, microstructure analysis of the preliminary welds was done to identify weld defects, lack of bonding, presence voids and excessive amount of flash of which also assisted in determining the suitable weld process parameters.

2.3 Microstructure analysis

Microstructure characterization of welds was done on the samples using an optical microscope. Samples were initially prepared and cut to size suitable for standard metallurgical evaluation using electrical discharge machining (EDM) to eliminate addition heat added to the samples during cutting and preparation. The samples were hot mounted in a PolyFast resin and wet ground with progressively finer grades of silicon carbide emery papers using water to both cool and lubricate. Ground samples were polished with Diapro Allogra diamond paste of 0.04-micron grain size. Finally, polished samples were etched using Kroll's reagent for approximately 30 s. Optical microscope was utilized to view microstructures of etched surfaces.

2.4 Tensile testing

Tensile testing was done on the samples produced. The tests were prepared using ASTM E8/E8M-13a standard test method. The gauge section of test specimens had a cross-section of 12.5 mm in diameter and a gauge length of 62.5 mm, as shown in Fig. 3. The tensile test ramp rate of 2 mm/min and a pre-load of 2 MPa were used respectively.

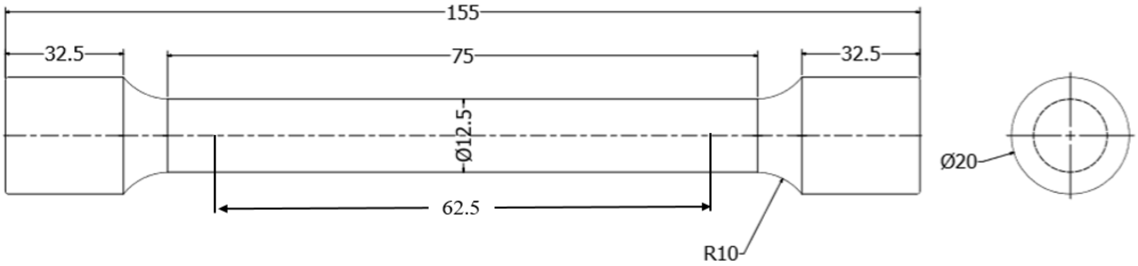

Fig. 3. Tensile test specimen (All measurements in millimeters)

3. Results and Discussion

3.1 Weld geometry

Fig. 4 illustrates a typical weld geometry of a weld joint obtained at a rotational speed of 1900 rpm and friction pressure of 40 MPa. The weld geometry of friction welded Titanium alloy is a significant aspect that demonstrate the quality of the weld joint produced. This can be attributed to different shapes and weld width that can be obtained in a rotary friction welding of Titanium alloys. A wider weld joint indicates that either rotational speed was high, heating time was longer or axial pressure was low. Therefore, this indicate poor weld joint properties [14, 2, 18]. Ti-6Al-4V weld joint produced at a rotational speed of 1900 rpm and 60 MPa (as seen in Fig. 4) had a very much similar shape to that of a bi-concave shape. This shape was also reported by Yate [1] on inertial friction welded Ti-6Al-4V. The width at the edges was almost twice the width at the weld center. This may be due to a variation of heat density and peripheral velocity along the weld interface. The heat density is higher at the center of the weld interface and gradually reduces at the edges. Peripheral speed increases with an increase in diameter at the interface. This was also confirmed by Vill [13] on the friction welding of metals. The heat density is inversely proportional to an increase in peripheral speed [13, 1]. The weld joint width depended mostly on rotational speed and axial pressure. At a lower rotational speed, weld joint was observed to have a narrower width. This may be due to the fact that at a lower rotational speed the coefficient of friction is high. Therefore, full plasticization was reached at a shorter heating time. Shorter heating time demotes heat propagation on the workpieces in an axial direction resulting in a smaller volume of material being affected by frictional heat. At a higher rotational speed, heat dissipation is promoted by longer heating time because of lower coefficient of friction. Larger volume of material got affected by frictional heat, which in turn caused a production of wider weld joint. On the other hand, friction pressure has a significant impact on the width of the weld joint as it controls the temperature gradient, energy required as well as upset distance [19]. However, specific amount of friction pressure depends upon the material to be joined and workpieces geometry. A narrower weld width was obtained at a friction pressure of 60 MPa. This may be attributed to an elevated friction coefficient caused by higher friction pressure. According to Attallah [20], heating rate increases with an increase in pressure preventing large volume of material from being affected by heat [20]. Dalgaard [19] backed this up on the linear friction welding of titanium alloys. In addition, a decrease in friction pressure limits heating with little or no upset distance. This occurs because of prolonged heating time. Greater amount of heat energy is dissipated axially through the workpieces and lost through radiation. Therefore, wider weld joint is produced from larger volume of material that plasticized. An increase in weld width increases the thickness of heat affected zone and thermos-mechanically affected zone [3, 21].

