# Experimental Investigations on Friction Welding of AL 6061 and SS 304

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**ABSTRACT**

The friction welding of dissimilar materials is more complicated than welding similar materials due to differences in the physical, thermal, chemical and mechanical properties of base materials. The welding of Al 6061 and SS 304 is susceptible to intermetallic layer formation. The interface properties are degraded due to formation of intermetallic layer at the weld interface. The formation of intermetallic compounds strongly depends on local temperature attained during the welding process. These intermetallic compounds are responsible for brittle failure of the components. In the present study experimental investigations are done on influence of joint geometry on the interface properties of Al 6061 and SS 304 friction welded parts. A new joint geometry is designed for friction welding to enhance the quality of weld joint. The shape of new joint geometry removes the oxides and other unwanted impurities from the joint interface due to formation of burrs during friction phase of welding process.

The advantages of the new joint geometry, when compared to regular joint geometry, are many, which include a) reduction in material consumption, b) reduction is energy consumption, c) use of machine with lower capacity, d) reduction in the formation of intermetallics, e) reduction in the size of the heat affected zone (HAZ) and f) improved mechanical strength

## INTRODUCTION

The combination of stainless steel and aluminium alloys are widely used in many applications such as aerospace, automotive, nuclear plants etc. Joining of aluminium alloys with stainless steel using fusion welding is more complex due to formation of intermetallic compounds in the weld. Friction welding is more effective in joining dissimilar metal than fusion welding because it is a solid state welding process. During friction welding, materials are not melted therefore it is free from solidification defects. Several studies are reported on joining of aluminium alloys and stainless steel. Initial studies were on process parameters and determination of mechanical strength [1].

Interdiffussion of each element at the weld interface between aluminium and stainless steel are studied by Okita et al [2] by using transmission electron microscope (TEM) with an energy dispersive spectroscopy (EDS) analysis attachment. Sudarshan and Murty [3] have studied intermetallic layer formation at the weld interface of aluminium alloys and stainless steel. The formation of intermetallic compounds strongly depends on temperature attained during the welding process. Effect of joint geometry on the interface properties are not investigated so far. In the present study, the influence of joint geometry on the interface properties of Al 6061 and SS 304 parts are investigated.

## EXPERIMENTAL PROCEDURE

Al 6061 and SS 304 are welded with direct drive friction welding setup as shown in Fig. 1. Two joint geometries are considered for investigation. The first joint geometry as shown in Fig. 2(a) is a regular joint geometry with flat faces welded together. The second joint geometry (referred as 'new joint geometry' in this paper) has cylindrical taper shape as shown in Fig. 2(b).

Diameter of both the joint geometries is 25 mm. Chemical composition of both the materials is given in Table 1 and weld parameters selected for welding are shown in Table 2.

Mechanical strength of the joint is determined by its tensile test at room temperature. Mmicrostructure of the interface and surrounding areas is examined by optical microscope attached with image analyzer and scanning electron microscope (SEM). Welding variables like rpm, friction pressure, forging pressure, material consumption and torque are measured by data acquisition system. Temperature at the weld interface is recorded with thermocouple embedded at 15 mm away from the joint interface to avoid destruction of the thermocouple during formation of flash.

## RESULTS AND DISCUSSIONS

### Characterization of heat generation with regular joint geometry

Heat produced during the process of friction welding is determined by relative rotation velocity, unit pressure, size of the cross section of the welded work piece and friction coefficient. Heat generation rate during friction phase can be calculated by $q_r = 2n\mu RNF_n$ where $q_r$ is the heat generation rate during friction phase, $\mu$ is coefficient of friction, N is rotation speed of work piece and $F_n$ is normal force applied on the work piece and R is the distance of the calculated point from the work piece axis. Heat generation due to plastic deformation $q_p$ is given as $q_p = \eta\sigma\varepsilon$, where $\eta$ is the inelastic heat fraction, $\sigma$ is the effective stress and $\varepsilon$ is the plastic strain.

