Mechanical Characterization of Rotary Friction Welded Dissimilar Aluminium Alloys

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Abstract. Joining of the similar & dissimilar materials alloys using heat of the friction in currently being used, especially for non-ferrous alloys which are considered as non-weldable alloys. Al 2024-T6 & Al 6061-T6 having length of 70mm and 12mm diameter were welded by using the friction welding process. Similar and dissimilar welded samples were obtained by applying different combinations of welding parameters like friction pressure 30bar, forging pressure from 50 to 60 bar, and rotational speed of 2200 rpm. Vickers microhardness and Tensile test was performed on similar and dissimilar welded samples. Test shows that ultimate tensile strength and hardness of the similar welded joint was greater than their respective base metals welds. Dissimilar weld samples have hardness and ultimate tensile strength greater than the base Al 6061-T6, and less than the base Al 2024-T6. From results, it was clearly shown that as forging pressure increased from 50 to 60 bar, ultimate tensile strength and hardness of the similar and dissimilar welded samples increased. Joints were analysed to investigate the fractography of all welded samples. All welded samples fractured on the base metal alloy and show the formation of the cup and cone like structure which indicate the ductile fracture of the joints.

Keywords: Friction Welding, Fractography, SEM, Al 2024-T6, Al 6061-T6

1 Introduction

Al 2024-T6 and Al 6061-T6 are being used in aerospace structures, in automobile industry for having due to their high strength to mass ratio[1]. Both alloys are recognized for their ability to get strength due to precipitation hardening. Fusion welding of 2024-T6 is difficult and considered as non-weldable due to their sensitivity of cracking at high temperature and joint strength decreases, but Al 6061-T6 has excellent weldability and different operations can be performed easily[2]. It has a property of corrosion resistant even when worked below its melting point but if it follows a particular deformation, Al 2024-T6 losses its corrosion resistance[3].

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In the process of the RFW[4], one of the specimens is fixed in static position on one side and other is fixed in chuck and rotated. The static part is brought close to the rotating part and rubbed with the rotating part with friction pressure. After a specific time called friction time, brakes were applied to stop the rotation of the machine and forging pressure is applied for a specific time called forging time. Mechanical energy gives the required heat to join the material by converting into heat energy. It is a complicated material working procedure that includes several factors such as pressure, time, rotational speed, along with phenomena of generation of frictional heat, plastic deformation, and atomic diffusion. Several modern structural applications, including as aerospace structures, aero plane fuselage panels require a high value of strength to weight ratios. Aluminum (Al) alloys with high strength to weight ratios, such as 6XXX and 2XXX, are frequently employed for this purpose[5]. The Al alloys need dependable and trustworthy joints for these applications. These alloys are generally lighter and typically require precipitation hardening before use, which causes precipitates to develop. Because of these precipitates, traditional fusion welding is declared unfit for joining these alloys. Because of this, these alloys are typically regarded as being non-weldable[6]. In this situation, these alloys are welded by RFW, which is one of the appropriate methods to join these alloys. Due to frictional heating between the contact surfaces of the combined parts, this solid-state joining method is observed to be the most effective for soft alloys like copper, aluminum, magnesium etc[7]. When compared to conventional welding, the weld developed by RFW has significantly fewer internal flaws[8]. Moreover, several variables, such as RPM, forging pressure, forging time, friction pressure, friction time, affect the weld's qualities and must be effectively controlled. About the optimization of these factors, numerous reports and extensive reviews were presented. RFW has many benefits over traditional welding, particularly low residual stresses and deformation, as well as the ability to be performed without the need of fumes, below the melting point of the welding metals, arc flash, filler metal, spatters or shielding gases. Owing to the benefits, (RFW) has been used extensively in the aerospace, automotive, and rail industries to join both similar and dissimilar materials. It can join the different metals having different thermal and mechanical properties[9].

S. Senthil Murugan et al. [8] joined the stainless steel and Al 6063 by changing the upset pressure from 18-21 MPa and found that welded joint strength and efficiency increased with increasing forging pressure. He also used different interlayers to increase the strength of the and found maximum strength obtained with Cr interlayer. Senkathir S et al. [9] join the Al 6061-T6 and SS AISI 304 using RFW process, found the optimized parameters to join the aluminum and steel. Intermetallic compounds were found at the joint interface which decreased the strength of the joint. The thickness of the joint decreased with the increase of the forging pressure and joint strength increased. Results show that welded joint has strength greater than the base metal alloys.

