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Friction spot brazing of stainless steel to titanium (grade 1) using aluminum foil

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Abstract
This paper demonstrates a simple and effective technique for friction spot brazing of stainless steel (st37) to titanium (grade 1). We use aluminum foil as a filler that is placed between the base metals. We evaluate the joints when using different rotational speeds: 1800, 2000, 2200, 2400, 2600, and 2800 RPM. We characterize the joint using scanning electron microscopy, optical microscopy, energy dispersive x-ray analysis, the microhardness of cross-sections, and fractography. We found that the strongest tensile strength joint (6 kN) come from friction spot brazing at 2000 RPM. The joint interface of the 2000 RPM sample contains intermetallic compounds such as FeTi, Fe3Al, FeAl2, and Ti3Al, which increases the tensile strength.

1. Introduction

Welding titanium requires the use of inert gas to avoid oxidation. Common welding techniques used for joining Titanium to other base metals, such as TiG and MiG, use Argon gas to avoid this problem. These welding techniques are expensive and require complex tools [1, 2]. Mechanical joining techniques such as friction brazing offers an alternative that is inexpensive, uses simpler tools and does not require the use of inert gases [3].

Traditional titanium welding techniques are expensive and require the use of complex tools to avoid the problem of oxidation. Common welding techniques used for joining Titanium to other base metals, such as TiG and MiG [4], use Argon gas to avoid oxidizing the Titanium metal [5]. These welding techniques are expensive and use complex tools that require the use of inert gas [6].

Mechanical joining techniques offer a simpler and cost-effective solution for joining Titanium to other alloys [7]. Several popular methods for mechanically joining materials include friction welding [8], ultrasonic welding [9], and friction-based joints [10]. Among these solid-state joining methods, friction spot brazing is a desirable process because it joins the metals below their melting temperatures [11].

In this process, the friction between the rotational tool and the base metal produces sufficient thermal energy to weld the materials together [12]. The joint is formed through intermolecular diffusion occurring between the metals [13, 14]. Friction welding and friction brazing are used to join similar materials but are now being applied to join dissimilar and incompatible materials such as stainless steel to titanium, aluminum to titanium, and ceramic to materials [15]. Various researchers reported evaluating the friction joints’ mechanical properties and microstructure characteristics [16].

Friction process joining, especially friction brazing, can join stainless steel to Titanium [17, 18], but the strength of these joints is insufficient for many industrial applications. Joints produced using friction suffer from the formation of brittle FeTi and CrTi intermetallic compounds (IMCs) that negatively affects joint strength [19–21]. Some research has been done to investigate the effects of friction joining parameters on the joining of stainless steel to titanium joints, even with IMCs phases, to increase the strength of the joints [21]. Interlayer materials such as powder or foil placed between base metals can avoid the formation of IMCs in the joint, resulting in stronger joints [22, 23].

This paper is the first to study the use of friction spot brazing (FSB) to join stainless steel to Titanium (grade 1) using Aluminum foil as an interlayer. We evaluate the joint characteristics when joining these metals at
different rotational speeds. We measured the formation of any reaction products during the joining process and evaluated the mechanical properties of the joints. We present optimized process parameters for this type of joint.

2. Experimental setup

This study characterizes joining a 0.5 mm stainless steel (St37) plate to a 0.5 mm titanium (grade 1) plate using friction spot brazing. Table 1 the chemical composition of the Titanium (grade 1) and stainless steel (St37) used in this experiment, and the Aluminum 6061 foil interlayer material used in between the joint.

After cutting the metal into 10 × 4 cm size plates, we used an ultrasonic bath containing ethanol and acetone to remove any surface contaminants. We placed a 4 × 4 cm aluminum 0.2 mm thick foil between the base metals.

Figure 1 shows the physical layout of the metal plates and the FSB joint. We created the FSB joint using a cylindrical pin-less tool made out of tungsten carbide (WC) with a 20 mm diameter shoulder as shown in figure 2. With a dwell time of 30 seconds and an upsetting of 0.9 mm, we varied the rotational speed of the tool to 1800, 2000, 2200, 2400, 2600, and 2800 RPM.

We examined joints of each sample using several tools. Cross-sections of the FSB sample were examined with an optical microscope (OM), a scanning electron microscope (SEM), A microhardness test to determine whether the rotational speed of the sample would influence its interfacial features and the Tensile lap shear test. Tensile lap shear test measures the strength of FSB joints. The speed of the tensile strength test was 0.2 mm min⁻¹. It has been achieved that the fracture load and displacement were measured as a result of the tensile lap shear test.

