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Friction welding of AZ31-SS316L for partially-degradable orthopaedic pins

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Abstract. Joining dissimilar metals with friction welding is very challenging due to the differences in physical, mechanical and metallurgical properties of the two parent metals. A careful design of welding parameter is necessary especially for joining two metals with a large difference in melting temperature. In this study, friction welding has been viewed as an attractive process to join degradable metal with corrosion resistant alloy. AZ31 type magnesium alloy was friction welded at a low heat input to 316L type stainless steel to form a partially-degradable pin for temporary bone implants. Meanwhile, 6103 type aluminium alloy was also joined with 202 type stainless steel for comparison. A modified lathe machine at a spindle speed of 1600 RPM was used to perform the friction welding. The strength of the weld joints was evaluated by tensile test and their hardness distribution was measured using Vickers micro hardness tester. The results showed that the optimum parameter for the AZ31-316L joint was obtained at the friction time = 78s, forging pressure = 40kPa and the burn-off = 25mm. Meanwhile, for the 6103-202 joint the optimum parameters were: friction time = 50s, forging pressure = 9.3kPa and burn-off = 12mm. Fracture surface analysis showed a spiral defect on the 6103-202 joint, while the fracture surface of AZ31-316L showed an oxide layer formation that prevent a good interfacial bond. In conclusion welding parameters affect the strength of the joint as a result of elemental diffusion between the two metals. The oxide layer disrupts diffusion in the interface of AZ31 and 316L. Vacuum or inert condition during friction is proposed to avoid the oxide layer formation at the interface of AZ31-316L.

Keywords: Friction welding, orthopaedic implant, pin, spiral defect.

1. Introduction

The connection of dissimilar materials is generally more challenging than the connection of similar materials because it has differences in the physical, mechanical and metallurgical properties of the parent material to be joined [1]. Connecting dissimilar materials using conventional welding (fusion welding) is difficult, because of the different physical properties such as the liquid point of the parent materials [2-4]. Another effect arising from the welding process is the shifting of metallurgical properties towards the worse, as in stainless steels there will be a decrease in corrosion resistance at the grain boundaries [5, 6], coarsening grains in weld zone and HAZ areas and decreased toughness and ductility [1].



Currently, the process of joining dissimilar materials is mostly done by the friction welding process. American Welding Society (AWS) classifies the friction welding process as a solid-state welding process (solid-state welding process) [7]. The result of this welding joint is caused by the friction of two solid materials that generate heat. This heat, known as heat input and heat input also affects elements of both parent material to diffuse to form metal bonds (intermetallic bonding) [4]. The heat input in the friction welding process depends on the welding parameters and the material properties [4, 8]. The main parameters in direct drive friction welding are friction pressure, forging pressure, friction time, forging time and the rotational speed of a spindle [4-6]. The parameters proportionately one to the other are interrelated [4]. Ochi, et al. (2001) says that there are two types of friction that affect the heat input; namely friction heat input which has a function of rotation and deformation heat input which has a function of torque [9]. Whereas according to Sahin (2009), practically friction welding is classified in two ways; namely continuous-drive friction welding and inertia-friction welding [10]. In the continuous-drive friction method (Fig 1. (a)), where one material rotates and the other material is stationary. Fig. 1. (b) shows the approach between parameters in continuous friction welding process [7, 10, 11].

Different authors such as James, J. A., and Sudhish, R., (2016) have observed the various effects of SS 304 and AISI 1040, which have circular or non-circular cross-sections, have different thermal and mechanical properties, can be easily incorporated by method friction welding [12]. B.M. Darras, B. and Kishta, E (2013) conducted welding of the commercial magnesium alloy AZ31B-H24, said friction welding produces grain structure into finer and more homogenized grain structure [13]. While D. Wang et al., (2014) said related to optimal welding parameters with the mechanical properties of the welding joints and microstructure characteristics of stainless steel metals [14].

