Friction stir welding of dissimilar Al alloys: effect of process parameters on mechanical properties

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A R T I C L E I N F O	A B S T R A C T
	In the present experimental study, two dissimilar sister aluminum alloys, 5083 and 5086, are welded through friction stir welding process. Different experiments are conducted on vertical milling machine through a fixture design and firm holding welding plates on it. These experiments are performed by varying welding parameters including welding speed, rpm, different pin profiles, tool tilt angle at five levels each. Two different mechanical properties of the welded specimen (i.e. tensile strength and percentage of elongation) have been tested and compared with the base metals to find out the joint efficiency. Also it is observed that rpm, tool tilt angle and different pin profiles make significant impacts on friction stir welded joints. Tool rpm increases the tensile strength to an extent. Also, tool pin profile affects the stirring or plastic flow of material under tool shoulder. It is shown through visual and optical analysis that surface finish and weld quality of joints depend on tool tilt angle.

1. Introduction

Friction stir welding (FSW) is a relatively new technique for joining metals as well as composites. Friction stir welding has received a great deal of attention as a new and easy way to weld wide range of materials without any environment hazard outputs. This welding uses a rotating tool to deform or stir the joining materials simultaneously without melting of these materials. Friction Stir Welding is rapidly accepted all over the world in such a small lap of time after its development in 1991 by The Welding Institute (TWI) at UK. The main cause behind this rapid growth is its ability to consistently produce high quality welds with low distortion, even in materials considered un-weldable by conventional techniques (Mishra & Ma, 2005; Vural et al., 2007, Rhodes et al., 2010). In addition, the accompanying reductions in weld inspection and re-weld procedures can also provide significant cost benefits. Due to solid state welding the defects that commonly occur in fusion welding are evaded. The

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reduced heat generation with respect to the fusion welding also results in a reduction in residual stress in the joints. Therefore, different aluminum alloys which cannot be easily welded through fusion weld can be friction stir welded without voids, cracking or very less distortion. Moreover, this process can be used successfully for joining dissimilar materials (Fotouhi et al., 2014; Akbari & Abdi Behnagh 2012; Akbari et al., 2012; Akbari Mousavi et al., 2012; Abdi Behnagh et al., 2012).

Friction stir welding is a solid state welding, therefore, residual stress plays a significant role on joint strength. During friction stir welding, stress is induced and residual stress in stirring zone is due to the rotational and the transverse speed of the tool (Steuwer et al., 2006). Maximum tensile strength of the joint is obtained at lower transverse speed of the tool. Also higher joint strength can be achieved as the penetration depth of the tool pin in friction stir welding of the aluminum alloy is increased (Uzun et al., 2005). When FSW is applied to high load bearing components then joint strength is a critical parameter and must be improved as per previous reports (Kim & Jang, 2006; Khorrami et al., 2012; Cavaliere, 2013; Rajakumar et al., 2011; Aliha et al., 2016). The effect of tool geometry on the welding strength is an important factor to study. Over the changing needs, numerical methods are used for analysis and micro structural study of the friction stir welding (Peel et al., 2003; He et al., 2014). RajKumar et al. (2014) investigated the influence of shoulder design for dissimilar aluminum alloys. In this research, the friction stir welding of two Al 5xxx series is performed experimentally and the influence of process parameters on the mechanical properties of the weldment is investigated.

2. Experimental setup

Experimentation is performed through the One Factor at a Time (OFAT) technique. Here four factors of rpm, tool tilt angle, welding speed/feed rate and tool pin profile are investigated. In this technique, one factor is varied at different levels and other factors or parameters are fixed at their average levels. Twenty pilot experiments are conducted for selection of the limit or range of different factors. Friction stir welding of two dissimilar aluminum alloys is carried out on vertical milling machine. The specifications of the machine tool are given in Table 1.

Table 1. Specifications of Vertical Milling Machine

Specification	Values	Specification	Values
Make	Bharat Fritz Werner Ltd.(Semi Automatic)	Cross Bed Range	250 mm
Spindle position	Vertical	Diameter of Tool Holder	ISO-40
RPM Range	45-2000	Main Motor(capacity/rpm)	3kw/1500rpm
Longitudinal Bed Range	560 mm	Longitudinal Feed Range	16-800 /min

According to welding workpiece dimensions, a fixture of cast iron is designed and manufactured for holding the work piece plates. It restricts three dimensional movements of two work pieces as shown in Fig. 1. The fixture has been given variable space dimensions arrangement for holding two equal thickness pieces for the future use.