Suppachai Chainarong et al. [10] welded the two dissimilar aluminum alloys using friction welding method and found that strength and hardness of the welded joint was higher. The effect of burn off length and rotational speed on the hardness and tensile strength were analysed. He further showed that obtained weld joint strength increased by increasing the burn off length and rotational speed. Mohammed Tashkandi et al. [11] joined the Al 6061 alloy and analyzed the effect of friction time on the mechanical properties of the welded joint. He found that when friction time increased up to 5s, joint strength increased, and further increment decreased the strength of the joint. As friction time is increased, the fracture of the sample changes from ductile to brittle.

Table.1. Chemical Composition Al 2024-T6 & Al 6061-T6

Element (wt%)	Al	Cu	Si	Mg	Mn	Fe	Cr	Ti	Others
Al 2024-T6	93.68	3.70	0.19	1.22	0.73	0.41	0.07	-	-
Al 6061-T6	97.59	0.25	0.57	0.89	0.10	0.30	0.14	0.01	≤0.15

2 Materials and methods

Al 2024-T6 and Al 6061-T6 were used as joining material. They were in circular shape having dimensions of 70 mm length and of 12 mm diameter. Chemical composition of aluminum alloys is given in Table.1. The welding process is carried out on a computer-controlled lathe machine. Al 2024-T6 is on the rotating side and Al 6061-T6 is on the non-rotating side. Before starting the welding process, the joining surfaces of each sample were washed with acetone to remove any contaminants like dirt, grease etc. to increase the quality of the joints.

A computer-controlled lathe was used to perform the experimentation. All other welding parameters were kept constant except for forging pressure. Selection of the process parameters is a difficult task to obtain a sound welded joint which has no defect. In this research, different combinations were applied to obtain a defect free joint, and best parameters were selected by visual inspection of the welded joint. The welding process was performed in accordance with the parameters shown in Table 2. Similar and dissimilar welds were obtained by changing the forging pressure and keeping the other parameters constant and prepared for tensile and hardness testing. Welded samples for similar and dissimilar were shown.

Fig.1. Welding setup

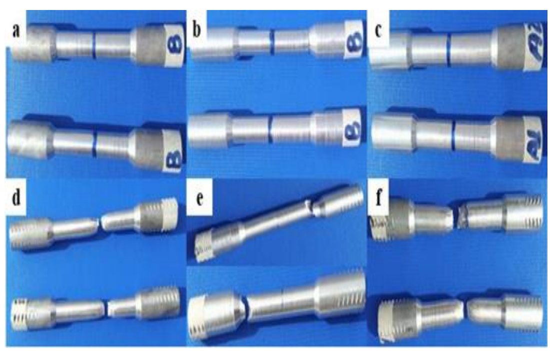

Fig.2. (a) Similar welds 6061-T6, (b) Similar welds 2024-T6, (c) Dissimilar Welds, (d) fractured samples of Similar welds 6061-T6, (e) Fractured samples of 2024-T6, (f) Fractured sampled of dissimilar welds.
(ASTM-E8 Standard samples)

For tensile testing sample was prepared using standard ASTM-E8 with 115mm length. The gauge length of the sample was 50mm. After preparation, the sample was tested using Electrohydraulic Universal Testing Machine of Hebei Gaotiejian Test Instrument Co. Ltd. For microhardness testing and microstructural analysis, samples were cut perpendicular to the joint, finished with emery papers ranging from 320- 5000 series, polished with diamond paste and after that Keller reagent (190ml distilled water, 5ml Nitric acid, 2ml Hydrofluoric acid, and 3ml Hydrochloric acid) was used to etch for 15s to visualize the features of the different zones. Results of the microhardness was obtained using Micro Vickers hardness tester with load applied was 1kgf at the dwell time of 10sec. Three values at different positions on the welded joint was obtained to get an average value. Fractography of the fractured samples was done using scanning electron microscopy.