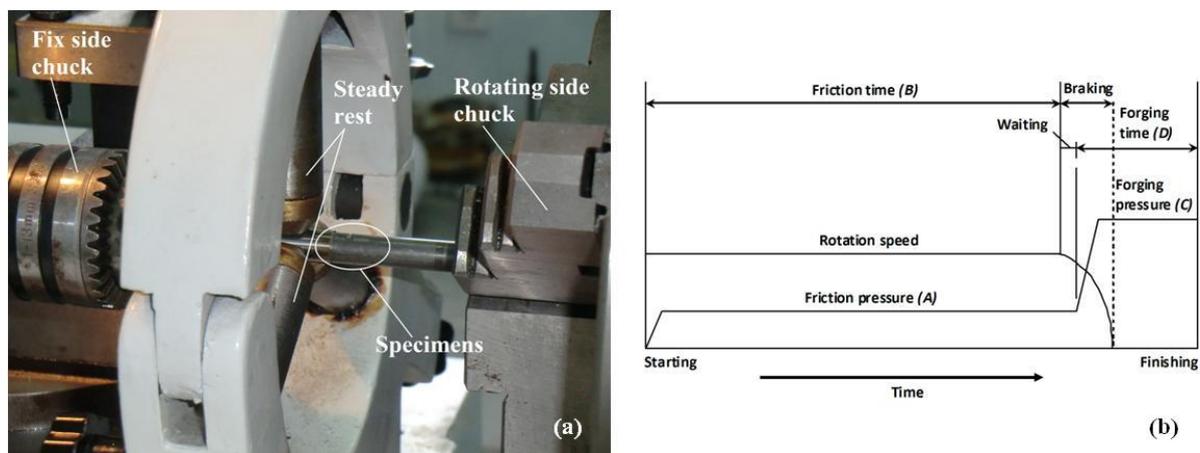


Figure 1. (a) General view of friction welding machine used in the present study. (b) Relation between continuous friction welding parameters.

There are several advantages obtained using friction welding processes such as low heat input, bonds formed under the melting point of the welded material, resulting in higher joint properties and lower distortion [15]. Other advantages are good microstructure, energy efficient process, environmentally friendly and low UV radiation [15, 16]. Therefore, friction welding is done with low heat input, using materials with very different melting points and different applications. A joining between of materials AZ31 and SS316L for biomedical implant applications, while joint of materials AA6103 with SS202 is used for transport applications as a comparison. The result of the welded joint is characterized in the weld zone, tensile test and hardness test.

2. Material

The parent material used in this joining process is a magnesium alloy AZ31 with SS316L and an aluminum alloy AA6103 with SS202 for comparison. The magnesium alloy AZ31 with SS316L is a cylindrical stem with a diameter of 10 mm and a length of 70 mm. As for the aluminum alloy series AA6103 with stainless steel series SS202 shaped cylindrical diameter 12.7 mm and 75 mm long. The chemical composition of the parent metal was obtained from the compositional test results using EDS (Hitachi TM3000, Japan) in Table 1. The mechanical properties of the parent metal were obtained from the tensile test results using Universal Tensile Strength (Controlab-TN 20 MD, France) in Table 2.

Table 1. Chemical composition of parent metals (wt.%).

Materials	Al	C	Mn	Si	Cu	Mg	Zn	Cr	Ni	Mo	Fe
AZ31	2.74	-	0.29	0.02		Bal.	0.75	-	-	-	-
AA6103	Bal.	-	0.06	0.93	0.22	1.11	0.12	-	-	-	0.60
SS316L	-	0.03	2.30	0.60	-	-	-	17.80	10.50	2.74	Bal.
SS202	-	0.15	8.50	0.66	0.45	-	-	17.09	3.27	0.12	Bal.

Table 2. Mechanical properties of parent metals.

Property	σ_U (MPa)	σ_Y (MPa)	ϵ (%)
AZ31	290	180	15
AA6103	339	286	16
SS316L	718	637	45
SS202	1038	768	60

3. Experimental

Friction welding experiments was carried out by modifying lathe machine the type of Knuht DM 1000A-5.7 kW with a maximum spindle rotation speed of 1600 RPM. The material position scheme is shown in Fig. 1. (a). Prior to welding process, the parent metal surface was cleaned in order not to be contaminated, especially with dirt such as grease and the oxide film which would reduce the quality of the connection. This cleansing is an important part to do considering the materials used (magnesium alloys and aluminum alloys) have a high affinity for oxygen [15]. Cleaning was done by sandpaper with size 1000 and then cleaned and wiped using a dry cloth. Furthermore, the welded specimen was disposed of using a lathe machine to be a tensile specimen with a length of 30.0 mm and a diameter of 6.0 mm for AZ31 / SS316L and a gauge length of 45.0 mm and a diameter of 9.0 mm for AA6103 / SS202 following the standard [17].