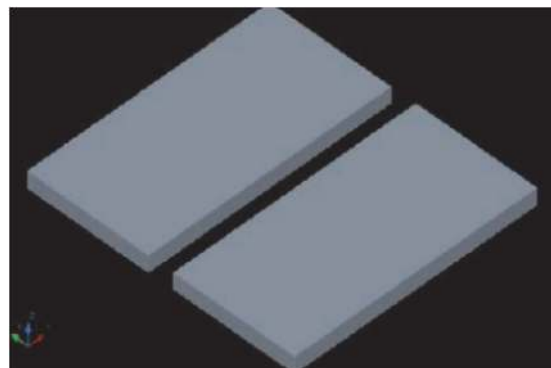**Fig.1.** Actual design of the fixture used for FSW   **Fig. 2.** Aluminium Alloy plates 5083 and 5086 used for FSW butt joint

Two grades of Aluminum Alloy 5086 H116 and 5083 H321 are used for the experimentation as shown in Fig. 2. Each aluminum alloy plate is 6 mm thick and chemical composition is given in Table 2. Two plates have following dimensions: For AA 5086 dimensions are 100×95×6 mm cube and 100×70×6 mm cube for AA 5083. Both grades are sister alloy of aluminum having small change in properties. AA 5086 is taken at advancing side (AS) and 5083 is taken at retreating side (RS) of the welding. As more heat is dissipated in advancing side so hard material AA 5086 has been taken for this side.

Table 2. Chemical composition of AA 5086 and AA5083.

Elements→	Mg	Mn	Fe	Si	Zn	Cr	Al
AA 5086	4.0	0.45	0.38	0.34	0.25	0.15	Remainder
AA 5083	4.3	0.63	0.13	0.076	0.06	0.03	Remainder

A chromium-molybdenum tool made of hot work tool steel H13 is used for the stirring and joining of two aluminum alloy plates. The specification of the tool is given in Table 3.

Table 3. Specification of tool used.

Material	H13 Tool Steel
Shoulder Diameter	18 mm
Pin Length	5.9 mm
Pin Base Diameter	6 mm

Five different types of pin profiles are used for the pilot experiments— threaded, square, cylindrical, tapered and triangular.

3. Parameters for FSW

For the experimentation, a pilot study is undertaken using OFAT technique. Four different parameters— tool rotational speed, tool tilt angle, welding speed, shoulder pin profile— are selected and experimentation is carried out. The welding parameters with different levels are given in Table 4. The values of welding parameters are chosen according to the maximum range with the constraint of the operating vertical milling machine.

Table 4. Variation of different factors and experiment plan

Sample no.	Welding speed (mm/min)	Rotational speed (rpm)	Tool tilt angle (degree)	Tool pin profile
S1	20	355	3	Square
S2	20	710	3	Square
S3	20	1000	3	Square
S4	20	1400	3	Square
S5	20	2000	3	Square
S6	20	1000	0	Square
S7	20	1000	2	Square
S8	20	1000	4	Square
S9	20	1000	6	Square
S10	20	1000	8	Square
S11	16	1000	3	Square
S12	20	1000	3	Square
S13	40	1000	3	Square
S14	50	1000	3	Square
S15	63	1000	3	Square
S16	20	1000	3	Threaded
S17	20	1000	3	Cylindrical
S18	20	1000	3	Square
S19	20	1000	3	Triangular
S20	20	1000	3	Taper

The values of feed and welding speed are taken according to their availability on the used vertical milling machine. Initial heating time or dwell time is kept constant for tool at 8 seconds. Plunge depth

is also kept constant at 0.12 mm for all the experiments. Fig. 3 shows different welding plates and the effects of parameters on weld surface quality. Joints numbered 2, 3, 11 and 17 have better visual surface finish as well as strength.

Fig. 3. Different welding joints

4. Mechanical Properties

Different mechanical properties of the welding joint are studied for the selection of best range of parameter values. Tensile strength, percent elongation and joint efficiency are different parameters of interest for research in this paper.

