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Friction stir welding of dissimilar joint of aluminum alloy 5083 and commercially pure titanium

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Abstract

In this research, sound dissimilar joints between commercially pure titanium and aluminum alloy 5083 were produced in the butt joint configuration by friction stir welding using a rotation speed of 1120 rpm and a welding speed of 50 mm min^{-1}. To investigate the properties of the created joint, microstructure and hardness of the weld zone were evaluated. The results show that three zones exist in the stir zone, namely aluminum base metal, titanium base metal, and the area composed of intermetallic compounds of aluminum and titanium. It is also observed that the joint region in the aluminum side consists of stir zone, thermo-mechanically affected zone and heat affected zone, while the joint region on the titanium side includes stir zone and heat affected zone. The highest hardness was measured in the stir zone, 480 VHN, which is due to excessive plastic deformation and intermetallic compounds formation.

Key words: commercially pure titanium, aluminum H-321 5083, friction stir welding, microstructure, mechanical properties

1. Introduction

Aluminum alloys are widely used in automobile industry, aerospace and shipbuilding. Titanium alloys are also considered in these industries because of high strength and high corrosion resistance. By increasing demand for lightweight equipment, application of these alloys has been very widespread. In some special cases, the positive properties of both aluminum and titanium alloys such as high strength, low weight and cost are required. Because of the great differences between these two metals, such as differences in the crystal lattice, melting temperature, thermal conductivity, and linear expansion coefficient, creating a healthy connection of these two metals is very difficult [1, 2].

Aluminum alloy 5083 has shown good weldability features and high corrosion resistance. As such, it is used in the marine environment. Magnesium element in the aluminum alloy 5083 causes strengthening through the creation of solid solution and increasing work hardening rate (which is the most important strengthening mechanism in this alloy) [1]. Titanium and its alloys have high specific strength and good corrosion resistance and because of these two favorable features, they are widely used in the aerospace, chemical, and nuclear industries. The use of conventional fusion welding methods for titanium leads to the formation of brittle casting, distortion, and high residual tensions. So, solid state connection methods are more appropriate to avoid problems caused by the melting and freezing routes [2].

The friction stir welding (FSW) technique is widely accepted as one of the most significant welding techniques to have emerged in the last 20 years. Friction stir welding, which was developed and patented in the UK in the early 1990s by The Welding Institute (TWI), is usually used in welding of plates and is different from conventional friction welding [3, 4]. In this technique, the plates-to-be-welded are clamped together rigidly in butt or overlap condition, and a stirring tool with a suitable geometry moves along them while the pieces-to-be-joined are moving over each other in conventional friction welding method. In this method, the stirring tool rotating at a high

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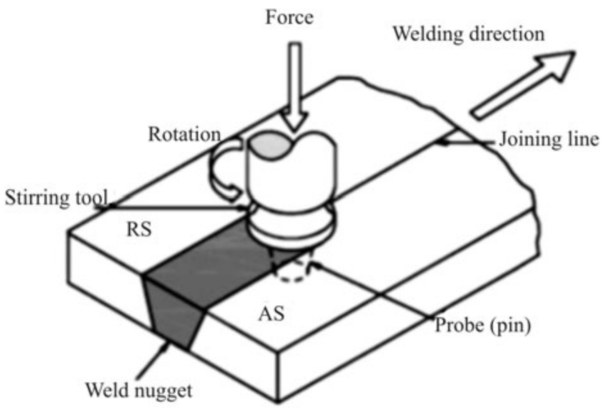

Fig. 1. Schematic presentation of FSW technique [3].

rate is plunged into the clamped plates causing friction. The heat caused by the friction between the tool shoulder and the workpiece results in an intense local heating that does not melt the plates to be joined but plasticizes the material around the tool [3]. The application of this method is shown schematically in Fig. 1. This joining technique is originally regarded to display similar solid state bonding conditions as the extrusion process [3].

The advantages of FSW over conventional fusion welding processes are as follows: it is possible to weld metals in the solid phase; there is no need for filler metal; the heat input during the welding is lower, therefore, the loss of the mechanical properties is less; shrinkage, distortion, and residual stresses are very small especially in thin plates, and because it is a solid state welding, problems encountered in conventional fusion welding methods, such as cracking and porosity formation, are not experienced [3, 4]. FSW process involves complex interactions between a variety of simultaneous thermomechanical processes. The interactions affect the heating and cooling rates, plastic deformation and flow, dynamic recrystallization phenomena and the mechanical integrity of the joint [5]. FSW has evolved as a technique of choice in the routine joining of aluminum components; its applications for joining difficult metals and metals other than aluminum are growing, albeit at a slower pace. There have been widespread benefits resulting from the application of FSW in, for example, aerospace, shipbuilding, automotive and railway industries [5]. FSW method is most widely applied to age-hardened and non-age--hardened Al-alloy such as 2XXX, 5XXX, 6XXX, and 7XXX series. Some efforts were put into studying the FSW of the similar and dissimilar AA2024/5754 [6], AA5086 [7], AA6061 [8–10], AA7075 [11, 12], and AA6061/7075 [13, 14] series of alloys.