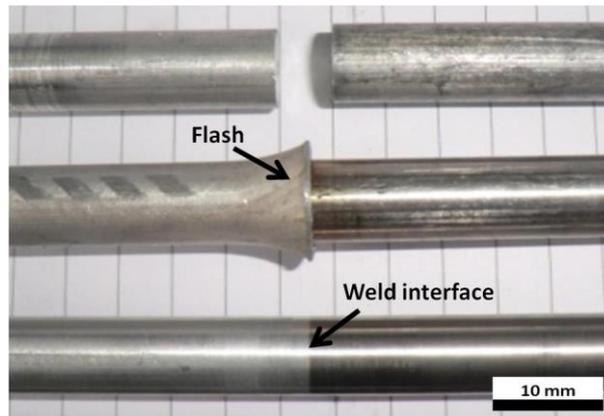


Figure 2. Photograph of a specimen before welding until tensile specimen before testing untuk AA6103/SS202.

The strength of the welded joints was evaluated by tensile testing using a universal tensile testing machine (Controlab-TN 20 MD, France). For microstructure and hardness test, the specimen is cross-cut using electric discharge machining (EDM). The specimen grinding was using abrasive paper grit 1200. Hardness testing was performed using a micro hard test machine (Matsuzawa DVK II, Japan) with a load of 5 kg with a time of 15s and following the ASTM E384 standard. For microstructure, the grinding material was followed by a polish with 0.05 μm diamond paste for etching and analyzed using an optical microscope (Leica DM2500M, UK).

4. Results and discussion

4.1. Tensile tests

The effect of friction welding parameters is noted in the matrix as shown in table 3 (a). In order to obtain the mechanical properties of the result of the connection, a tensile test at room temperature was used to evaluate the mechanical properties of each of the connections shown in table 3 (b).

Table 3. (a) The friction welding parameters, (b) Results of the tensile test of the as-welded for different combination of friction welding parameters.

(a)											
Parameters	AA6103/SS202					AZ31/SS316L					
	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T6
Friction pressure (kPa)	3.1	3.1	3.1	3.1	3.1	5	5	10	5	10	5
Friction time (sec)	50	50	50	35	70	50	50	50	140	78	154
Forging pressure (kPa)	9.3	22.9	18.6	17	18.6	15	25	40	40	40	50
Burn-off (mm)	12	20	17	16	17	12	15	25	25	25	25

(b)											
Parameters	AA6103/SS202					AZ31/SS316L					
	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5	T6
UTS (MPa)	233	214	208	211	211	122	123	122	121	138	79
0.2% YS (MPa)	173	148	146	158	166	-	-	-	-	-	-
ϵ (%)	8	9	12	7.5	10	-	-	-	-	-	-
Location of failure	**10	**10.4	**10.1	**10.5	**11.2	*WI	*WI	*WI	*WI	*WI	*WI

*WI=Weld interface

** mm from WI

T=Trials

Test results in Fig. 3. (a) and (b) show that the tensile strength of the weld samples is almost all very close to each other. There is a small increase in tensile strength by allowing a friction time of 78 s for the AZ31/SS316L connection. As a results, connection AA6103/SS202 is seen by providing a friction pressure and burn-off a smaller yield higher tensile strength. From this observation, it can be seen that the increase in tensile strength is related to the amount of heat input. While for the joint the AZ31/SS316L, all tensile test results have broken in the welded joint. The fracture shape of the tensile test results shown in Fig. 4.