3 Results and discussions

Macrostructures of base and welded joint were shown in figure 3. In all specimens, metal will flow outside the joint and flash was formed. Formation of the flash mainly depends upon the properties of alloy being welded which consequently depend upon the heat produced during friction welding. The heat produced proportional to the rubbing velocity across the joining surfaces, which is maximum at the surface and minimum at the centre[12]. From figure 3, it is cleared that the flow of the metal is more in the side of Al 6061-T6 in comparison to the Al 2024-T6. Due to the differential in thermal conductivity, frictional heat moves from the joint contact to the side of the AA6061-T6 alloy, giving the impression that the Al/Mg joints have an asymmetrical temperature profile. Heat produced at the magnesium side helps for plastic deformation that took place on the magnesium side and Mg is ejected from the joint to the surface to form a significant quantity of hammered metal, which ultimately results in an asymmetrical appearance. Heat will flow easily to the material that has high thermal conductivity and Al 6061-T6 has thermal conductivity greater than the Al 2024-T6. But Al 2024-T6 has hardness greater than the Al 6061-T6 which is the reason for less deformation[13].

Table.2. Experimentation results for UTS & Micro Vickers Hardness

Sr No	Samples	Rotational Speed (rpm)	Friction Pressure (bar)	Forging Pressure (bar)	UTS (MPa)	Hardness (MvH)
1	Base Al 6061-T6	-	-	-	480	142
2	Base Al 2024-T6	-	-	-	310	107
3	Similar Weld Al 6061-T6	2200	30	50	316.3	109.5
4	Similar Weld Al 6061-T6	2200	30	60	317.6	111.2
5	Similar Weld Al 2024-T6	2200	30	50	481.3	145.6
6	Similar Weld Al 2024-T6	2200	30	60	485.7	147.2
7	Dissimilar Welds	2200	30	50	348.13	117
8	Dissimilar Welds	2200	30	60	352.46	120.7

The microstructure of the samples is shown in figure 4. As heat transfers from welded region to base metal alloys, microstructure of the welded samples changed. The heat produced, when transferred from the joint to the base metal, causes a different temperature profile which consequently changes the microstructure from joint to the base metal. At the welding area, the grain size decreased progressively. Welded region grains are fine due to the recrystallization of the grains. Welded joint width mainly depends upon the heat generated during rubbing action which is also caused by increasing friction time. Grains in

Al 2024-T6 are fine than Al 6061-T6 when friction time increased[14]. Initial coarse and large grains of the base metals converted into the small and in fine grains at the weld region due to aging and recrystallization of the grains in weld region[15].

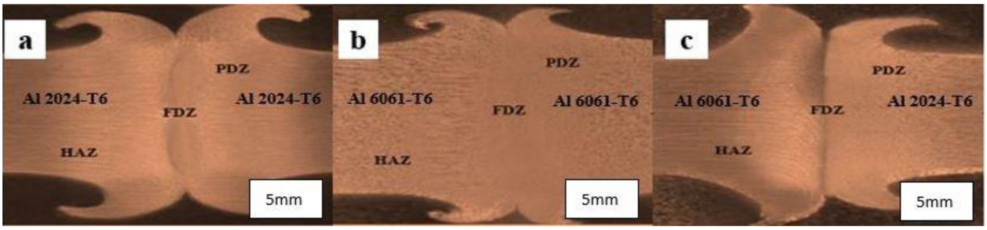

Figure.3. Macrostructures: (a) Similar welds 2024-T6,(b) Similar welds 6061-T6, (c) Dissimilar weld

Further analysis was done using scanning electron microscope. In Al 2024-T6, fracture occurred in base metal, Al 6061-T6 and dissimilar welded sample shows cup and cone type fracture near the welded joint[16]. SEM images in Figure 5, show that the dissimilar welded joint has large number of porosities, then the same welded joints. Fractured behaviour was analyzed by cutting the portion of the fractured surface and analysing using scanning electron microscope. Figure 5d,5e,5f. shows that all the welded joints experience a large amount of deformation, dimple structure formed and shows a ductile fracture.