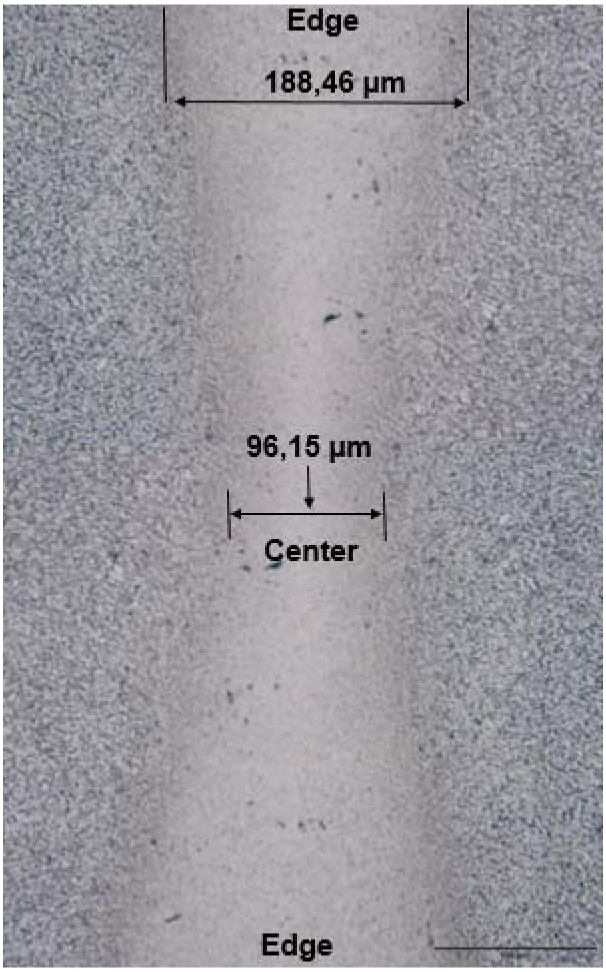

Fig. 4. Weld geometry

3.1 Microstructure characterization

The micrograph of the parent material revealed a modal microstructure. Alpha grains (light) were interspersed in a matrix of a transformed beta (dark), as seen in Fig. 5. The well distributed equiaxed alpha grains in a matrix of transformed beta was the result of prior processing and heat treatment of the material [3, 9, 7].

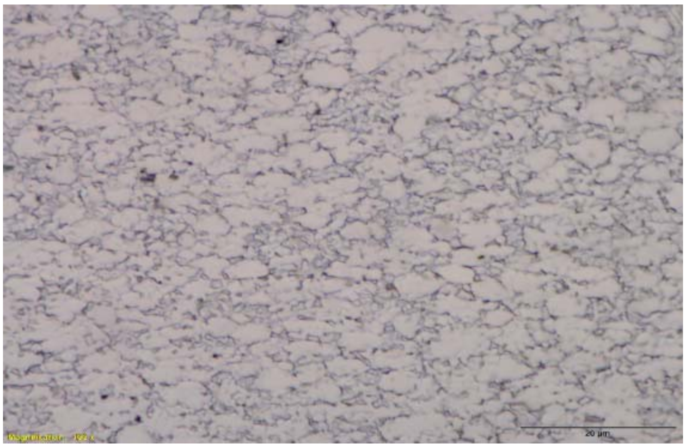

Fig. 5. Parent material Microstructure (100X)