As per previous studies [4] the heat generation pattern in regular joint geometry is shown in Fig. 3. The heat generated at the outer region is more than the inner region due to relatively low linear velocity at the inner region. Hence, bonding is not complete at the inner region as shown in Fig. 4. The effect of cross section area on unbonded area is shown in Fig. 5. Sufficient amount of heat can be generated at the inner region by increasing the friction time but it would result in increase in heat at the outer region and may lead to increase in intermetallic layer thickness in the outer region as shown in Fig. 6. As per previous studies [5] welding process starts from the outer periphery and progresses to inner region as shown in the Fig. 7. The tensile strength of half size specimen is less than full size specimen due to region without bonding at the inner portion. The same can be observed in the fractured tensile specimen as shown in Fig. 8. It shows small particles of Al 6061 attached to outer periphery of the SS 304 specimen.

### Characterization of heat generation with new joint geometry

With optimized new joint geometry uniform heat generation can be achieved. In this case, heat generation and welding process starts from the inner region and it propagates to outer region during friction phase of the welding process as shown in Fig. 9. This helps in uniform heat generation across the cross section of the work piece. The same can be observed in the fractured tensile specimen as shown in Fig. 10. It shows small amount of Al 6061 is attached at the inner region of the SS 304 specimen.

### Tensile Strength

Results of tensile test are given in Table 3. The tensile strength of new joint geometry is 278.65 MPa where as tensile strength of regular joint geometry is 254 MPa. The tensile strength of new joint geometry is more than regular joint geometry. The loss of length in new joint geometry is only 7.5 mm, where as in regular joint geometry the loss of length is 13.4. The net material saving of 5.9 mm is achieved by using new joint geometry. The tensile strength of parent Al 6061 is 269.24 MPa which is determined by tensile test to know the joint efficiency. The tensile test for half size and full size specimens are performed to evaluate weld condition at the inner region. The results of half size and full size test specimens are given in Table 4. In regular joint geometry, the difference in tensile strength of half size and full size specimen is very large. This indicates inferior weld strength at the inner region. In new joint geometry the difference between half and full size tensile specimen is very small and both the specimen failed in parent material. This indicates good weld condition at outer and inner region.

The temperature generated during friction welding is as shown in the Table 3. Interface temperature developed in new joint geometry is less than that developed in the regular joint geometry, which indirectly indicates reduction in heat affected zone. Tendency of intermetallic layer is reduced as welding is done at lower temperature. The intermetallic compound at the weld interface strongly depends on the local temperature attained during welding.

### Microstructure and Micro hardness

Microstructures of the weld specimens with regular and new joint geometries are shown in Fig. 11 (a) and Fig. 11 (b) respectively. In regular joint geometry symmetrical flash of Al 6061 alloy was uniformly formed around the entire weld circumference where as in new joint geometry Al 6061 burrs are formed along with symmetrical flash around the entire weld circumference. Flash formed in regular joint geometry is more than that in new joint geometry. Excellent contact is obtained along the weld joint of new joint geometry due to removal of oxides and other unwanted impurities from the weld interface because of formation of burrs and also due to good temperature distribution along the weld joint. Microstructure of new joint geometry weld interface is shown in figure 12. Very fine grain size is observed in Al 6061 near the weld joint and it decreases as the distance from the weld line decreases. There is negligible change in microstructure on SS 304 side. Thickness of intermetallic layer of new joint geometry and regular joint geometry was examined using microscope attached with image analyzer. The intermetallic thickness of new joint geometry was less than 1 μm where as the intermetallic thickness of regular joint geometry was more than 2.5 μm. This was because the weld temperature attained during welding of new joint geometry was less than regular joint geometry. Earlier studies reported the formation of $Fe_2Al_5$, Fe Al and $Fe_3Al$ compounds at the weld interface and formation of these compounds strongly depends on local temperature attained during welding process and are basically responsible for brittle failure of these weld joints. Variation of hardness for new joint geometry is shown in Fig. 13. The large strains and temperature at the weld interface causes changes in the hardness. The increase in hardness was observed near the weld and it is due to strain hardening and grain size reduction.

**Variation in welding parameters during welding**

Variation in rpm, friction pressure, forging pressure, torque and consumption of parent material observed from the analysis of data acquired using data acquisition system indicate the following.

a) New joint geometry requires less energy for welding compared to regular joint geometry.

b) Lower capacity machine can be used for welding with new joint geometry compared to regular joint geometry.

