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DOI: 10.21278/TOF.41107
ISSN 1333-1124
eISSN 1849-1391

FRICTION STIR WELDING OF DISSIMILAR JOINTS BETWEEN COMMERCIALLY PURE TITANIUM ALLOY AND 7075 ALUMINIUM ALLOY

Summary

In this study, a joint between commercially pure titanium alloy and 7075 aluminium alloy was butt welded by using friction stir welding at a rotational speed of 1120 rpm and a traverse speed of 50 $mm \cdot min^{-1}$. The evaluation of hardness and microstructure was performed by using scanning electron microscopy. The phases in the weld area were identified by applying the X-ray diffraction technique and the Energy Dispersive X-ray Spectroscopy (EDS) analysis was used for the evaluation of intermetallic compounds of the weld area. The weld zone is cone-shaped and consists of aluminium and titanium particles that play an important role in increasing hardness and tensile strength. The weld area has three zones, namely the titanium base metal zone, the aluminium base metal zone, and the titanium-aluminium intermetallic compound mixed zone. It was also observed that the joint area on the aluminium side includes the stirred area, the thermo-mechanically affected zone, and the heat-affected zone, while the titanium joint area contains the stirred zone and the heat-affected zone. The hardness value of the weld area was around 360 HV, which means that in this area, compared to the base metal of titanium and aluminium, hardness has increased by 6% and 20%, respectively. This can be attributed to severe plastic deformation and formation of intermetallic compounds of titanium and aluminium in this area.

Key words: *aluminium 7075, pure titanium, friction stir welding, microstructure, mechanical properties*

1. Introduction

Friction stir welding is a solid state process that is relatively new, efficient in terms of energy consumption, environmentally friendly and versatile. In particular, this method is used for the joining of high-strength aluminium alloys in aerospace industry, for example, in the process of manufacturing a space shuttle external tank [1]. High quality, low residual stress, zero defects, minimum distortion and low cost of joint preparation are considered as the main advantages of this method [2]. Aluminum alloys are widely used in automotive industry, aerospace industry and shipbuilding. Titanium alloys have also attracted much attention in these industries due to their high strength and high corrosion resistance. With the increasing demand for lightweight equipment, these alloys have been increasingly used. In many applications, superior properties of both aluminium alloys and titanium alloys, such as high strength, low weight and low cost are needed. Because of many differences between these two metals, such as differences in crystal lattice, melting temperature, thermal conductivity, and coefficient of linear expansion, it is very difficult to achieve a defect-free joint between these two alloys [3-4]. The 7075 aluminium alloy, in which zinc is the main alloying element, is a precipitation hardened alloy. It is one of the strongest aluminium alloys which is used in many spatial structures and places that require high strength-to-weight ratio [5-6]. Titanium and its alloys have high specific strength and good corrosion resistance and because of these two desirable properties, they have been widely used in the aerospace industry. Nowadays, due to the increasing application of titanium alloys, the joining of aluminium alloys to titanium alloys has to be considered carefully. The use of conventional fusion welding of titanium leads to the formation of brittleness, distortion and high residual stresses. Therefore, solid state joining processes are more appropriate to avoid problems caused by melting and freezing [7-8]. Friction stir welding is widely used for heat treatable and non-heat treatable aluminium alloys, such as 2xxx, 3xxx, 5xxx, and 7xxx series. Some attempts have been made to study friction stir welding on similar and dissimilar alloys, such as the alloy series AA 2024 / 5754 [9], 5086 [10], AA6061 [11-13], AA7075 [14-15], and AA6061 / 7075 [16] , as well as on aluminium die casting alloys and aluminium foams [17-22].

Hua et al. [23] studied common characteristics of the interface produced by friction stir welding of aluminium to titanium. They concluded that the interface between aluminium and titanium is severely changed by varying the welding parameters. In this regard, the amount of hardness obtained into the weld zone was around 502 HV, which was twice the hardness of aluminium alloy hardness and four times higher than titanium hardness. This increase in hardness was related to the form of the intermetallic compound of titanium-aluminium in the weld area.