Microstructures of weld center obtained at different rotational speeds and friction pressures are shown in Fig. 6. These microstructures have significant similarities to those obtained by Threadgill [21] and Yates [1] on the friction welded Ti-6Al-4V. The weld center had very fine acicular grains within a basket-weave microstructure as a result of cooling from above beta transus temperature. Martensitic 'Needle like' alpha grains within the matrix of re-crystallized beta grains were observed to be more visible in the weld joints produced at a friction pressure of 60 MPa. This was due to heating and cooling processes in a short period at elevated friction pressure. Very fine equiaxed grains observed in all welds may be attributed to the recrystallization that occurred because of elevated temperature beyond beta transus and application of higher axial pressure. The microstructure of lower rotational speed was observed to have more refined grain size than that of higher rotational speed, although they are all equiaxed. This may be due to faster cooling rate at lower rotational speed as a result of higher temperature gradient between weld joint and parent material as well as low heat propagation rate of Ti-6Al-4V. This was backed up by Dalgaard [19] on the linear friction welded Ti-6Al-4V alloy [14].

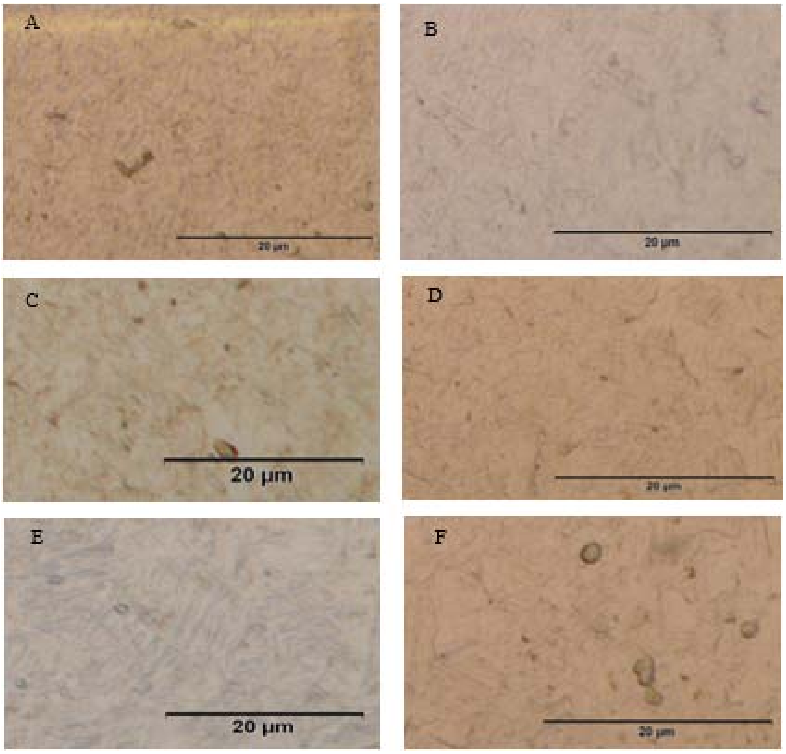

Fig. 6. Microstructures of weld center obtained at; A) 1600 rpm and 40 MPa, B) 1900 rpm and 40 MPa, C) 2300 rpm and 40 MPa, D) 1600 rpm and 60 MPa, E) 1900 rpm and 60 MPa and F) 2300 rpm and 60 MPa

The heat affected zone (HAZ), which is another region of Ti-6Al-4V weld zone, was observed to have material flow in one direction, as shown in Fig. 7. This observation was noted at higher axial pressure and rotational speed. Elongated equiaxed grains in the HAZ microstructure were arranged in a certain flow pattern. This is the result of rotation nature of RFW process. The same observation was reported by Halford [22]. At high rotational speed larger volume of material becomes soft because of high heat propagation rate. This result in a loose of torsional stiffness.