The joining of titanium alloy with aluminum alloy could have a major application in the field of aerospace and automobile industry where high strength and low weight are desirable [15, 16]. However, fusion welding joints between titanium and aluminum exhibit inferior mechanical properties due to the formation of brittle intermetallic phases in weld [16–17]. Other solid-state welding methods for joining these two materials such as FSW process have also been reported. Hua et al. studied the interface properties caused by FSW of aluminum to titanium, as an interface connection of titanium to aluminum changes greatly by changing parameters. The hardness of the weld zone was announced 502 Vickers that was two times more than that of titanium alloy and four times more than that of aluminum alloy. The reason for increasing difficulty is the creation of an intermetallic combination of titanium-aluminum in the weld zone [16].

Chen et al. investigated the interface properties of dissimilar connection and overlap of the edges of titanium to aluminum caused by the process of FSW. Mechanical properties of the connection were derived from the presence of intermetallic compounds. Breaking force of all connections was lower than the base metal breaking force and breaking in all connections occurred at the weld interface. Maximum breaking force is equal to 9.39 kN, which is related to the welded sample with the rotational speed of 1500 rpm and the advancing speed of 90 millimeters per minute [17].

Desler et al. investigated butt connection of aluminum alloy 2024 and titanium by using the frictional stirring method. Optimal parameters of welding were obtained at the rotational speed of 800 rpm and the advancing speed of 80 millimeters per minute. The stir zone was a mixture of the recrystallization aluminum layer and titanium particles. The tensile strength was 73 % more than that of aluminum base metal 2024, due to the creation of aluminum-titanium combination in the weld zone [18].

According to the few researches that were conducted about dissimilar connection of commercially pure titanium to the aluminum alloy 5083 by FSM method, in the present research, welding with optimal parameters of the rotational speed of 1120 rpm and welding speed of 50 mm min^{-1} was used to investigate the hardness and microstructure of dissimilarly connected commercially pure titanium to the aluminum alloy 5083.

2. Materials and methods

The alloys used in this research were prepared from commercially pure titanium alloy sheet and aluminum 5083 H-321 with the compositions listed in Tables 1 and 2. Pieces with $120 \times 60 \times 3$ mm^3 dimensions were cut from the mentioned sheets. Then, to remove grease and surface contaminants, the sheets were washed in a solution of acetone and alcohol and were ultrasonically cleaned.

T a b l e 1. Chemical composition of commercially pure titanium alloy (wt.%)

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

T a b l e 2. Chemical composition of aluminum alloy H-321 5083 (wt.%)

Al	Mg	Si	Sn	Nb	Mo	Mn	Fe	Cu	Cr	V	Zn
Base	4.19	0.117	0.0100	0.03	0.03	0.428	0.202	0.0503	0.0605	0.0120	0.0104

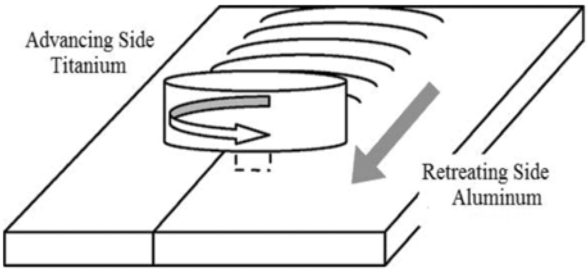

Fig. 2. Schematic of FSW process used in this research [4].

Geometrical shape and dimensions of the tool are the most important and influential variables of FSW process so that some cases such as welding properties, the amount of used energy, type of used device, the speed of the process, etc. are a function of the used tools [19]. To connect titanium alloy to aluminum by FSW method, the best shape of the pin is a conical tool. The joint design of the present study was the butt joint, and its schematic is shown in Fig. 2.

After joining by FSW process, the samples were etched, ground, polished and prepared in a solution of hydrofluoric acid (2 vol.%), nitric acid (4 vol.%) and water (94 vol.%) for 40 s. Their structures were investigated by optical and scanning electron microscopes. Vickers microhardness method with a load of 100 g and 10 s duration of force application was used to measure the hardness. Hardness test was performed for each sample from a cross section and at nine points, and the hardness values were reported by averaging.