Chen et al. [24] studied the properties of the area achieved by the friction stir butt-welding of titanium to aluminium dissimilar alloys. Mechanical properties were derived from the intermetallic compounds. The authors found that the fracture strength of all joints was lower than the fracture strength of the base metal, and in all joints, fracture occurred at the interface of the parts welded. The maximum fracture strength was equal to 9.39 KN for the samples welded at a rotational speed of 1500 rpm and a traverse speed of 90 $mm \cdot min^{-1}$.

Desler et al. [25] investigated the butt joint between 2024 aluminium alloy and titanium welded by friction stir welding. The optimal parameters for welding were obtained at a rotation speed of 800 rpm and a traverse speed of 80 $mm \cdot min^{-1}$. The stirred zone was a mixture of a recrystallization layer of aluminium and titanium particles. The tensile strength was 73% higher than that of the aluminium 2024 base metal. This can be attributed to the formation of an aluminium-titanium compound in the weld area.

Bang et al. [26] worked on the friction stir welded butt joint between aluminium 6061 and titanium dissimilar alloys. The stirred area was a mixture of recrystallized particles of titanium and aluminium. A hardness of 350 HV was achieved in the stirred area. Also, the obtained bond strength was 134 MPa, which was around 35% of the strength of the aluminium base metal. All joints had less strength than the base metal because the probe tip was in an area that cannot perform the stirring operation effectively.

Sadeghi et al. [27] studied butt joints between aluminium 5083 and commercially pure titanium dissimilar alloys friction stir welded at a rotation speed of 50 $mm \cdot min^{-1}$ and a traverse speed of 1120 $mm \cdot min^{-1}$. The hardness of the weld area was 480 HV, which was due to the presence of the interphase compounds of aluminium and titanium.

It is to be noted that there is a limited research on dissimilar joints between commercially pure titanium and 7075 aluminium alloy achieved by friction stir welding. Finally, in this study the effect of the friction stir welding process carried out at a constant rotational speed of 1120 rpm and a traverse speed of 50 $mm \cdot min^{-1}$ on hardness, tensile strength, and microstructure of the dissimilar joint between commercially pure titanium and 7075 aluminium alloy are investigated.

2. Materials and Methods

Three mm thick sheets of commercially pure titanium (ASTM B265, UNS R50400) [28] and **7075** aluminium alloy (ASTM B209, UNS A97075) [29], whose composition is presented in Tables 1 and 2, were prepared. 120 mm long and 60 mm wide pieces were cut from these sheets. Then, to remove grease and surface contaminants, the sheets were washed in acetone and alcohol solutions, and were cleaned ultrasonically. Geometry and dimensions of the welding tool is the most important and influential variable of the friction stir welding process, so that some factors such as welding properties, amount of consumed energy, type of the used device, speed of the process and so on are related to the used tool [30]. Geometry and dimensions of the designed tool are presented in Figure 1. Based on a pervious study, in order to join titanium with aluminium alloy by applying the friction stir welding method, a cone-shaped pin was selected [30]. The joint configuration of the present study is a butt joint, which is schematically shown in Figure 2.

Table 1 Chemical composition of commercially pure titanium alloy (weight percentage) [28].

Ti	Si	Zr	Sn	Nb	Mo	Mn	Fe	Cu	Cr	V	Al
Base	0.01	0.01	0.05<	0.03	0.01	0.01	0.04	0.02	0.01	0.05<	0.01

Table 2 Chemical composition of 7075 aluminium alloy (weight percentage) [29].

