Friction welding of dissimilar metals (aluminium AL 6061 T6 and stainless steel AISI 304)

Senkathir S and Siddharth V B
Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamilnadu, India.

E-mail: sb3268@srmist.edu.in

Abstract. In friction welding, welding takes place due to exterior pressure applied on the cylindrical rods. Both the specimen to be welded are having a linear motion or a rotary motion. The main benefit of friction welding, is that it produces low distortion. The other advantage is absence of defects and comparatively high weld strength. It can also be employed to weld materials that are considered difficult to weld by older welding methods. Friction welded specimen do not require any external auxiliary such as tools or filler rods and thus helps to save cost. Also, this method requires relatively lesser welding times as compared to other welding processes. Using this technology, we can achieve welding of a large number of materials which have distinct mechanical properties and chemical composition. Friction Welding also helps to reduce the costs of process by a significant amount. This also has shown prominent reduction in overall weight of the component. This study encapsulates the work done in friction welding, presents the summary of the testing done in this field till date in brief. The identification of proper welding parameters such as Friction Load, Friction Time and Forge Load is an important task. The problem of obtaining good weldability as well as high weld strength is tackled and dealt with hereby. Friction welding could be a discovery in production technology, a leap which will profit a large variety of industries, as well as the aviation, naval industries. It also has use in manufacturing drilling tools.

1. Introduction
Friction welding is a type of welding method in which welding takes place between two solid metals, and hence can be categorized as solid-state welding. In this method, no additional heat is given from outside heat. Complete melting of either if parent metals does not occur. The joining of the two metals is facilitated due to the force that is being applied externally, as specified by the user. In this method, the specimen to be welded are rotated or kept in a linear motion against each other, which leads to the generation of friction, on the contact surface between the two materials. The amount of friction load to be given is specified by the user, and this input is given to the machine. The amount of time that the metals are in contact and heat is generated is described as friction time. At the end, a high plunge force, known as forge load is applied till the weld is completed. This welding process is achieved by the proper application of pressure. Friction causes heat to be generated, as the two surfaces rub against each other. If appropriate amount of heat is generated, the temperature where both the work pieces are in contact, can increase such that the metals melt to a semi-solid stage and join together. The forge load is applied until the interface temperature is achieved. After this transition phase, a uniform plunge force is made to act for a specific time period, during which a permanent joint is made. Rotation between the two pieces takes place while the pieces are, at the same time, pressured together. Once a
good amount of heat is produced at the weld interface between the two specimens, the rotating chuck is brought to a halt and the two work pieces under consideration are joined together under forge pressure which is of a greater value than the friction load. The forge force additionally helps to achieve plastic deformation of softer metal (in dissimilar metals).

Kimura et al. [1] studied the tensile strength and joining phenomena on friction welding specimen of pure aluminum and AISI 304 Steel. Usually, an intermetallic layer is formed when joining dissimilar metals, leading to poor tensile strength and weak bonding. Paventhan R et al. [2] explains about the experimental work that has been conducted was on a trial-and-error basis, and hence, the initial values of the input parameters on an approximate basis as observed from previous works. After going through various studies conducted by the research scholars, it was observed that the various input parameters having an effect on the weld strength were namely Friction Load, Friction Time and Forge Load. Satish et al. [3] selected Aluminium and Steel for the initial welding trials. They conducted several microscopic studies regarding the subject. In this study, aluminium was joined to copper by friction welding. Shinde G et al. [4] explains various methods to find out the optimised parameters for the procedure of friction welding of dissimilar metals. Thus, the experimental trials that were performed in order to obtain proper welding of the two metals, as well as to get good weld strength have been summarised. SONG Y et al. [5] studies about the microstructural characteristics of Al under SEM, EDS etc and explains about the intermetallic compounds formed during welding of dissimilar materials. Taban et al. [6] conducted friction welding trials to study the properties and the microstructure. For this purpose, they selected 6061-T6 Aluminium and AISI Steel as the 2 metals. Lee WB et al. [7] discussed about the parameters used in the welding processes which were varied, specifically friction pressure, forge pressure, speed etc. Nine trials were then conducted using different combinations of input parameters. Kumar S et al. [8] conducted tensile tests for the welded specimens to determine the strength of the weld, and accordingly, the optimised parameters were obtained. Further, Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS) Analysis was carried out, to identify the formation of Intermetallics. Sahin M et al. [9] conducted tensile strength tests to find the strength of the joint. All samples failed at the weld interface barring one, which failed at parent metal side, an indication of the weld strength being more than parent metal strength, hence showing that welding was strong. The strongest weld was obtained at load of 96.3 kN and tensile strength of 343.25 N/sq.m. Kimura M et al. [10] uses the impact of welding parameters such as force load, friction time on the strength of the joint and was observed. The material failed at the weld interface, with no sign of Intermetallics being formed. The temperature at weld interface was found to be 573 K at forge pressure of 150 MPa. Successful friction welding was then obtained using optimized parameters. After welding was performed, mechanical tests were performed to find the strength of the weld joint. Microstructure was also studied under SEM, EDS etc. Joint Strength of upto 250 MPa was obtained, indicating strong welding. The forge pressure was kept at 60 MPa. Some pieces failed at low strengths. It was observed that this took place on the aluminium side. Microstructure analysis proved the existence of Intermetallics, which were on an average, about 250nm thick. With the help of inferences, it is clear that the friction load and the duration of time for which the load is applied has the maximum influence on the outcome of the final weld quality, followed by the forge time and forge pressure. The experimental work that has been conducted was on a trial-and-error basis, and hence, the initial values of the input parameters on an approximate basis as observed from previous works. After going through various studies conducted by the research scholars, it was observed that the various input parameters having an effect on the weld strength were namely Friction Load, Friction Time and Forge Load. Various studies have been conducted on combination of similar as well as dissimilar metals, but very less research has been done on the Aluminium Alloy and Stainless Steel. The initial trials conducted showed that proper weld was not being obtained. This was due to the fact that the input parameters specified for the welding were insufficient, and thus, only mechanical joining was taking place.
2. Experimental Procedure