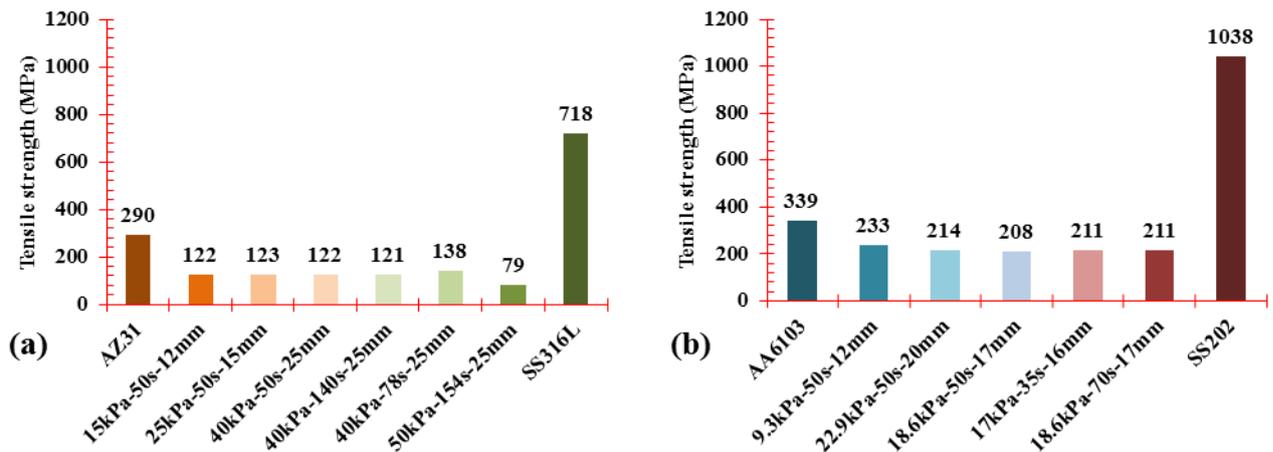


Figure 3. Tensile strength of welded specimens (a) AZ31/SS316L, (b) AA6103/SS202



Figure 4. (a-b) The macro photographs of the tensile tested and the ductile fracture surface of tensile tested specimen AZ31/SS316L. (c-d) The macro photographs of the tensile tested and the brittle fracture surface of tensile tested specimen AA6103/SS202.

4.2. Hardness variations of welded parts

The hardness test of each sample was performed using the Vickers method under a 5 kg load. However, due to the narrow interface area, the hardness test near the area would be compared with the result of the microstructure. The hardness distribution in the weld zone of the friction welding joints is typically divided into five zones for different materials [18, 19]. First referred to as the undeformed zone (UZ), it is a zone that is not affected by heat (parent metal). The second zone is called the partially deformed zone (PDZ) or better known as the Heat Affected Zone (HAZ). The third zone is called a plasticized zone (PZ) where this zone is the second diffusion region of the material. The width of each of these zones depends on the thermal conductivity of the welded material [2]. The higher the thermal conductivity of the material the wider the zone is formed, and vice versa. In addition, welding parameters can also affect the width of the zone [20], as for the distribution of hardness in the connection zone can be seen in Fig. 5.

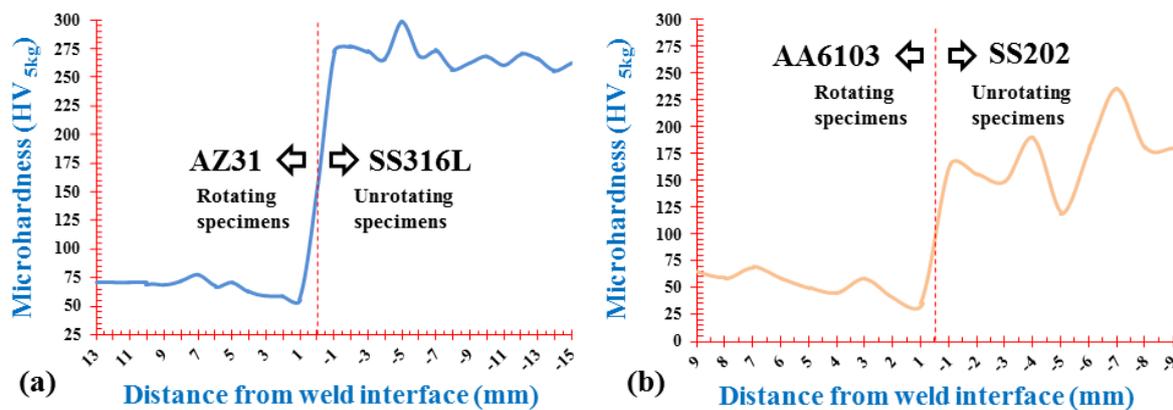


Figure 5. (a) Hardness distribution across the weld of AZ31/SS316L. (b) Hardness distribution across the weld of AA6103/SS202.