Al	Zn	Mg	Si	Sn	Ni	Co	Mn	Fe	Cu	Cr	V
Base	6.36	2.77	0.108	0.01	0.005	0.003	0.281	0.175	1.61	0.277	0.0048

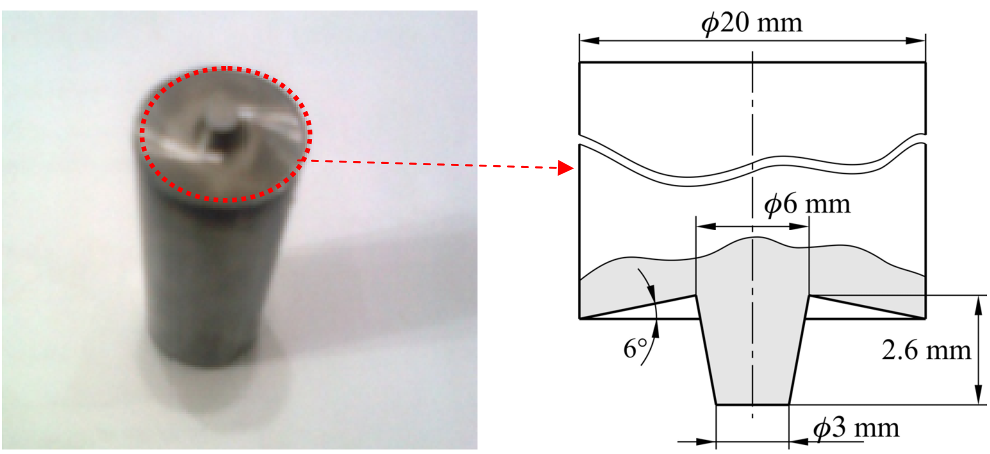


Fig. 1 Scheme of the designed tool.

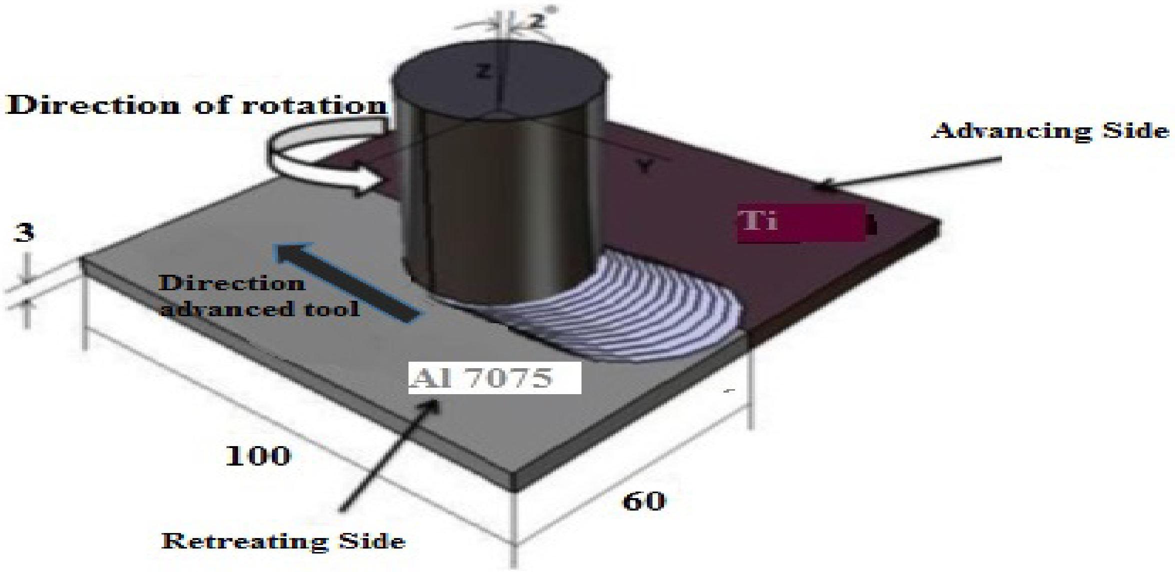


Fig. 2 Scheme of the welding configuration [1].