3. Results and discussion

3.1. Appearance

Figure 3 shows the appearance joint of FSB samples with five different rotational speeds. Steel plates were joined to titanium (grade 1) plate using an aluminum foil filler. These samples are easily joined in air without oxidation and use low energy, compared with other joining processes such as roll bonding, MiG/TIG, fusion welding, laser welding, and vacuum brazing. The steel plate has shown a completely uniform heat affected zone (HAZ) related to the constant heat transfer of pin-less tool to welding nugget. Despite of friction spot stir welding (FSSW), the joint surface is almost smooth, and no keyhole observes because of using the pin-less tool and no material distortion.

| Material         | H  | C  | N  | O  | Al | Si | P  | S  | Ti | Cr | Mn | Fe | Ni | Zr |
|-------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Titanium Grade 1  | 0.015 | 0.08 | 0.03 | 0.18 | 0.2 |    |    |    |    |    |    |    |    | +99 |
| Aluminum 6061     |    | 96.4 | 0.48 | 0.13 | 0.13 | 0.24 |    |    |    |    |    |    |    |    |
| Steel St37        | 0.11 | 0.03 | 0.007 | 0.005 | 0.07 | 0.56 | 0.03 |    |    |    |    |    |    |    |
3.2. Optical inspection of interface

Figure 4 shows the cross-section of the samples and their interfacial features for the FSB joints while varying the rotational speed of the tool. Each sample was cut in the transverse direction at the center of the FSB joint. Each figure is created by stitching multiple photos taken with an optical microscope at 50× magnification that spans the entire 40 mm width. The vertical strip pattern is a result of the microscope’s vignetting.

The 1600 RPM sample is not smooth and does not have a uniform interface surface. The tensile strength of the joint is less than 2 kN, because the low friction does not generate enough heat to fuse the metals. The figure shows a gap between the interface metals.

Increasing the rotational speed of the tool from 1600 to 2000 RPM increases the joint strength, melting and defusing the aluminum foil to base metals. This produces a more uniform interface between base metals. At 2000 RPM the tensile strength of the joint is 6 kN. Increasing the tools rotational speed above 2000 RPM reduces the joint strength and increases the thickness of the interlayer, which is brittle and suffers from more cracks. The cracks are a result of the different heat transfer coefficients between the metals and the different solidification coefficient of molten aluminum.

Increasing the rotational speed of tool from 2600 RPM to 2800 RPM and the higher pressure of rotational tool results in plastic deformation of the stainless steel. The higher pressure of the FSB tool shoulder on the sample breaks the surface iron oxide film and creates a direct contact between the iron and molten aluminum, which increases the diffusion rate of aluminum to base metals.

3.3. Interface microstructure

Figure 5 shows cross sections of the 1600 RPM and 1800 RPM FSB samples taken with a SEM. The low heat transfer results in a weak joint. Increasing the rotational speed to 1800 RPM, results in generating more heat that partially melts the aluminum foil. In both cases no intermetallic phases are detected.

Increasing the rotational speed to 2000 RPM generates sufficient heat to melt the metals at the joint zone. The main three metals have a melting points of 1536 °C for Fe, 2370 °C for Ti, and 660 °C for Al. Melting these three metals results in intermetallic phases that considerably increase the joint’s strength.

Figure 6 shows diffusion of aluminum to stainless steel is higher than the diffusion of aluminum to titanium, which results in a higher concentration of intermetallic phases on stainless steel side than on the titanium side. FeAl3 and Fe3Al form on the stainless-steel side and TiAl3 forms on the titanium side.
Figure 3. Appearance joint of samples after the FSB at the different rotational speeds.

Figure 4. Cross-section of FSB samples as seen with an optical microscope. Each line is stitched together from multiple photos without vignetting correction resulting in a stripped pattern.
Figure 7 shows that the higher heat and pressure generated when using a rotational speed of 2200 RPM causes transverse cracks in the interface. These cracks reduce the joint’s strength. Figures 7(b)–(c) shows that a eutectoid structure and FeAl phase at the interface has been formed. Eutectoid structure reduces the concentration of intermetallic phases.

Figure 8(a) shows that increasing the rotational speed increases the diffusion of aluminum to stainless steel, but reduces the tensile strength because of cracks in the interlayer. The higher heat forms additional intermetallic phases, i.e., TiAl2, FeAl3, and Ti3Al, near the base metals [22, 23]. The differences in the volumetric shrinkage coefficient of the base metals leads to transverse cracks in the interface, which weaken the joint.