3. Results and discussion

3.1. Microstructure of aluminum 5083-H321

The images obtained from the microstructure of aluminum alloy 5083 by optical microscopy and scanning electron microscopy are given in Figs. 3a and 3b, respectively. Study of the images indicates the presence of three zones: stir zone (SZ), thermo-mechanically affected zone (TMAZ), and heat affected zone (HAZ). The microstructure of stir zone includes coaxial micro grains that are recrystallized. The presence of equiaxed micro and recrystallized grains is a specific feature of FSW that has also been reported by other researchers [16, 17, 20]. The formation of these grains is related to severe plastic deformation caused by the rotational and progressive motion of tools and followed by the occurrence of dynamic recrystallization [16, 17, 20].

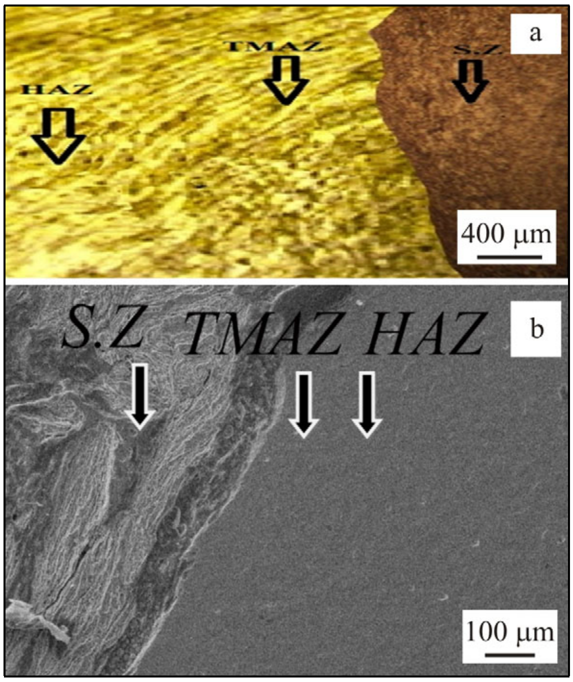

Fig. 3. a) Image obtained from the optical microscope and b) image of the welded sample obtained from scanning electron microscope in aluminum 5083 zone.

Deformed and elongated grains were observed in the thermo-mechanically affected zone. The intensity of plastic deformation in this zone is not enough for the occurrence of dynamic recrystallization in this area, and the grains are deformed only beside the stir zone in an upward direction. In the heat affected zone, the microstructure and mechanical properties of the material have been altered because of the entered thermal

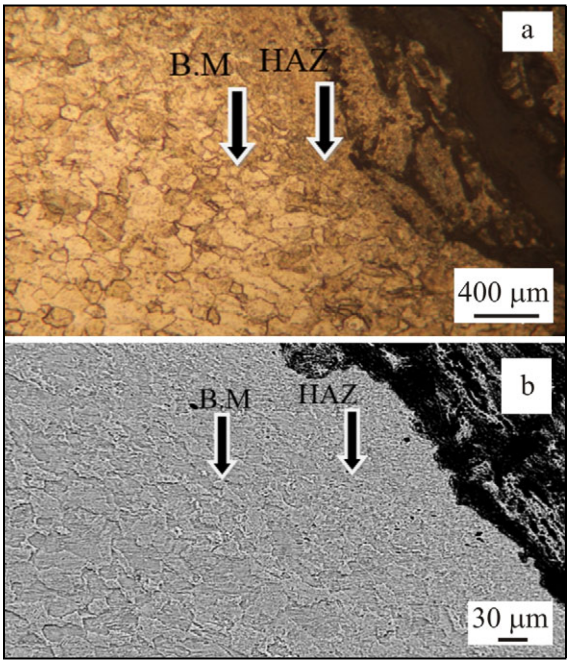

Fig. 4. a) Image obtained from the optical microscope and b) image of the welded sample obtained from scanning electron microscope in pure titanium zone.

cycle, without mechanical deformation [20].

3.2. Microstructure of titanium

Figures 4a and 4b show the microstructure of this zone obtained by optical and scanning electron microscopies. Study of these images indicates that a sharp boundary is between stir zone and heat affected zone. Therefore, there is no thermo-mechanically affected zone. This is due to the low thermal conductivity of titanium that causes no heat distribution in the welding process. Therefore, cool and more secure areas around the weld zone cause resistance against deformation that creates the thermodynamically affected zone. This result, the absence of thermo-mechanically affected zone in titanium and its alloys, has also been reported by other researchers [2, 21–24].

In the heat affected zone, microstructure and mechanical properties of the material have changed because of the entered thermal cycles without mechanical deformation and its grains are smaller than those in the base metal.