-Tensile test

Tensile test specimens were tested on UTM and ultimate tensile strength, percentage of elongation and joint efficiency have been evaluated. Tensile specimens were prepared with the direction being perpendicular to the welding direction, so that the weld zone could be located in the middle of the specimen. The tensile tests were performed at a small strain rate on the universal testing machine of H&T Company make. The ultimate tensile strength and the percentage elongation values were recorded. The test specimen is prepared according to ASTM E8 and different dimensional values in mm are shown in Fig. 4.
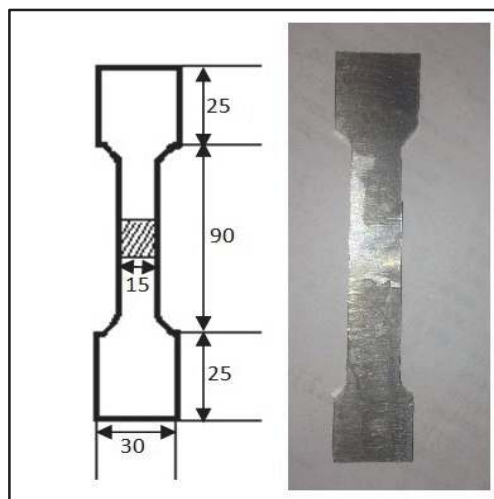

Fig. 4. Sample prepared for Universal Testing Machine

After the testing of the specimen the values of tensile strength, elongation and joint efficiency are calculated which are presented in Table 5. For the joint efficiency the base material strength is taken as the average tensile strength of two aluminum grades.

Table 5. Experimental data obtained from the tensile test experiments

Sample no.	Tensile strength (MPa)	Elongation (mm)	Elongation (%)	Joint Efficiency (%)
S1	195.5	8.6	9.5	65.9
S2	213.3	8.6	9.5	71.9
S3	274.4	13.6	15.1	92.5
S4	155.5	7.6	8.4	52.4
S5	205.5	9.4	10.4	69.3
S6	210.2	9.1	10.1	71.5
S7	203.3	9.3	10.3	68.5
S8	207.8	8.9	9.9	64.4
S9	176.7	8.4	9.3	59.5
S10	140.0	7.8	8.7	47.2
S11	226.7	11	12.2	76.4
S12	172.2	8.9	9.9	58.0
S13	85.5	6.5	7.2	28.8
S14	113.3	8.5	9.4	38.2
S15	152.2	6.9	7.7	51.3
S16	113.3	10.2	11.3	38.2
S17	231.1	12.6	14	77.9
S18	274.1	13.7	15.0	92.5
S19	138.9	7.3	8.1	46.8
S20	94.4	6.9	7.7	31.8

- *SEM Analysis*

During the friction stir welding, re-crystallization occurs at nugget zone and transformation of grains is seen at thermo-mechanical heat affected zone (TMAZ) and heat affected zone (HAZ). Fig. 5 shows the weld macrostructure on the joint cross section. During friction stir welding, two materials are intermixed through the stir action of the pin. Onion rings are formed at the surface as shown in Fig. 5. Sample numbers 13 and 20 exhibit poor joint strength due to micro cracks in the weld joint. At the nugget zone proper mixing of two material and re crystallization make strong bonding but at heat affected zone can lose the base material properties.

Fig. 5. SEM optical microstructure and texture of cross section of different welding joints

5. Results and Discussion

Each parameter is assigned five levels keeping other parameters at their average levels and the results of the experiments are reported in table 5. Figure 6 plotted in Minitab v16 shows the value of the tensile strength at all twenty points with different variables. It shows effects of different factors on tensile strength at different levels. For a factor, tensile strength is tested at five levels. Graph plotted in Fig. 7 shows the effect of first parameter (i.e. tool rotational speed) on tensile strength. The tensile strength at level 1 of tool rotational speed (355 rpm) is 195.5 MPa and it increases to 213.3 MPa at level 2 of the parameter. Tensile strength is increasing continuously up to level 3 and then starts decreasing. As the RPM increases, friction heat also increases up to a maximum level. So, value of tensile strength is 274.4 MPa at 1000 rpm. Therefore, the input parameter (tool rpm) has significant impact on friction stir welding strength.
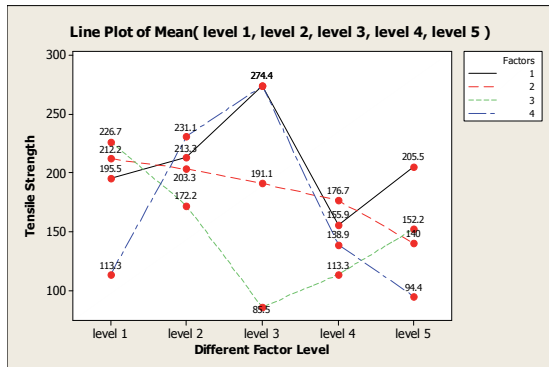