Appearance hardness distribution from joint AZ31/SS316L (Fig.5 (a)) does not fluctuate considerably when compared to joint A6103/SS202 (Fig.5 (b)). The results of microhardness testing seen in zone PZ (AA6103) shows recovery and recrystallization resulting from friction and deformation heat, so when approaching UZ, softening occurs. The softening process in the zone of PDZ (AA6103) is already visible in the turning process during flash discharges, as shown in Fig. 6.

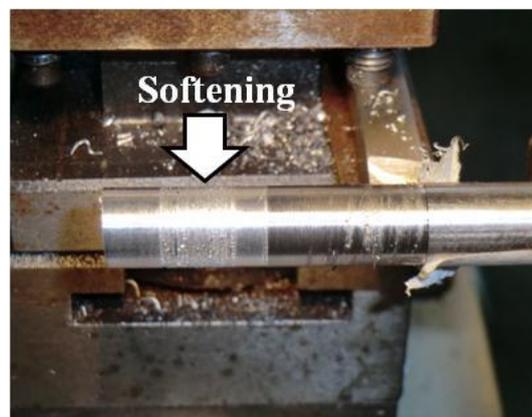


Figure 6. Softening of the aluminium alloy after welding of AA6103/SS202.

4.3. Microstructure of welded parts

Based on the macrostructure the welded sample is shown in Fig. 7. It can be observed that for the joint AZ31/SS316L (Fig.7 (a)) there is no diffusion zone at the interface for all of the weld samples. As for the joint AA6103/SS202 (Fig 7. (b)) visible diffusion zone with an average width of 0.4 mm (sample trial 1) known as intermetallic zone (IMZ). Analysis performed for welding joint AZ31/SS316L using EDS, the diffusion process is hindered by the oxidation in the interface. According to Çelikyürek et al, (2011) the acceleration of diffusion depends on temperature rise, friction time and pressure and to minimize oxidation can be applied to preheat and spraying Argon gas [20]. This does not occur in the AZ31/SS316L welding joints because if preheat is done prior to welding, it will form a layer of oxide on the workpiece [10]. Post weld heat treatment (PWHT) process has also been performed on AZ31/SS316L welding results, but no diffusion zone is formed. So the steps to be taken for the joint AZ31/SS316L by conditioning the welding environment such as vacuum or spray an inert gas (Argon gas) [20] during welding. The absence of diffusion zone in the AZ31/SS316L welding joints becomes evidence or reason for the insignificant hardness distribution. While the weld joint AA6103/SS202 looks more fluctuating and this is the influence of the diffusion of atomic elements of both materials. This is also seen in Fig. 8 which is a the fractograph of welding joint AA6103/SS202.