Figure 9 shows the wavy shape of the stainless steel and aluminum interface formed by increasing the heat input to the joint. The diffusion rate of aluminum to stainless steel is more than the titanium side. Figure 9(b) shows the Ti3Al intermetallic phase formed in the interface of aluminum foil and a titanium plate. FeAl2 and FeAl intermetallic phases are formed in the interface between the steel and aluminum. Figure 9(c) shows the interface layer is full of cracks that reduces the tensile strength of joint.

Figure 10(a) shows higher rotational speed and higher heat input form a eutectoid structure in the interface of the sample. Figure 10(b) shows the FeTi and TiAl intermetallic phase is formed because of higher heat and increased diffusion. Figure 10(d) shows in the titanium side, the TiAl3 phase is formed.

Figure 10(g) shows the 2800 RPM sample that suffers from transverse cracks because of the higher pressure of tool and the differences in the volumetric shrinkage coefficients. This reduces tensile strength joint of 2800 RPM FSB samples. Friction spot brazing at 2000 RPM results in the the highest tensile strength (6 kN), and the joint strength is reduces as we increased the tools rotational speed.
3.4. Microhardness test

Figure 11 shows the results of the microhardness test for the stainless steel and titanium interface layer. Each data point is the average of 7 hardness tests done on a sample.

Increasing the rotational speed from 1600 RPM to 2000 RPM activates hardening mechanism because the pressure of the tool increases the microhardness of the samples. Increasing the rotational speed to 2200 RPM reduces the microhardness because the higher heat input overcomes the work hardening mechanism. The cross-section surface of the 2400 RPM FSB sample has the highest microhardness because the high pressure on the joint zone results in high plastic deformation. The intermetallic FeAl$_3$ [24] and TiAl$_2$ [25] phases overcome the
work softening mechanism [26]. At higher speeds, between 2600 RPM to 2800 RPM, the higher heat results in work softening that lowers the microhardness further.

As the rotational speed increases, the friction rate between the tool and the stainless steel surface increases. As a result, the heat input increases. Then, due to the activation of the work-softening mechanism, plastic deformation occurs. The plastic deformation associated with the locking of dislocations thus increases the hardness and strength of the joint.

3.5. Tensile lap shear strength

Figure 12 shows the sketch of the tensile lap shear strength of samples and figure 13 shows the results of an EDS line measured across the diameter of the 20 mm FSB joint for each sample. The diffusion rate of base metals and aluminum foil filler increases as the rotational speed increases. We measured the tensile strength using the
**Figure 12.** The sketch of tensile lap shear strength sample.

**Figure 13.** EDS-line of FSB samples at the different rotational speeds—diffusion rate of Al foil to base metals.
ASTM E8 standard with a speed of 0.2 mm min$^{-1}$. We chose the lowest speed because the formed intermetallic layer between base metals was brittle.

Increasing the rotational speed from 2000 RPM to 2800 RPM causes the diffusion rate of iron into the interlayer to increase. The Iron diffuses more than titanium because of its lower melting points. The diffusion rate of aluminum into the base metals increases with the increasing rotational speed because of the higher heat input. The diffusion rate of titanium into the interlayer increases substantially for 2800 RPM, compared to any of the lower samples, because the higher heat input substantially increased the diffusion coefficient. The equal amount of stainless steel and aluminum were diffused into the titanium base metal to form a solid solution. Figures 14 and 15 show the load-displacement curves obtained from a tensile strength test of base metals and joints across different rotational speeds. Figure 14 shows the tensile strength of the individual base metals. Stainless steel has a tensile strength of ~9.1 kN while titanium has a maximum tensile strength of ~5.9 kN.

Figure 15 show that increasing the rotational speed from 1600 RPM to 2000 RPM results in increasing the tensile strength of joints. The highest strength joint is the 2000 RPM FSB sample with a tensile strength 6 kN.

Figure 14. Tensile strength of base metals.

Figure 15. Tensile strength of FSB joints at the different rotational speeds.
The strength of 2000 RPM sample and titanium base metal are approximately the same because of the higher diffusion of aluminum into base metals and the lack of cracks in the interlayer.

Figure 15 shows that increasing the heat input and rotational speed reduces the tensile strength of joints. Higher rotational speed increases the intermetallic layer thickness and produces more cracks. The higher pressure of the tool on the friction zone pushes out excess aluminum and results in a higher tensile strength for the 2400 RPM and 2800 RPM samples over the 2200 RPM and 2600 RPM samples. Also, the 2200 RPM and 2600 RPM samples have more cracks in the interlayer. Errors in the process may have applied higher pressure to joint zone, which may explain the reduced tensile strength of 2600 RPM sample. We excluded any higher rotational speeds that deform and/or damage the stainless steel.