2.1. Material Selection

The two materials chosen for the friction welding are ALUMINIUM 6061 T6 and STAINLESS STEEL AISI 304 rods with length of 250 mm and 150 mm respectively as shown in figure. Both the rods have a diameter of 25 mm respectively.

![Friction Welding Machine](image)

**Figure 1.** Friction Welding Machine.

2.2. Working Steps

Initial frictional welding trials were conducted with the Aluminium specimen kept in the rotating chuck and the Stainless Steel specimen kept on stationary side. It was found that even after varying different parameters such as friction pressure, rotation speed, forge load, friction time etc., the weld that formed was improper. Very little flash was formed in all the trials. The strength of the weld was also found to be very low. 17 Drop test was conducted after each trial, and the welded specimen failed each time. The probable cause of failure was found to be insufficient parameters and formation of intermetallics between Aluminium and Stainless Steel. Intermetallic compounds usually contain two or more metallic elements, producing a new phase with its own properties, crystal structure and composition. They are usually very hard and brittle. They have a higher melting point than either of a parent atom.

2.3. Factor Information

The most influencing parameters namely, friction load, friction time and forge time were chosen for the experimental study. The input parameters and their levels are shown in table 1.

| Sl No. | Factor                  | Type   | Levels | Values          |
|--------|-------------------------|--------|--------|-----------------|
| 1      | Friction Load (Nm)      | Fixed  | 3      | 1400,1500,1600  |
| 2      | Friction Time (sec)     | Fixed  | 3      | 8,10,12         |
| 3      | Forge Load Nm           | Fixed  | 3      | 1400,1500,1600  |
2.4. Outcome of first trial
The outcome of the first trial run is explained in table 2.

| Sl No. | Speed (RPM) | Soft Load (Nm) | Time (sec) | Friction Load (Nm) | Friction Time (sec) | Forge Load (Nm) | Forge Time (sec) | Cooling Time (sec) |
|-------|-------------|----------------|------------|-------------------|-------------------|----------------|----------------|------------------|
| 1     | 2000        | 300            | 3          | 750               | 6                 | 950            | 7              | 5                |

2.5. Trial Run Parameters
Further trials were conducted with the Stainless Steel specimen kept in the rotating chuck and the Aluminium specimen kept as stationary. The parameters were varied accordingly after suitable optimisation, and flash was obtained. Furthermore, drop tests were conducted and the specimen passed the tests, but it then failed the tensile test with appreciable strength.

![Figure 2. Specimen after Friction Welding.](image)

2.6. Statistical Analysis
For optimization of the welding process, L9 Array was designed using the MINITAB Software to find out optimised parameters, using which 9 final trials were conducted. The statistical analysis of this data was also done to draw the conclusion of the process.

The ultimate tensile strength values, which were obtained from the laboratory, were used as the response factors for the optimization process. For input parameters, it was noted that the friction load, friction time and forge load had maximum effect on the output tensile strength of the weld joint.

It was observed that maximum tensile strength was found to be 178.65 MPa, when friction load, friction time and forge load were kept at 1500 Nm, 10 seconds, 1600 Nm respectively.