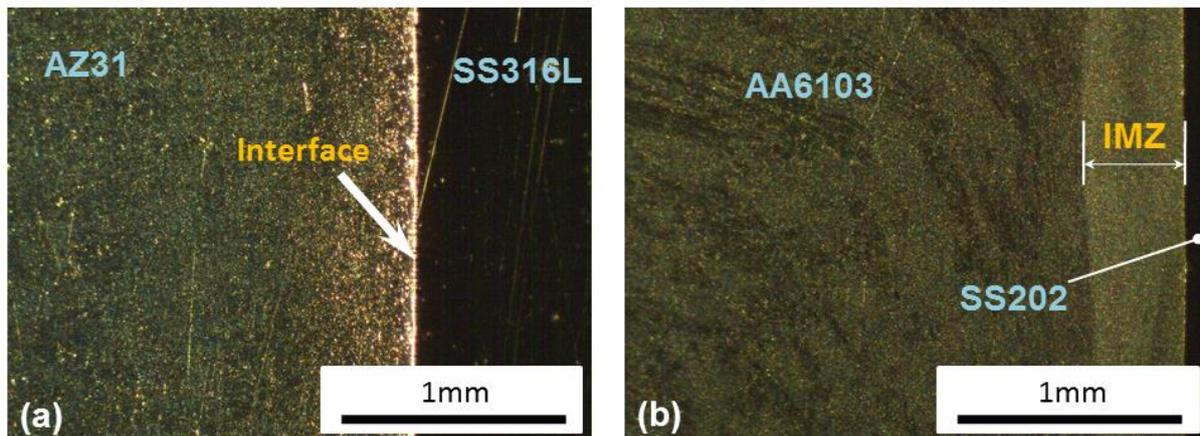


Figure 7. (a) Macrostructure of AZ31/SS316L, (b) Macrostructure of AA6103/SS202.

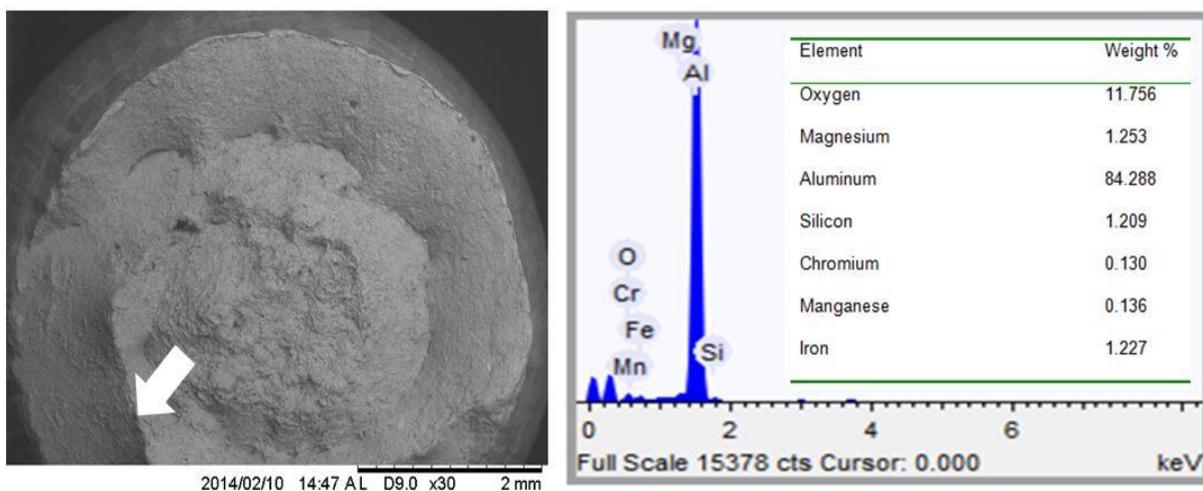


Figure 8. Fractograph of welding joint AA6103/SS202.

Analysis using EDS shows that this area has a large element of 1.25% Mg, 1.21% Si, 1.23% Fe and 11.76% O. If in the welding joint zone has a large number of foreign elements it will tend to form spiral defects and is the beginning the formation of the crack [21]. In contrasting dissimilar materials for medical implants such as the manufacture of orthopedic implants (pins) the distances of very much diffusion are undesirable since the alloy compositions of non-degradable metals contain many toxic elements such as Ni and Cr [22]. Therefore, this is the reason why different metal connections for medical implant applications use low heat input to anticipate large diffusion and away from the interface. According to Çelikyürek et al, (2011), the elements of Cr and Ni atoms can diffuse into the diffusion zone with a short friction time [20].

5. Conclusion

Friction welding can be used successfully to connect AZ31/SS316L. The welding joint shows bad characteristics. The effect of welding parameters on dissimilar materials greatly affects the magnitude and distance of atomic diffusion from the interface. This paper shows that the friction welding between AZ31/SS316L goes perfect but there is no intermetallic bond at the welded joint. Where the oxide layer blocks the diffusion process at the welded joint. Further research can be carried out using a vacuum process or providing a protective inert gas for welding AZ31 / SS316L.

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