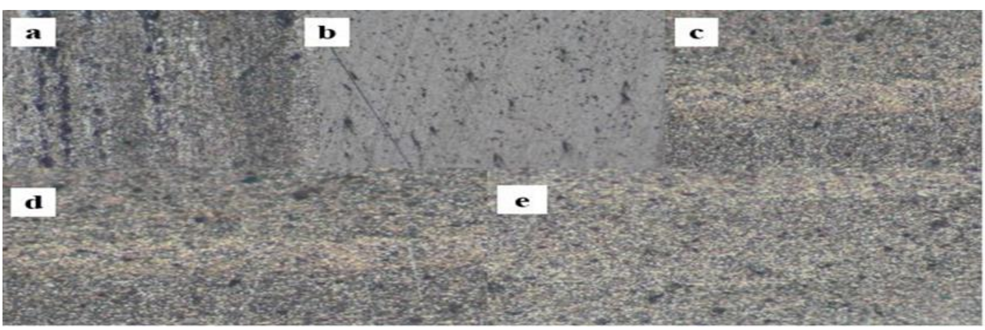

Figure.4. Microstructures(20X) (a) Base Al 2024-T6, (b) Base Al 6061-T6, (c) Dissimilar Welded, (d) Similar weld 2024-T6, (e) Similar weld 6061-T6

Ultimate tensile strength of the base metals, similar and dissimilar welded joint are given in figure 6. From figure 6, tensile strength of the same welded Al 2024-T6 are greater than either base metal or dissimilar joints. UTS of the dissimilar joints was greater than the base Al 6061-T6 but less than the Al 2024-T6. The effect of the forging pressure on the tensile strength of the welded joints is shown in Table.2. From all parameters, forging pressure shows significant effect on the hardness and strength[17]. By increasing the forging pressure, increment in UTS of the joint was analyzed.

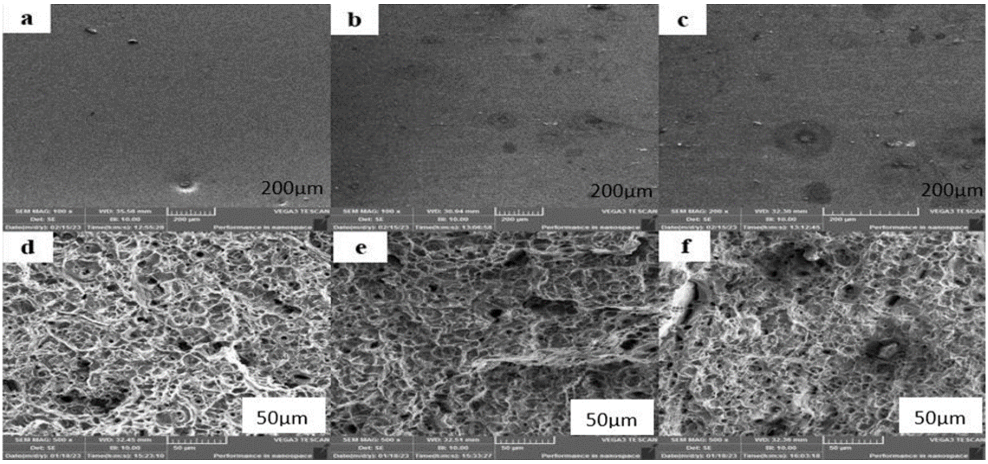

Fig.5. SEM images: (a) Similar weld 6061-T6(200µm) , (b) Similar weld 2024-T6(200µm), (c) Dissimilar weld(200µm), (d) Fracture surface of the Similar weld 6061-T6(50µm), (e) Fracture surface of the similar weld 2024- T6(50µm), (f) Fracture surface of the dissimilar weld(50µm)

Micro Vickers hardness of the base alloys, similar welds and dissimilar welds were shown in figure 7. As Al 2024-T6 & Al 6061-T6 are hardened by precipitation, this precipitation gives strength to the alloy and goes into the solid solution in HAZ. Difference in the hardness of the two alloys is due to the difference in their thermal conductivities and thus the effect of transfer of heat is different in these alloys. As hardness of the Al 2024-T6 is higher than the Al 6061-T6, heat absorbed by the Al 2024-T6 was less than the Al 6061-T6. From figure 7. The weld region has hardness greater than the base metal alloys due to large amount of deformation of the grains at the weld region. Table 7. shows the hardness values of the base metals, same alloy welds and dissimilar welded joints. By increasing the forging pressure, value of the hardness going to increase in all welds.