Fig. 6. Line plot of tensile strength (in MPa) vs. different factor levels
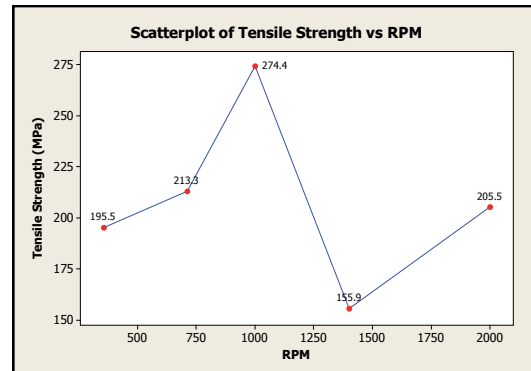

Fig. 7. Scatter plot of tensile strength vs. tool rotation speed (in RPM)

The second parameter tool tilt angle has an inverse effect on tensile strength of the friction stir welding joint. As shown in Fig. 8, tensile strength is 210.2 MPa at first level of tilt angle (zero degree). With increasing tilt angle of the tool from 2 to 8 degree, the value of the tensile strength is decreasing from 203.3 to 152.2 MPa. As the tilt angle of the tool increases, the friction force on the leading edge decreases. The temperature at trailing edge is higher due to which plastic deformation and mixing of materials are uniform. But at higher tool tilt angle pin material fill up is not done properly by tool shoulder and weak welding joint is made. In this way tool tilt angle affects the welding temperature as well as strength of the joint. Therefore value of the tool tilt angle also plays an important role for tensile strength of FSW joint.
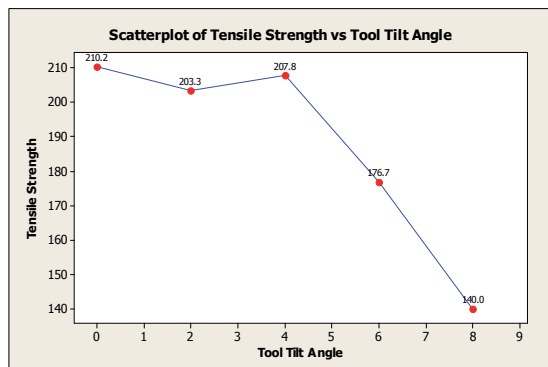

Fig. 8. Scatter plot of tensile strength vs. tool tilt angle
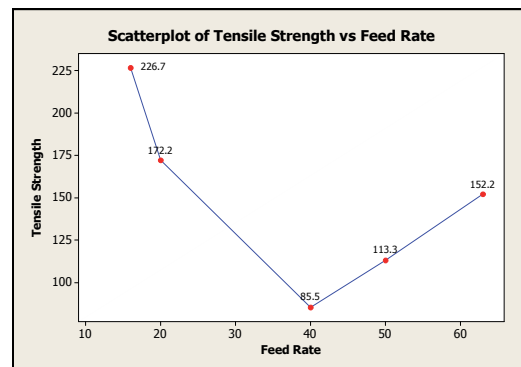

Fig. 9. Scatter plot of tensile strength (in MPa) vs. feed rate (in mm/min)

Third factor, tool feed rate, is also varied from 16 mm/min to 63 mm/min at five different levels. It is revealed from the Fig. 9 that tensile strength drops drastically as the feed rate increases from level 1 to level 3 and then it starts increasing with increasing levels.
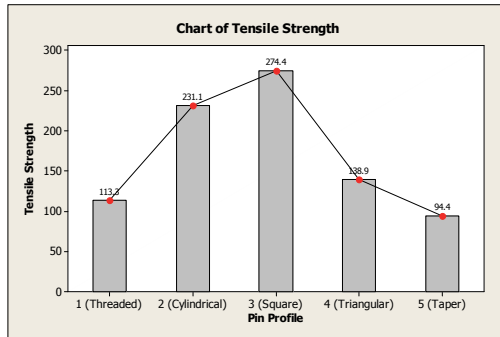
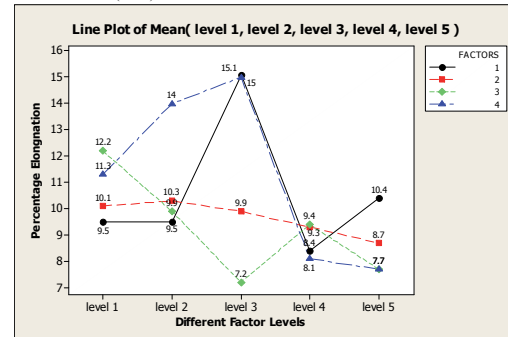**Fig. 10.** Bar plot of tensile strength vs. tool pin profile