Figure 16 depicts the stress-strain curve of FSB samples with varying rotational speeds. According to figure 16, the 2200 RPM sample has the highest degree of toughness. The highest toughness is because of the higher diffusion of the aluminum layer to base metals. Also, the thickness of the intermetallic increases the strength of the 2200 RPM FSB joint. In addition, increasing the rotational speed of the tool and increasing the friction between the tool and stainless steel will result in more aluminum melting between the two metals. By increasing the rotational speed and friction between stainless steel and the tool, the diffusion of aluminum foil to base metals is accelerated. This increases the strength and rigidity of the FSB joints.

3.6. Fractography

Figure 17 shows the thickness of the intermetallic layer between base metals increases with the rotational speed. The diffusion of aluminum to stainless steel is higher than diffusion of aluminum to titanium, because of the different melting points of base metals. The higher rotational speed and higher heat input increase the HAZ in the joint. Increasing the rotational speed increase the friction between base metals and the tool, which in turn increases the HAZ.

Figure 17 shows that increasing the rotational speed and friction results in melting the aluminum foil and improving the distribution of aluminum between the base metals. The ductile fracture occurs because of the low thickness of the intermetallic layer. We can avoid the ductile fracture by increasing the rotational speed to 2800 RPM, which increases the intermetallic layer thickness. Figure 17 shows that increasing the rotational speed generates higher heat input that melts the aluminum foil. As a result, aluminum is softer than base metals increasing the intermetallic thickness.

Figure 17 shows the FSB fracture patterns indicating that in each case a ductile fracture occurred. Steel and titanium fracture surfaces have cup and cone structures between 2200–2600 RPM. The increase in heat input results in a deepening the cup and cone as the RPM increases.
4. Conclusion

This paper successfully achieved the dissimilar joining of St37 to Ti (grade 1) via the FSB process. Friction spot brazing is one of the easiest and least expensive method of joining different metals. FSB doesn’t produce fumes, and it is environmentally friendly. The main results are as follows:

1. Without any keyhole, brazed joints are fabricated. The highest joint strength of 2000 RPM sample is 6 kN and it is almost equal to Ti base metal.

2. The increasing of rotational speed, the TiAl₃—FeAl₃—Fe₃Al intermetallic phases are formed, and cracking is observed in these intermetallic compounds.

3. EDS analysis results show the highest diffusion of Al as a filler is achieved in the 2800 RPM FSB sample. Overall, higher rotational speed cause higher heat input and higher diffusion of filler to base metals.