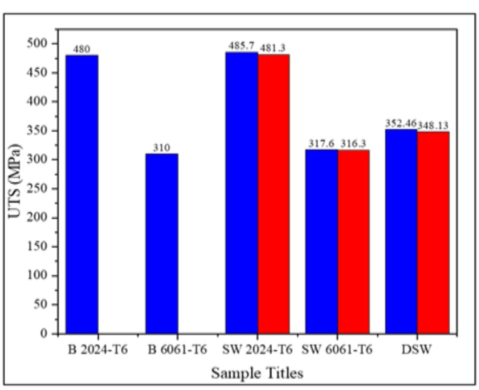

Figure.6. UTS of the base, similar & Dissimilar welds

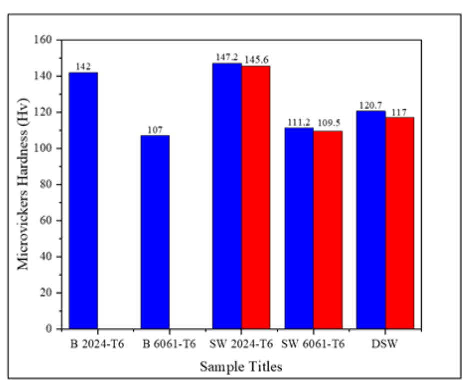

Figure.7. Micro Vickers hardness of the base, similar & Dissimilar welds

4 Conclusions

In this research, similar and dissimilar aluminum alloys were welded successfully, their properties like hardness and ultimate tensile strength of the joint were compared. In addition, experimentation was done by varying the forging pressure, its effect on the properties were analyzed.

- ❖ Similar and dissimilar aluminum alloys were successfully welded with strength greater than the respective base metal alloys. But in case of dissimilar alloys, strength was greater than the Al 6061-T6 and less than the Al 2024-T6. Ultimate tensile strength in case of the similar Al 2024-T6 was 485.7MPa, Al 6061-T6 was 317.6MPa, Dissimilar alloys were 352.46MPa. micro-Vickers hardness was also greater than the respective metal alloys and found to be 147.2M_VH in Al 2024-T6, 111.2M_VH in Al 6061-T6, 120.7M_VH in Dissimilar aluminum alloys. Various metallurgical events occur at the interface during friction welding, such as element diffusion, hardening, grain refining, and precipitation, which increase the ultimate tensile strength and hardness value.
- ❖ Forging pressure has a significant effect on the hardness and strength of the joint either in case of similar or dissimilar aluminum alloys. Hardness and Ultimate tensile strength were found to be increasing with increasing the forging pressure while keeping all other parameters constant.
- ❖ Fractography analysis shows that plastic deformation experiences by similar weld Al 2024-T6 was greater than the similar weld Al 6061-T6 and dissimilar welds. Also, the percentage elongation and energy absorbed by the Al 2024-T6 was greater than the others. Al 2024-T6 shows more ductile fracture as compared to dissimilar and similar Al 6061-T6 welds.

It is found that friction welding is an appropriate method to join the similar and dissimilar aluminum alloys. Results can be significantly improved by selecting proper parameters. Forging pressure significantly improve the properties of the joint. Dissimilar aluminum joints were usefully employed in situations where combination of resistant t corrosion and high strength was required.

References

[1] D. Metals, "Thermal Model of Rotary Friction Welding for Similar and Dissimilar Metals", doi: 10.3390/met7060224.

[2] R. Adalarasan, M. Santhanakumar, and A. S. Sundaram, "Optimization of weld characteristics of friction welded AA 6061-AA 6351 joints using grey-principal component analysis (G-PCA) †," vol. **28**, no. 1, pp. 301–307, 2014, doi: 10.1007/s12206-013-0963-4.

[3] T. Dursun and C. Soutis, "Recent developments in advanced aircraft aluminium alloys," *J. Mater.*, vol. 56, pp. 862–871, 2014, doi: 10.1016/j.matdes.2013.12.002.