After fabricating the joints by applying the friction stir welding process, the weldments were exposed to common grinding and polishing processes and they were etched with a solution prepared by mixing 2 ml of HF, 4ml of HNO_3, and 94ml of H_2O for 40 seconds on the titanium side and the weld zone, as well as 1ml of HCl, 1.5ml of HNO_3, 2.5ml of HF, and 95ml of H_2O on the aluminium side. The structure of the welded samples was studied by using optical microscopy (model Nikon) and scanning electron microscopy (model LEO 435 VP). Vickers hardness was obtained using a force of 10g, and the dwell time of 10s was used for measuring hardness. Hardness of the cross-section was measured in nine points for each sample and was reported as the mean value of hardness. Hardness was determined by using a micro hardness testing machine (model Koopa MH1). In order to identify the intermetallic compounds and the created phases, the X-ray diffraction analysis was performed by using a Philips device (model Xpert MPD). In addition to the study on intermetallic compounds, the Energy Dispersive X-ray Spectroscopy (EDS) analysis of the welded area was performed.

3. Results and Discussion

3.1 Titanium microstructure

Microstructure of this area is presented in Figures 3a and 3b. As can be seen, there is a sharp boundary between the stirred area and the heat-affected zone, and thus there is no thermo-mechanically affected area. This is associated with low thermal conductivity of titanium, which results in a lack of heat transfer in the process of welding. Therefore, cooled and more secured areas around the welded area resist the deformation generated by the thermomechanical operation. This means that there is no thermo-mechanically affected zone in titanium and its alloys, which has also been reported by other researchers [7-31-32-33]. In the heat-affected zone, as a result of the thermal cycle, the material has changed in terms of microstructure and mechanical properties and it had finer grains compared to the base metal.

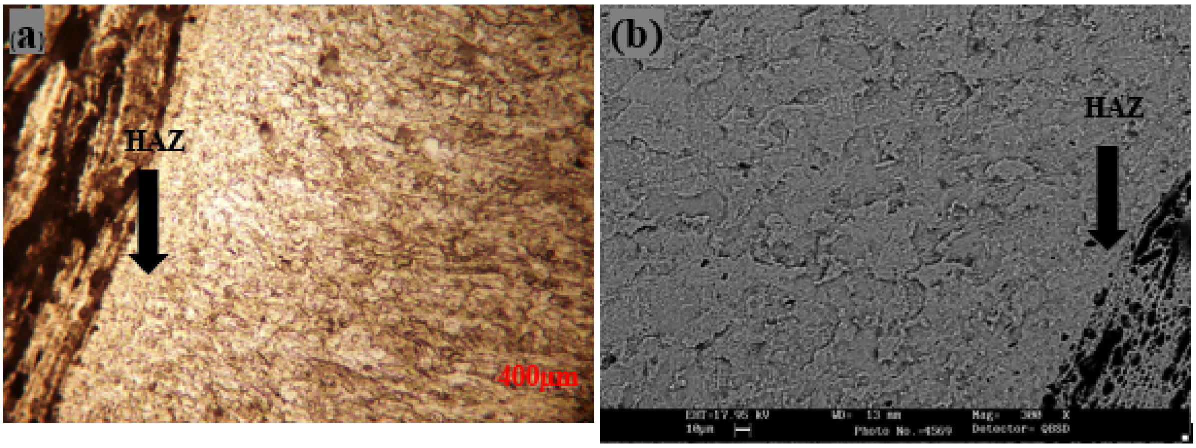


Fig. 3 a) Optical microscope image and b) Scanning electron microscope image of titanium microstructure.