Fig. 11. Line plot of % elongation vs. different factor levels
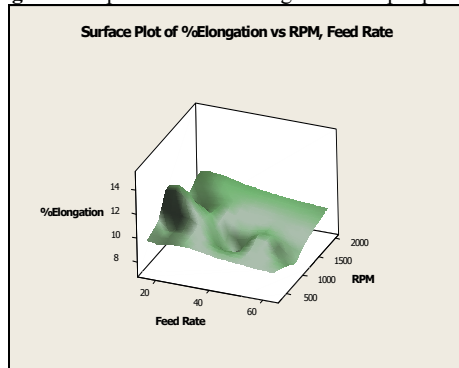

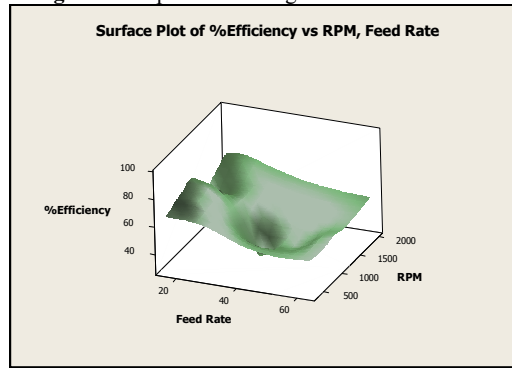**Fig. 12.** 3D plot of %Elongation vs. RPM and feed rate

Fig. 13. 3D plot of %efficiency vs. RPM and feed rate

A 3D surface plot of percentage of elongation versus RPM and feed rate clearly explains that maximum value of elongation is obtained at low feed rate and moderate rpm of the tool (Fig. 12). When values of feed rate and rpm continuously increase, elongation is also increased but at small rate. This variation of percentage of elongation is due to heat produced at nugget or welding point. Heat produced is higher at low feed rate and, therefore, percentage of elongation is at higher level and vice-versa. Fig. 13 presents the percentage of joint efficiency calculated for all factors at different levels. A 3D surface plot of %efficiency vs RPM and feed rate describes the variations. At low feed rate or low welding speed heat produced is high and, therefore, the semi solid materials intermix very well and strength of the joint is the maximum. In this experimentation maximum welding efficiency is 92.5% as compared to the base material.

6. Conclusions

Friction stir welding of two different grades of aluminum alloy 5083 and 5086 is performed. The following conclusions have been arrived from the experimentation and testing analysis of the welding joints.

a. Tool pin profile geometry affects significantly the weld quality. There is a change of plastic flow of the material under the tool shoulder with the change of the pin profile geometry. The stir conditions change with cylindrical as well as square pin profile.
b. RPM of the tool is strongly related with welding speed/feed rate to give the best ultimate tensile strength. At very low feed rate higher heat is produced at nugget zone to give higher joint efficiency. Higher heat per unit area is produced at welding joint.
c. Surface quality of the weld joint depends upon tool tilt angle. As the tool tilt angle increase it gives less flow of semi solid material and fill up of material is also less due to less heat dissipating so that welding defects like flaws, worm holes increase as the tilt angle increases.
d. The ultimate tensile strength increases with increasing value of RPM, feed rate and tool tilt angle up to a range and then it starts decreasing. Joint strength is also good at higher tensile strength at the optimum range of 1000 rpm, 2 degree tool tilt angle and minimum value of feed rate.

References

Abdi Behnagh, R., BesharatiGivi, M. K., & Akbari, M. (2012). Mechanical properties, corrosion resistance, and microstructural changes during friction stir processing of 5083 aluminum rolled plates. *Materials and manufacturing processes*, *27*(6), 636-640.