[4] R. Paventhan and P. R. Lakshminarayanan, "Optimization of Friction Welding Process Parameters for Joining Carbon Steel and Stainless Steel," vol. **19**, no. 1, pp. 66–71, 2012.

[5] C. Yashwant, K. Dinesh, and S. S. Salim, "Friction welding of Aluminium Alloy 6063 with copper," vol. 2004, pp. 2–7, 2020.

[6] E. Moumi, P. Wilhelmi, B. Kuhfuss, C. Schenck, and K. Tracht, "Wire joining by rotary swaging," *Procedia Eng.*, vol. **81**, no. October 2014, pp. 2012–2017, 2017, doi: 10.1016/j.proeng.2014.10.273.

[7] P. Taylor, K. Kato, and H. Tokisue, "Dissimilar friction welding of aluminium alloys to other materials Dissimilar friction welding of aluminium alloys to other,"

no. January 2015, pp. 37–41, 2010, doi: 10.1533/wint.2004.3345.
[8] S. S. Murugan and P. S. A. Noorul, “Experimental study on the effect of silver , nickel and chromium interlayers and upset pressure in joining SS304L - AA6063 alloys through direct drive friction welding process,” *J. Brazilian Soc. Mech. Sci. Eng.*, vol. **7**, 2020, doi: 10.1007/s40430-020-02687-7.
[9] S. Senkathir and V. B. Siddharth, “Friction welding of dissimilar metals (aluminium AL 6061 T6 and stainless steel AISI 304),” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. **912**, no. 3, 2020, doi: 10.1088/1757-899X/912/3/032043.
[10] S. Chainarong, C. Meengam, and M. Tehyo, “Rotary friction welding of dissimilar joints between SSM356 and SSM6061 aluminium alloys produced by GISS,” *Eng. J.*, vol. **21**, no. 1, pp. 181–191, 2017, doi: 10.4186/ej.2017.21.1.181.
[11] M. A. Tashkandi, “Effect of Friction Time on the Mechanical and Microstructural Properties of AA6061 Joints by Continuous Drive Friction Welding,” vol. **10**, no. 3, pp. 5596–5602, 2020.
[12] M. Azizieh, M. Khamisi, D. J. Lee, E. Y. Yoon, and H. S. Kim, “Characterizations of dissimilar friction welding of ST37 and CK60 steels,” *Int. J. Adv. Manuf. Technol.*, vol. **85**, no. 9–12, pp. 2773–2781, 2016, doi: 10.1007/s00170-015-8107-x.
[13] M. N. Ahmad Fauzi, M. B. Uday, H. Zuhailawati, and A. B. Ismail, “Microstructure and mechanical properties of alumina-6061 aluminum alloy joined by friction welding,” *Mater. Des.*, vol. **31**, no. 2, pp. 670–676, 2010, doi: 10.1016/j.matdes.2009.08.019.
[14] V. Y. Rud, V. M. Kosolapov, C. Carloganu, M. Petr, and G. Vacchiano, “Effect of gaussian beam on microstructural and mechanical properties of dissimilarlaser welding ofAA5083 and AA6061 alloys Effect of gaussian beam on microstructural and mechanical properties of dissimilarlaser welding ofAA5083 and AA6061 alloys,” 2018, doi: 10.1088/1757-899X/330/1/012066.
[15] C. Shanjeevi, S. Satish Kumar, and P. Sathiya, “Evaluation of mechanical and metallurgical properties of dissimilar materials by friction welding,” *Procedia Eng.*, vol. **64**, pp. 1514–1523, 2013, doi: 10.1016/j.proeng.2013.09.233.
[16] M. Ashfaq and K. J. Rao, “Comparing bond formation mechanism between similar and dissimilar aluminium alloy friction welds,” vol. **30**, no. 3, pp. 329–338, 2024, doi: 10.1179/1743284713Y.0000000360.
[17] G. A. Rao and N. Ramanaiah, “Materials Today : Proceedings Dissimilar metals AISI 304 steel and AA 2219 aluminium alloy joining by friction welding method,” *Mater. Today Proc.*, no. xxxx, pp. 1–6, 2019, doi: 10.1016/j.matpr.2019.09.028.