Similarly, minimum tensile strength was found to be 80.69 MPa, when friction load, friction time and forge load were kept at 1600 Nm, 12 seconds, 1500 Nm respectively. Statistical analysis was performed in order to find out effect of input parameters on the weld strength and which parameter has the most influence on the output. The L9 Array was performed in Minitab software and the optimised parameters were found for the friction welding of Aluminium Alloy and Stainless Steel is described in table 3.
3. Results and Discussion

The inference from the experimental work has been summarized in the form of graphs and plots of ultimate tensile strength. High values of Ultimate Tensile Strength (UTS) indicate stronger mechanical bonding, and hence, stronger the strength of the weld. The analysis of the obtained results also gives an indication of the effect the various input parameters have on the output. There will be numerous applications of friction welding across industries. The welding between similar as well as dissimilar metals is possible and for that purpose, the parameters have to be set accordingly. It was also observed that friction load had the highest impact on the ultimate tensile strength among the input parameters, while friction time had the least effect among the three. Also, friction time directly affects the amount of upset created, as on increasing the time, a bulge type deformation was obtained. Increase of forge load had an effect on the upset, as it is applied at the end.

Contour plot of UTS (Mpa) vs friction time (sec) is shown in the figure 3.

| Friction Load (Nm) | Friction Time (sec) | Forge load (Nm) | Tensile Force (KN) | Ultimate Tensile Strength (Mpa) |
|--------------------|---------------------|-----------------|--------------------|-------------------------------|
| 1400               | 8                   | 1400            | 69.12              | 142.40                        |
| 1400               | 10                  | 1500            | 68.70              | 140.28                        |
| 1400               | 12                  | 1000            | 67.72              | 139.53                        |
| 1500               | 8                   | 1000            | 43.71              | 90.27                         |
| 1500               | 10                  | 1600            | 86.76              | 178.65                        |
| 1500               | 12                  | 1400            | 83.41              | 171.84                        |
| 1600               | 8                   | 1600            | 62.52              | 128.70                        |
| 1600               | 10                  | 1500            | 62.32              | 128.18                        |
| 1600               | 12                  | 1400            | 39.20              | 80.69                         |

Figure 3. Contour plot of UTS (MPa) vs Forge Time (sec), Friction Load (Nm).
The contour plot indicates the outcome of friction load, friction time on the tensile strength. The dark green region indicates high tensile strength of around 140 MPa which is obtained between friction load of 1400-1500 Nm at moderate friction times of 9-12 seconds. The region which follows the dark green region depicts tensile strength values of about 120-140 MPa at friction loads of 1400-1550 Nm and friction time values of roughly about 9-12 seconds. The light green region shows tensile strength of the order 100-120 MPa at friction pressure of 1600 MPa and friction time of around 8-9 seconds.

Contour plot of UTS(MPa) vs Forge Load(N m), Friction Load(Nm) is shown in the figure 4.

![Figure 4. Contour plot of UTS (MPa) vs Forge Load(N m), Friction Load(Nm).](image)

This contour plot indicates the effect of friction load and forge load on the tensile strength. The dark green region indicates high tensile strength of the order of 180 MPa, which is obtained between friction load of 1500 Nm and forge load values of 1400 Nm. The region after the dark green region depicts tensile strength values of 160 MPa at friction loads of 1400-1500 Nm and forges load values of 1400 Nm. The light green region shows tensile strength of the order 120-140 MPa at friction pressure of about 1600 MPa and forge load values of about 1600 MPa. The end regions are the light green in colour, which indicate the poor tensile strength values.

3.1. Statistical processes using analysis of variance

The process of Analysis of Variance (ANOVA) was performed and the obtained results have been described in table 4.

| Sl No. | Source                  | Degree of Freedom | Adj SS  | Adj MS   | F-Value | P-Value |
|-------|-------------------------|-------------------|---------|----------|---------|---------|
| 1     | Friction Load(Nm)       | 2                 | 2015    | 1007.7   | 1.76    | 0.363   |
| 2     | Friction Time(sec)      | 2                 | 1260    | 630.0    | 1.10    | 0.477   |
| 3     | Forge Load(Nm)          | 2                 | 3963    | 1981.3   | 3.45    | 0.224   |
| 4     | Error                   | 2                 | 1147    | 53.5     |         |         |
| 5     | Total                   | 8                 | 8385    |          |         |         |

Table 4. ANOVA table.

The Analysis of Variance process was performed in order to find out the effect of the various input parameters on the output, which is the welding strength. Friction Load, Friction Time and Forge Load were independent variables while the Tensile Strength was the dependent variable. It was found that
the effect of friction pressure was the maximum, followed by forge load, and finally the friction time. Thus, the statistical processes help to indicate the importance of the input parameters on the welding strength of the joint. The statistical processes were mainly performed in order to identify the effect of the input parameters on the output. A better parametric window is obtained from the work than what is obtained from the result shown in [6].