Akbari, M., & Abdi Behnagh, R. (2012). Dissimilar friction-stir lap joining of 5083 aluminum alloy to CuZn34 brass. *Metallurgical and Materials Transactions B*, *43*(5), 1177-1186.

Akbari, M., Abdi Behnagh, R., &Dadvand, A. (2012). Effect of materials position on friction stir lap welding of Al to Cu. *Science and Technology of Welding and Joining*, *17*(7), 581-588.

Akbari Mousavi, S. A. A., & Sham Abadi, S. H. (2012, January). Dissimilar Friction Stir Welds in AA 5086-AA 2024: The Effect of Process Parameters on Microstructures and Mechanical Properties. In *Advanced Materials Research* (Vol. 445, pp. 753-758). Trans Tech Publications.

Aliha, M. R. M., Shahheidari, M., Bisadi, M., Akbari, M., & Hossain, S. (2016). Mechanical and metallurgical properties of dissimilar AA6061-T6 and AA7277-T6 joint made by FSW technique. *The International Journal of Advanced Manufacturing Technology*, 1-15.

Cavaliere, P. (2013). Friction stir welding of Al alloys: analysis of processing parameters affecting mechanical behavior. *Procedia CIRP*, *11*, 139-144.

Fotouhi, Y., Rasaee, S., Askari, A., &Bisadi, H. (2014). Effect of transverse speed of the tool on microstructure and mechanical properties in dissimilar butt friction stir welding of al5083–copper sheets. *Engineering Solid Mechanics*, *2*(3), 239-246.

He, X., Gu, F., & Ball, A. (2014). A review of numerical analysis of friction stir welding. *Progress in Materials Science*, *65*, 1-66.

Khorrami, M. S., Kazeminezhad, M., &Kokabi, A. H. (2012). Mechanical properties of severely plastic deformed aluminum sheets joined by friction stir welding. *Materials Science and Engineering: A*, *543*, 243-248.

Kim, S. J., & Jang, S. K. (2006, February). A slow strain rate test experiment to evaluate the characteristics of high-strength Al-Mg alloy for application in ships. In *Materials science forum* (Vol. 510, pp. 162-165).

Mishra, R. S., & Ma, Z. Y. (2005). Friction stir welding and processing. *Materials Science and Engineering: R: Reports*, *50*(1), 1-78.

Peel, M., Steuwer, A., Preuss, M., & Withers, P. J. (2003). Microstructure, mechanical properties and residual stresses as a function of welding speed in aluminium AA5083 friction stir welds. *Actamaterialia*, *51*(16), 4791-4801.

Rajakumar, S., Muralidharan, C., &Balasubramanian, V. (2011). Influence of friction stir welding process and tool parameters on strength properties of AA7075-T 6 aluminium alloy joints. *Materials & Design*, *32*(2), 535-549.

RajKumar, V., VenkateshKannan, M., Sadeesh, P., Arivazhagan, N., &Ramkumar, K. D. (2014). Studies on effect of tool design and welding parameters on the friction stir welding of dissimilar aluminium alloys AA 5052–AA 6061. *Procedia Engineering*, *75*, 93-97.

Rhodes, C. G., Mahoney, M. W., &Bingel, W. H. (2010). Micro structural changes determining joint strength in friction stir welding of aluminum alloys. *Scripta Mater. R. palanivel, Dr. P. Koshy Mathews, Dr. N. murugan "Influences of tool pin profiles on the mechanical and metallurgical properties of FSW of dissimilar alloys" International Journal of Engineering Science and Technology*, *2*(6), 2109-2115.

Steuwer, A., Peel, M. J., & Withers, P. J. (2006). Dissimilar friction stir welds in AA5083–AA6082: the effect of process parameters on residual stress. *Materials Science and Engineering: A*, *441*(1), 187-196.

Uzun, H., Dalle Donne, C., Argagnotto, A., Ghidini, T., & Gambaro, C. (2005). Friction stir welding of dissimilar Al 6013-T4 to X5CrNi18-10 stainless steel. *Materials & design*, *26*(1), 41-46.

Vural, M., Ogur, A., Cam, G., &Ozarpa, C. (2007). On the friction stir welding of aluminium alloys EN AW 2024-0 and EN AW 5754-H22. *Archives of Materials Science and Engineering*, *28*(1), 49-54.