## CONCLUSIONS

1. The weld integrity of new joint geometry is superior to regular joint geometry as oxides and other impurities are removed due to formation of burrs during friction phase of welding.
2. The intermetallic layer thickness of new joint geometry is less than regular joint geometry as welding is done at relatively lower temperature.
3. A very fine grain size is observed in Al 6061 near the weld joint and it decreases as the distance from the weld line decreases.
4. Consumption of parent material in new joint geometry is less compared to regular joint geometry.
5. New joint geometry requires less energy for welding compared to regular joint geometry.
6. Lower capacity machine can be used for welding with new joint geometry compared to regular joint geometry.

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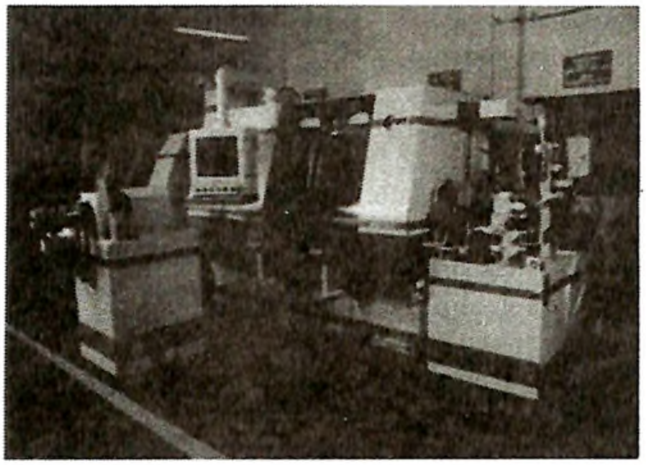

Figure 1(a) Friction Welding Machine

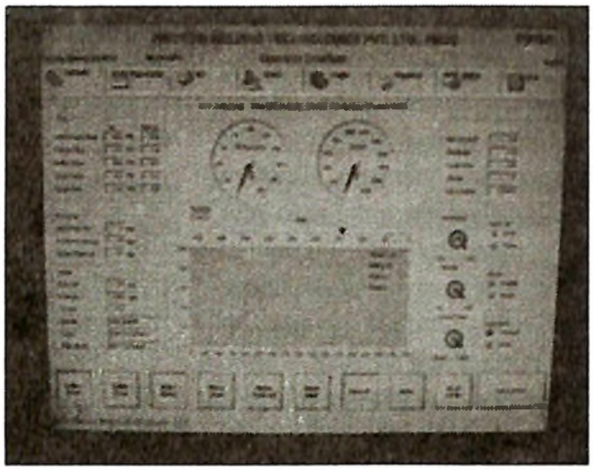

Figure 1(b) Data acquisition system

Figure 1 : Friction Welding Machine and Data Acquisition System


Figure 2 (b) Regular Joint Geometry


Figure 2 (b) New Joint Geometry

| **AL 6061** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
| 0.4 - 0.8 | 0.7 | 0.15 - 0.4 | 0.15 | 0.8 - 1.2 | 0.04 - 0.35 | 0.5 | 0.15 | Balance |
| **SS 304** | | | | | | | | |
| C | Si | Mn | P | S | Cr | Ni | Fe | |
| 0.07 | 0.3 | 1.38 | 0.4 | 0.28 | 18.4 | 8.1 | Balance | |

Table 1 : Chemical composition of Al 6061 and SS 304

| Sl. No. | Parameters | Values |
|---|---|---|
| 1. | RPM | 1400, 1700 & 2000 |
| 2. | Friction Pressure (Mpa) | 30, 50 & 70 |
| 3. | Friction Time (Seconds) | 1, 2 & 3 |
| 4. | Forging Pressure (Mpa) | 100, 120 & 140 |
| 5. | Forging Time (Seconds) | 2, 4 & 6 |

Table 2 : Welding Parameters.