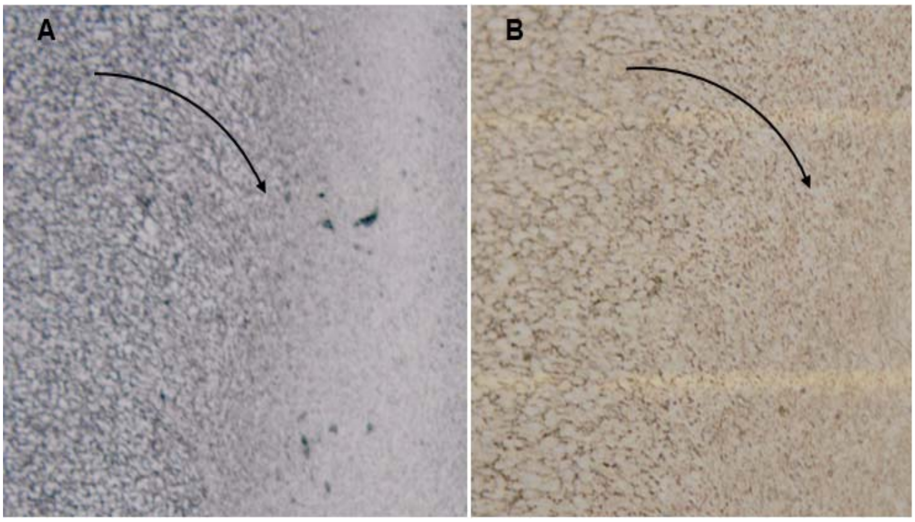

Fig. 7. Material flow in the HAZ (50X)

3.2 Tensile strength

Fig. 8 illustrates tensile test results of rotary friction welded Ti-6Al-4V specimens at different rotational speeds and friction pressure. The tensile test performed revealed that weld zones produced at 40 MPa friction pressure were stronger than the parent material. This was concluded after having fractures away from weld zone, as shown in Fig. 9A. This may be attributed to very fine equiaxed grained microstructure obtained in the weld zone, which is in agreement with the work reported by Dalgaard [19].