3.3. The weld zone

The weld zone microstructure obtained by optical and scanning electron microscopies is given in Figs. 5a and 5b. As it is clear, the area of the intersection has three different areas identified as 1, 2 and 3 zones. As can be seen in zone 3, this section consists of dark and

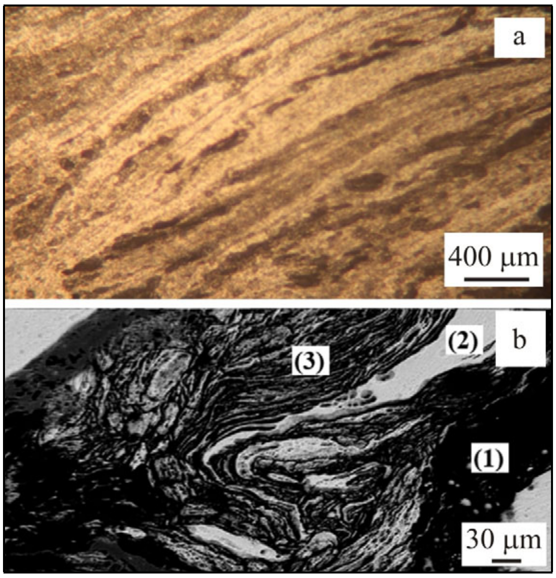

Fig. 5. a) Image obtained from the optical microscope and b) image of the welded sample obtained from scanning electron microscope in the weld zone.

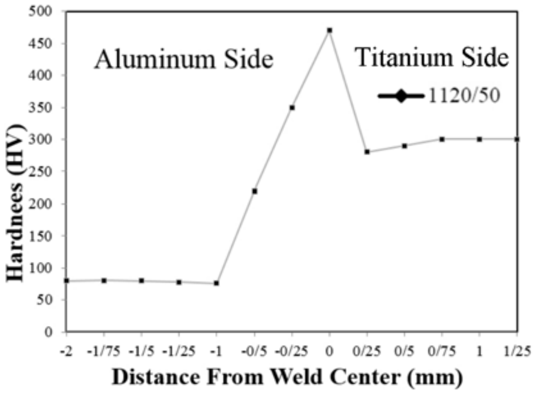

Fig. 6. Hardness profile in the butt connection of pure titanium and aluminum alloy 5083 created by friction stirring.

light parts. In this area, there is the basic metal of titanium and aluminum alloy with a ratio about 1:1 that indicates the creation of intermetallic compounds of titanium and aluminum [16]. Zone 1, which is marked in black, is the area rich in aluminum and can be explained by inserting aluminum alloy layers in the interface through the pinning force. Zone 2, which is marked in white, is the area rich in titanium in which a small amount of aluminum is dispersed as particles. The presence of the area consisting of the three zones mentioned above has also been reported by Hua [16].

3.4. Hardness measurement

The results of the hardness measurement of the welded specimens are shown in Fig. 6. As can be observed, the stir zone has the highest hardness and the base metal has the smallest hardness. This is due to the plastic deformation and the finer structure caused by dynamic recrystallization in the stir zone compared with the base metal. Results indicate that hardness is 480 Vickers in the connection area. In other words, the hardness in this area increased compared with the base metal of titanium and aluminum, 16 and 60 %, respectively. Increasing hardness in the weld zone has also been reported by other researchers [24, 25]. For example, Kitamura showed that the finer structure increased the strength, hardness is also directly associated with strength, and as the grain size is less in the stir zone, therefore, hardness increased in the stir zone [23]. Also, Hua et al. reported that formation of intermetallic compounds of aluminum and titanium in the stir zone is the main reason of higher hardness in this zone. In this study, the hardness of the stir zone has been reported 502 Vickers [16].

4. Conclusions

1. The dissimilar joining of pure titanium and aluminum alloy 5083 at 1120 rpm rotation speed and a welding speed of 50 mm min^{-1} in the butt joint by a friction stir welding was performed successfully in this research.

2. In the FSW process between aluminum alloy 321-H5083 and commercially pure titanium, the joint region in the aluminum side consists of stir zone, thermo-mechanically affected zone and heat affected zone, and the joint region on the titanium side includes stir zone and heat affected zone. The absence of thermodynamically affected zone is because of low thermal conductivity of titanium, which causes no temperature distribution in the welding process.

3. In the stir zone, the microstructure of the weld consists of three zones, base metal aluminum zone, base metal titanium zone, and aluminum and titanium intermetallic compounds zone. The highest hardness of side to side connection of pure titanium and aluminum alloy 5083 is related to the stir zone with a hardness of 480 Vickers. The cause of higher hardness is the plastic deformation that occurred in the stir zone, and formation of intermetallic compounds of aluminum and titanium.

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