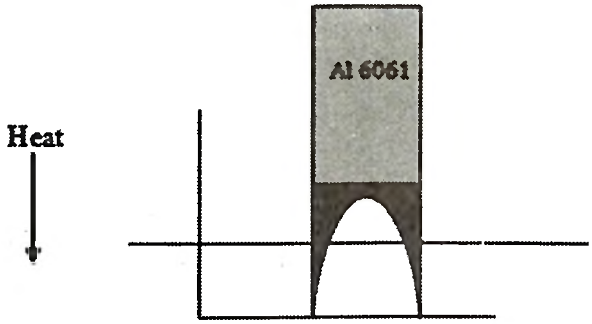


Fig. 3 : Heat generation pattern in regular joint geometry


Fig. 4 : Region without bonding (indicated by white box)

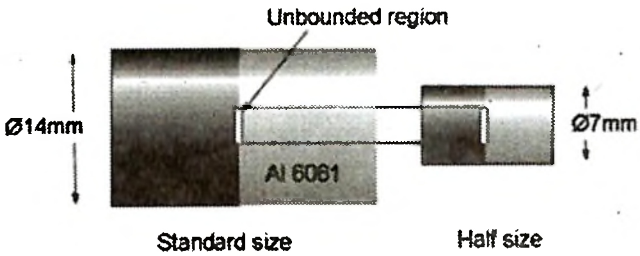


Fig. 5 : Effect of cross section area on area on unbonding


Fig. 6 : Increase in intermetallic layer thickness with Increase in heating time (Regular joint geometry


Fig.7 : Weld progresses from outer periphery to inner region (Regular joint geometry)

Fig.8 : Shows small particles of Al 6061 are attached to the outer periphery of SS 304 full size tensile test fractured regular joint geometry specimen


Fig. 9 : Weld progresses from inner region to outer region (Regular joint geometry)

Fig. 10 : Shows small particles of Al 6061 are attached to inner region of SS 304 full size tensile test fracture new joint geometry specimen

| Sl.No. | Material | Joint Geometry | Loss of length (mm) | Temp °C | UTS |
|---|---|---|---|---|---|
| 1 | Al 6061 - SS 304 | New Joint Geometry | 7.5 | 205 | 278.65 |
| 2 | Al 6061 - SS 304 | Regular Joint Geometry | 13.4 | 384 | 254 |

Table 3 : Tensile strehgth of regular joint geometry and new joint ge0metry at optimized weld parameters

| Sl.No. | Joint Geometry | Full Size / Half Size | Tensile Strength (MPA) |
|---|---|---|---|
| 1 | New Joint geometry | Full Size | 278.65 |
| 2 | New Joint geometry | Half Size | 272.40 |
| 3 | Regular Joint geometry | Full size | 254.00 |
| 4 | Regular Joint geometry | Half Size | 212.00 |

Table 4 : Variation of tensile strength according to sie of test specimen

Fig. 11 : (a) Flash of regular joint geometry

Fig. 11 : (b) Flash of new joint geometry

Fig. 12 (a) Microstructure of welding interface

Fig. 12 (b) Microstructure of parent Al 6061

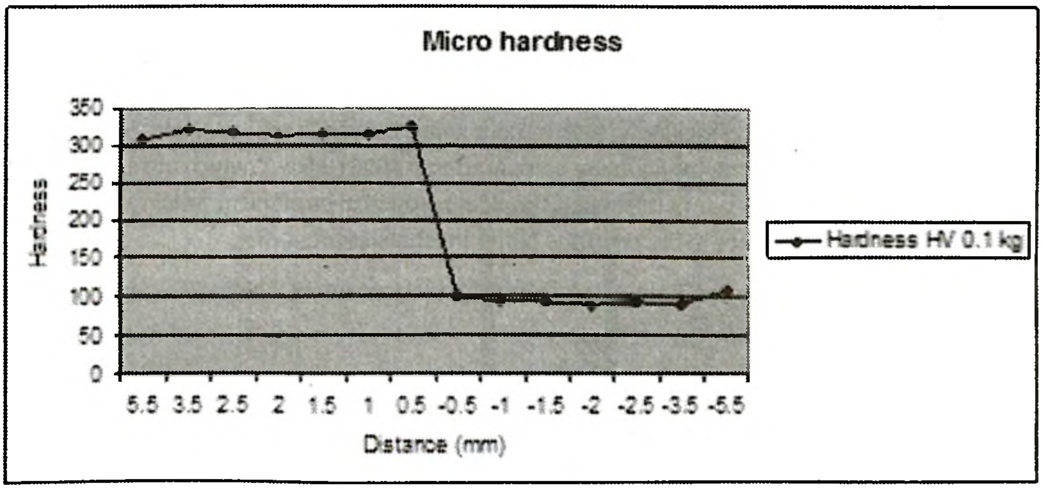


Fig. 13 : Variation of microhardness for new joint geometry

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