3.2 Microstructure of 7075 aluminium alloy

Figures 4a and 4b show the microstructure of **7075** aluminium alloy. A survey of the images indicates three zones including the stirred zone (SZ), the thermo-mechanically affected zone (TMAZ), and the heat-affected zone (HAZ). The microstructure of the stirred zone includes fine equiaxial and recrystallized grains. The presence of recrystallized and equiaxial grains is one of the main characteristics of friction stir welding that has been reported by other researchers [34]. These grains are formed because of plastic deformation caused by the rotational movement and the progressive tool followed by dynamic recrystallization [35]. In the thermo-mechanically affected zone, deformed and elongated grains are observed. In fact, severe plastic deformation is not enough in this area for dynamic recrystallization to occur and the grains have only become deformed near the stirred zone toward the upper part of the weld area. In the heat-affected zone, as a result of the thermal cycle, the material has changed in terms of microstructure and mechanical properties [34].

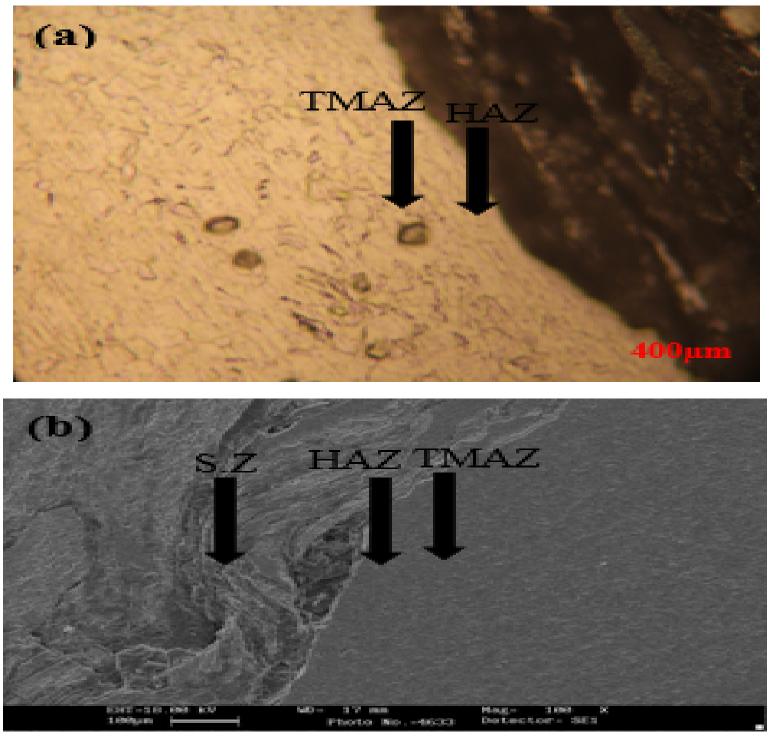
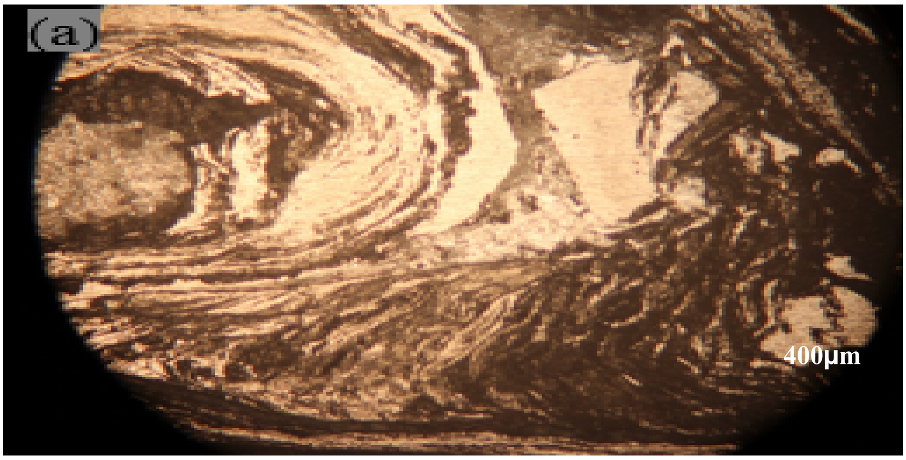


Fig. 4 The image of welding aluminium obtained using a) an optical microscope and b) a scanning electron microscopy.