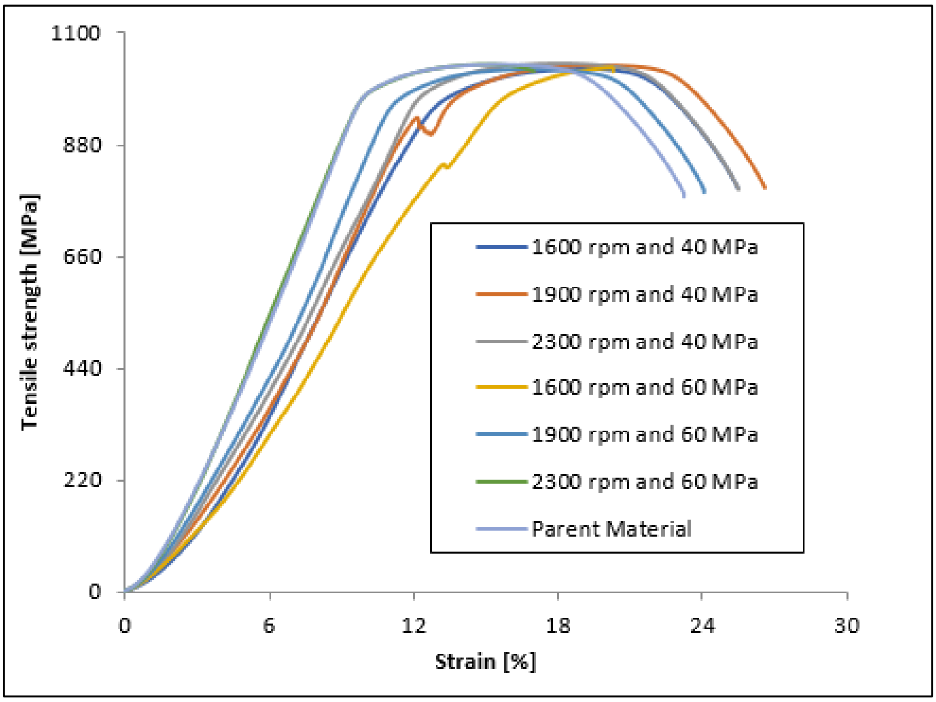

Fig. 8. Tensile test graph

On the other hand, the tensile test of specimens welded at 60 MPa friction pressure had specimen failures within the weld zone. This was observed from specimens welded at 1600 rpm and 2300 rpm, as seen in Fig. 9B. This was attributed to the fact that these speeds are the lower and upper limits of optimum speeds respectively. This may also be related to heating and cooling processes that reduce ductility of weld joint, which in turn reduces percentage elongation. In addition, discoloration and oxidation in the weld join may have affected the weld joint quality.

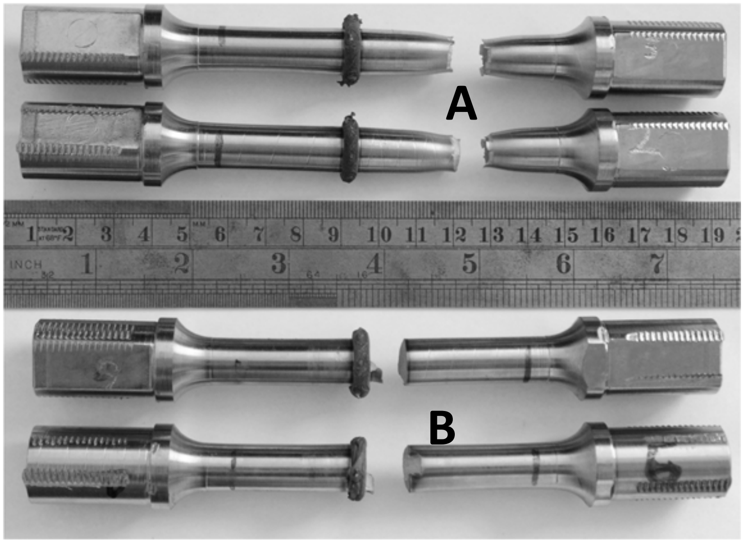

Fig. 9. Tensile test specimens A) Failed away from weld zone and B) failed on the weld zone

The ultimate tensile strength of all friction welded specimens was almost similar to that of parent material of 1030 MPa. This was linked with specimens' failure occurring within the parent material and weld zone. The change in rotational speed at a lower pressure did not have a significant influence on the tensile properties of the weld joint. At elevated friction pressure, significant influence of speed variation was observed on elasticity gradient and percentage elongation. An increase in rotational speed at elevated friction pressure increased gradient of elastic region and reduces elongation because of heat dissipation. This revealed that rotational speed is proportional to gradient of elastic region and inversely proportional to elongation.

4. Conclusion

Ti-6Al-4V alloy rods of 25.4 mm diameter were joined successfully using a continuous-drive friction welding process at different speeds and friction pressures. The thickness of weld joint widened with rotational speed increase because of increase in heat propagation rate. Weld width was proportional to rotational speed and inversely proportional to axially applied pressure. The weld center had basket weave microstructure containing very fine equiaxed grains relative to parent material. Martensitic alpha grains within re-crystallized beta were more visible at higher pressure and low speed. The microstructure produced at higher speed had larger grains than that produced at lower speed. The weld zone of Ti-6Al-4V was stronger that parent material due to failure occurring far away from the weld zone. Variation in rotational speed at 40 MPa friction pressure did not have effect on the tensile strength of welded Ti-6Al-4V. At rotational speed of 1600 rpm and 2300 rpm, and friction pressure of 60 MPa failure occurred within the weld zone as a result of oxidation and discoloration occurred. At 60 MPa pressure rotational speed was proportionality to gradient of elastic region and inversely proportional to percent elongation.

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