4. The highest hardness was almost 850 HV, which relates to the 2400 RPM FSBed sample due to more intermetallic phases.

5. Increasing the rotational speed form more intermetallic phases and microcracking.

Figure 17. Fractography of fracture surface of FSB joints.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Fu B, Shen J, Suhuddin U F H R, Pereira A A C, Maawad E, dos Santos J F, Klusermann B and Rethmeier M 2021 Revealing joining mechanism in refill friction stir spot welding of aa31 magnesium alloy to galvanized dp600 steel Mater. Des. 209 109997
[2] Zhang P, Fang Z and Li S 2021 Microstructure and interfacial reactions of resistance brazed lap joints between tc4 titanium alloy and 304 stainless steel using metal powder interlayers Materials 14 180
[3] Muralimohan C H, Muthupandi V and Sivaprashad K 2014 The influence of aluminium intermediate layer in dissimilar friction welds: Paper presented at international conference on engineering materials and processes (icemap 2013), 23–24, 2013, tagore engineering college, chennai, tamilnadu, india Int. J. Mater. Res. 105 350–7
[4] Atabaki M M, Nikolodinovski M, Chenier P, Ma J, Harooni M and Kovacevic R 2014 Welding of aluminum alloys to steels: an overview Journal for Manufacturing Science and Production 14 59–78
[5] Ma Y, Liu S, Zhang H, Feng Y, Gou S and Bai H 2020 Study on affecting factors and mechanism of oil tubing corrosion in northern shaanxi oil field Mater. Sci. Forum 977 108–14
[6] Paidar M, Bokov D, Mehrez S, Nasution M K, Ojo O O and Zain A M 2022 The influence of the backing plate materials on microstructure and mechanical properties of friction spot extrusion brazing of aa2024-t3 aluminum alloy and brass sheets J. Manuf. Processes 74 28–39
[7] Mahdi A Z, Amin S A and Bakhy S H 2020 Influence of refill friction stir spot welding technique on the mechanical properties and microstructure of aluminum aa5052 and aa6061-t3 IOP Conference Series: Materials Science and Engineering vol 671 (Bristol: IOP Publishing) 012156
[8] He X, Wang Y, Lu Y, Zeng K, Gu F and Ball A 2015 Self-piercing riveting of similar and dissimilar titanium sheet materials Int. J. Adv. Manuf. Technol. 80 2105–15
[9] Elrefaey A and Tillmann W 2010 Brazing of titanium to steel with different filler metals: Analysis and comparison J. Mater. Sci. 45 4332–8
[10] Zhang C Q, Robson J D and Prangnell P B 2016 Dissimilar ultrasonic spot welding of aerospace aluminum alloy AA2139 to titanium alloy TiAl6V4 J. Mater. Process. Technol. 231 382–8
[11] Muralimohan C H, Ahsaq M, Ashiri R, Muthupandi V and Sivaprashad K 2016 Analysis and characterization of the role of ni interlayer in the friction welding of titanium and 304 austenitic stainless steel Metall. Mater. Trans. A 47 347–59
[12] Zhang C Q, Robson J D and Prangnell P B 2016 Dissimilar ultrasonic spot welding of aerospace aluminum alloy AA2139 to titanium alloy TiAl6V4 J. Mater. Process. Technol. 231 382–8
[13] Azizieh M, Shoebi R, Tahmasebi M, Mashtizadeh A and Dezfuli M A 2019 Friction stir spot brazing of low carbon to galvanized steel Trans. Indian Inst. Met. 72 2375–9
[14] Azizieh M, Tahmasebi M, Mashtizadeh A, Miraalii M, Lariki A N and Mazaheri M 2019 Friction stir spot soldering galvanized steel using tin interlayer Mater. Res. Express 6 086555
[15] Li Y, Tang X, Xu L, Cui H and Zhang R 2022 Interfacial behaviors and joint properties of the dual beam laser fusion brazing ti6al4v/aa7075 dissimilar metals J. Manuf. Processes 73 279–89
[16] Muralimohan C H, Haribabu S, Reddy Y H, Muthupandi V and Sivaprashad K 2014 Evaluation of microstructures and mechanical properties of dissimilar materials by friction welding Procedia Materials Science 5 1107–13
[17] Yıldız B S, Sahin A Z, Kahraman N and Al-Garni A Z 1995 Friction welding of StAl and AlCu materials Journal of Materials Processing Techn. 49 431–43
[18] Cao R, Sun J H and Chen J H 2013 Mechanisms of joining aluminum A6061-T6 and titanium Ti-6Al-4V alloys by cold metal transfer technology Sci. Technol. Weld. Joining 18 425–33
[19] Fuji A, North T H, Ameayka Y and Futamata M 1992 Improving tensile strength and bend ductility of titanium/AlSi 304L stainless steel friction welds Materials Science and Technology (United Kingdom) 8 219–35
[20] Muralimohan C H, Muthupandi V and Sivaprashad K 2014 Properties of friction welding titanium-stainless steel joints with a nickel interlayer Procedia Materials Science 5 1120–9
[21] Dey H C, Ashfaq M, Bhandari A K and Rao K P 2009 Joining of titanium to 304L stainless steel by friction welding J. Mater. Process. Technol. 209 5862–70
[22] Wang S Q, Patel V K, Bhole S D, Wen G D and Chen D L 2015 Microstructure and mechanical properties of ultrasonic spot welded Al/Ti alloy joints Mater. Des. 78 33–41
[23] Peng H, Chen D L, Bai X F, Wang P Q, Li D Y and Jiang X Q 2020 Microstructure and mechanical properties of Mg-to-Al dissimilar welded joints with an Ag interlayer using ultrasonic spot welding J. Mater. Process. Technol. 269 58–63
[24] Yuan R, Deng S, Cui H, Chen Y and Lu F 2019 Interface characterization and mechanical properties of dual beam laser welding-brazing Al/titanium dissimilar metals J. Manuf. Processes 40 37–45
[25] Zhou X, Duan J, Zhang F and Zhang S 2019 The study on mechanical strength of titanium-aluminum dissimilar butt joints by laser welding-brazing process Materials 12 712
[26] Azizieh M, Yazdi M, Tahmasebi M, Miraali M and Mashtizadeh A 2018 Characteristics of dissimilar friction stir spot brazing between aluminum and galvanized steel Mater. Res. Express 6 026515