3.3 The Weld Area

Microstructure of the welded area is presented in Figures 5a and 5b. As can be observed, the welded area is divided into three different areas, which are specified as areas 1, 2 and 3. Area 3 is dark and composed of sections. In this region, titanium as a base metal and aluminium alloy have a ratio close to 1:1, which represents the formation of the intermetallic titanium and aluminium compound in this area [23]. The morphology of area 1 has a black structure and its type and its elements are very close to aluminium metal, and it explains that the layers of aluminium alloy have entered the intersection by pin forces. The main element in layer 2 is titanium and there is a small amount of aluminium alloy in the form of dispersed particles [23].

In order to identify the elements in the welded area, a part of this area which is marked with (*) and denoted as (3) in Figure 5, was analysed by EDS, and the obtained results are shown in Figure 6. As can be seen, intermetallic compounds are observed in this area. The results of the X-ray diffraction are given in Figure 7. As can be observed, a variety of intermetallic compounds formed between titanium and aluminium can be identified, and these compounds increase the hardness of the joint. As can also be observed, the intermetallic compounds are distinguished as $Al\ Ti_3$, $Al\ Ti_2$, and $Al_2\ Ti$.



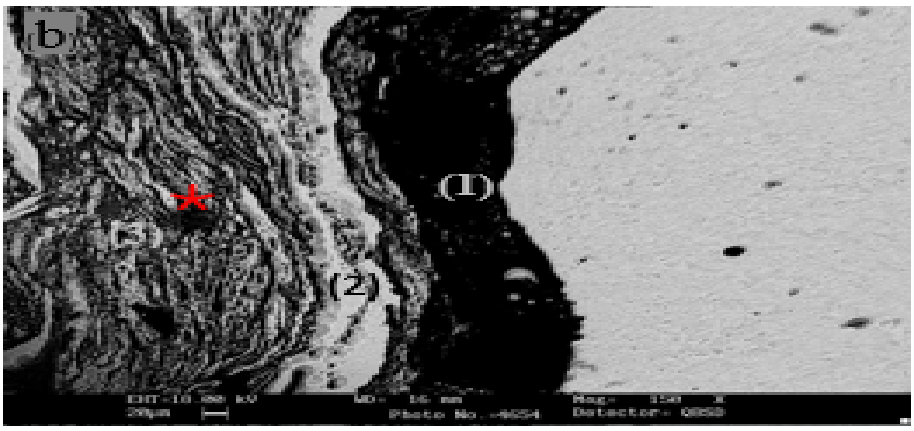


Fig. 5 a) Optical microscope image, b) Scanning electron microscope image of the welded area.