3.2. Regression Equation
Regression analysis was performed and the obtained results have been described in table 5.

| Sl No. | Term                  | Coefficient | SE Coefficient | T-value | P-value | VIF |
|--------|-----------------------|-------------|----------------|---------|---------|-----|
| 1      | Constant              | 133.39      | 7.98           | 16.71   | 0.004   |     |
| 2      | Friction Load(Nm)     | 1400        | 7.4            | 11.3    | 0.65    | 1.33|
| 3      | 1400                  | 1500        | 13.5           | 11.3    | 1.20    | 1.33|
| 4      | Friction Time(sec)    | 8           | -13.0          | 11.3    | 1.15    | 0.37|
| 5      | 8                     | 10          | 15.7           | 11.3    | 1.39    | 0.30|
| 6      | Forge Load(Nm)        | 1400        | 14.1           | 11.3    | 1.25    | 0.33|
| 7      | 1500                  | -29.7       | 11.3           | -2.63   | 0.119   | 1.33|

Ultimate Tensile Strength (MPa) = 133.39 + 7.4(1400) + 13.5(1500) – 20.9(1600) – 13.0(8) + 15.7(10) – 2.7(12) + 14.1(1400) – 29.7(1500) + 15.6(1600)
= 2526.01 MPa

3.3. SEM Analysis
The scanned electron microscope image of the welded region is shown in Figure 5.
From the above SEM image, the intermetallics region mainly $\text{Al}_2\text{O}_3$ is formed due to some chemical reactions and due to some external influences. Intermetallics area in the welded region is shown as dark spots present in the image. In figure 6, the intermetallics region is more exposed and more in number specifying the less quality of the welded areas. Intermetallics are known to be some external solid shape like structures which can sometimes alter the properties of welded area. Welded areas with less intermetallics shows better weld strength.

![SEM image at 400x magnification.](image)

Figure 6. SEM image at 400x magnification.

In figure 6, the intermetallics mainly $\text{Al}_2\text{O}_3$ region is less exposed when compared to the other SEM image showing the quality of the weld. The best result is obtained in this SEM image when compared to the results shown in figure 5.

4. Conclusion

In this project, friction welding of Aluminium 6061 T6 and Stainless Steel AISI 304 was carried out in order to determine the weld strength that is formed. Tensile test was carried out to determine the strength of the joint.

Based on the various tensile strength values obtained, the optimised parameters were found out because higher the tensile strength values, stronger are the weld that is formed.

Thus, the main objective is to find out the optimised parameters as per this combination of dissimilar metals. Thus after conducting various trials and observing the strength of the weld formed, the following conclusions were obtained:

- The strength of the weld formed depends on three main input parameters, namely Friction Load, Friction Time and Forge Load.
- The formation of intermetallics reduces the value of the tensile strength because it hinders the proper weld formation and hence, weakens the bond between the metals.
- The highest value of tensile strength was obtained at around 179 MPa at Friction Pressure=1500 Nm, Friction Time=10 seconds and Forge Load = 1600 Nm
• The effect of the input parameters on the output, i.e., the weld strength was observed. It was seen that Friction Pressure had the highest impact on the output, while friction time had the least effect on the weld strength.

• The optimised parameters for the friction welding for this particular combination of metals were obtained.

• The importance of identifying approximate values of the parameters to be given as input is high. Insufficient parameters will lead to improper welding, poor joint strength, non-formation of flash.

• Weld strength obtained was observed to be sometimes stronger than the strength of the parent metal

5. References
[1] Kimura M, Suzuki K, Kusaka M and Kaizu 2017 JOM 25 116-125
[2] Paventhan R, Lakshminarayanan P and Balasubramanian 2006 Tran. Nonfe. Met. Soc Chi. 21 1480-1485
[3] Satish R, Rao V S, Ananthapadmanaban D and Ravi, B.2016 JTIE. 97 121-126
[4] Shinde G, Mulani S, Gunavant P and Suryawanshi A. 2018 J. Mater. Process. Technol. 211 496–502
[5] Song Y, Liu Y, Zhu X, Yu and Zhang 2008 Trans: Nonfe Met Soc 18 14-18
[6] Taban E, Gould J. E and Lippold J C 2010 Mat: Des 31 2305–2311
[7] Lee WB, Yeon YM, Kim DU, Jung SB 2003 Mater Sci Technol 19 773–8
[8] Kumar S, Kumar R, Singla YK. 2012 Int J Mech Eng Rob Res 3 43–50
[9] Sahin M. 2009 Int J Adv Manuf Technol 41 487–97
[10] Kimura M, Kusaka M, Seo K, Fuji A. 2005 Sci Technol Weld Joining 10 378–83
[11] Fukumoto S, Tsubakino H, Aritoshi M, Tomita T, Okita K. 2002 Mater Sci Technol 18 219–25
[12] Hasegawa T, Yakou T, Shimizu M, Karashima S. 1976 Trans Jpn Inst Met 17 414–8