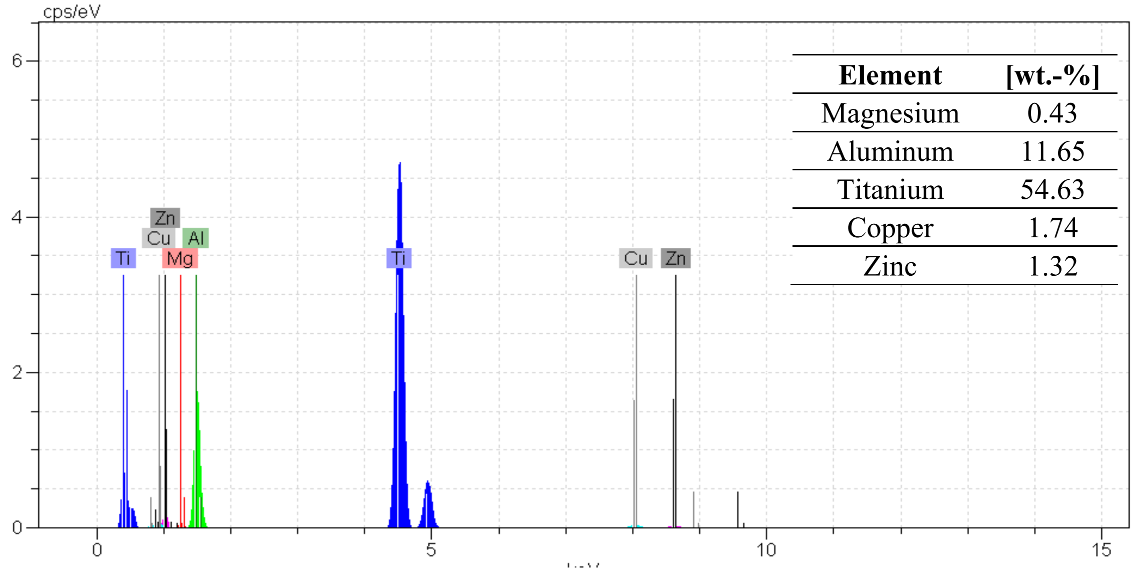


Fig. 6 EDS analysis of the welded area in zone 3.

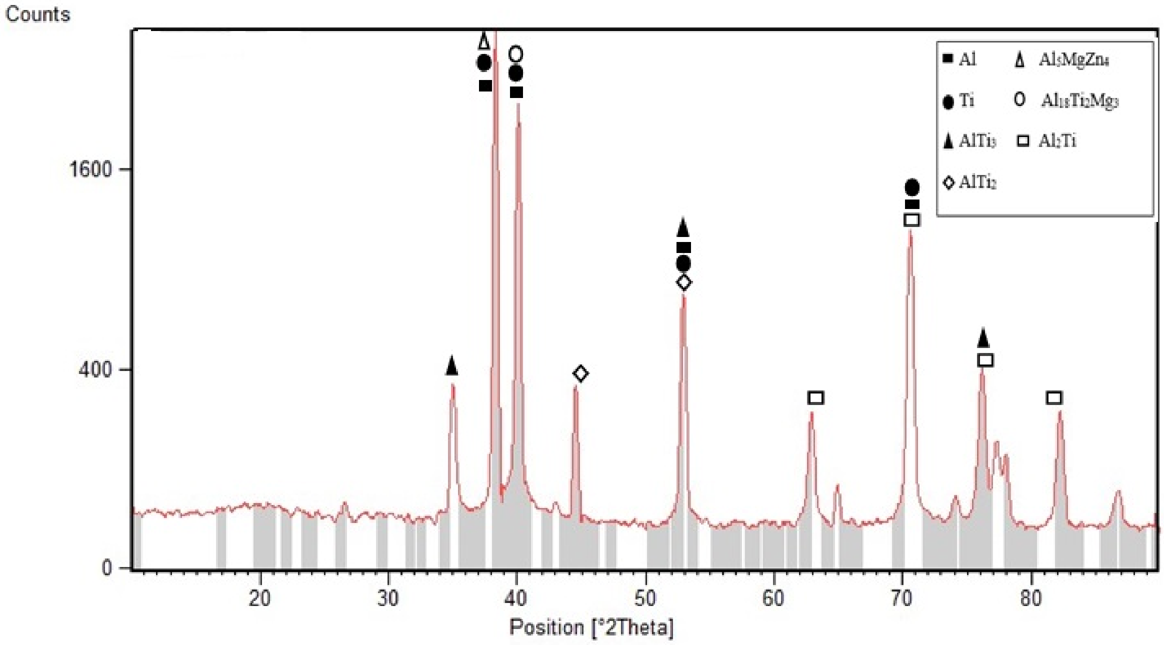


Fig. 7 X-ray diffraction results.

3.4 Analysis of hardness

The results obtained from the analysis of hardness of the weldments are shown in Figure 8. As can be observed, in all the weldments, the stirred zone exhibits hardness higher than the heat-affected zone and the base metal has the lowest hardness. This can be attributed to two reasons. Firstly, plastic deformation occurred in the stirred zone and the heat-affected zone, and secondly, the structure of the stirred area is finer than that of the base metal due to dynamic recrystallization in this area. The results showed 360 HV10 hardness in the joint area, which means that the hardness in the area of the titanium base metal and aluminium is increased by 6% and 20%, respectively. The increase in hardness has been reported by other researchers as well [31-36]. For example, Kitamura showed that smaller particles increase the strength of the structure, and that hardness is also directly associated with strength, and as the grains have smaller size in the stirred zone the hardness of the stirred zone increases [36]. Hua also showed that a mixture of aluminium and titanium is formed in the stirred zone, so that the mixed zone is composed of an intermetallic compound and this increases the hardness. He also reported that hardness in the area reached 502 HV10 [23].

On the titanium side, the minimum hardness, namely 280 HV10, is related to the heat-affected zone, which is due to the effect of annealing that leads to softening of this area compared with the base metal [23].

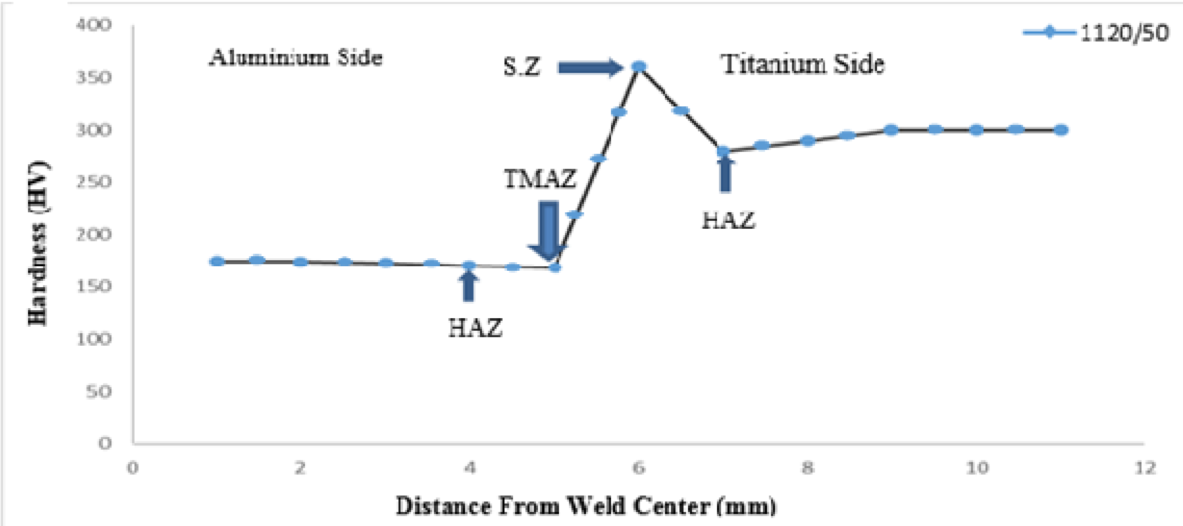


Fig. 8 Hardness profiles with distances from the weld to the base metal of titanium and 7075 aluminium.

4. Conclusions

In the stirred zone, the weld microstructure contains three areas: the aluminium base metal, the titanium base metal, and a mechanical mixture of aluminium and titanium. The joint zone on the aluminium side included the stirred zone, the thermo-mechanically affected zone, and the heat-affected zone, while the titanium joint area only included the stirred zone and the heat-affected zones. The maximum hardness is achieved in the stirred zone with a value of 360 HV10 because of plastic deformation that occurs in this zone as well as because of titanium aluminium intermetallic compounds, which are mainly Al Ti_3, Al Ti_2, and Al_2 Ti.

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Submitted: 26.3.2016

Accepted: 22.7.2016

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