Experimental investigation of friction stir blind riveting process for similar and dissimilar alloy sheets

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Abstract
Friction stir blind riveting (FSBR) is a new joining method which eliminates the need to predrill a hole for rivet insertion. A new one-sided mechanical joining process, friction stir blind riveting (FSBR) was developed to form lap-shear joints for similar and dissimilar alloy sheets in different combinations. The similar and dissimilar joints are made from copper, Al 5052-H32, Al 6061-T6 metals. The process window was investigated of CNC machines using only three spindle speeds: 1110, 1750 and 2750 rpm. FSBR joints were observed and discussed during tensile testing. All the similar and dissimilar joints are well fabricated at 1750 rpm. Tensile testing results show that any material with copper combinations (copper used as a top plate) at 1750 rpm as riveting speed gives the appreciable ultimate tensile strength. Further study revealed micro structure of the joint interfaces, when compared with different combinations.

Keywords: Aluminum alloys, Copper, FSBR, Mechanical properties, Microstructure analysis

1. Introduction

Solid riveting is an important metal joining process in which a hole is made in the sheets and then the rivets are used to join the sheets. A self-piercing riveting was introduced to improve the process. Both these processes require the two sided access, which may be difficult and significantly slow down the joining process. A new metal joining process called as Friction stir blind riveting (FSBR) was developed by Wang and Stevenson, (2007). This process involves a combination of friction stir welding and blind riveting. FSBR process eliminates the need for the separate hole making operation required in the conventional blind riveting process while retaining the advantage of one-sided accessibility. The advantages of FSBR process are: (i) Most of the FSBR processes eliminate the need for a predrilled hole, thereby reducing the difficulties in laminating the multiple holes during joining. (ii) The methods are capable of joining both similar and dissimilar materials with a wide variety of material selections. (iii) They are highly suitable for batch production and automated feeding system. (iv) FSBR processes require a shorter span of process times including post processing and sample preparations as compared to other joining methods, e.g., adhesive bonding combined with welding. (v) FSBR joints have relatively high strengths and large displacements before fracture. (vi) FSBR processes allow the development of newer products and sophisticated design that were previously not possible with conventional joining processes. Gao et al., (2009) conducted experiments on 3 mm-thick AA 5052 sheets using FSBR joints and clearly found that the joints withstand a larger tensile load and possess a high fatigue resistance compared to electrical resistance spot welded joints. Changing et al., (2011) joined a dissimilar high strength steel DP600 (1mm) and magnesium alloys AZ31B (3 mm) sheets using FSBR process. Lathabai et al., (2011) made riveted joints in die cast and wrought Al alloys as well as Mg AZ31 sheet using FSBR process with several types of blind rivets. They concluded that rivets with a hollow mandrel head capture the work piece material displaced by the rivet within...
the mandrel head cavity and require lower penetration forces. Zhang et al., (2011) employed FSBR process for joining the Mg AZ31 and DP600 steel sheets. Min et al., (2014) joined CFRP and aluminum alloy sheets using FSBR process. Three combinations of material stack-ups in a lap shear joint configuration such as CFRP-CFRP, CFRP-AA6111, and AA6111-CFRP were fabricated. Min et al., (2014) made joints between AA6111-T4 (0.9 mm) and AA6022-T4 (2.0 mm) using FSBR process with spindle speeds of 1750 and 2750 rpm and various feed rates. Tensile tests were carried out to investigate the mechanical properties of the joints. Min et al., (2015) explained the mechanics in the FSBR process when joining similar and dissimilar Al alloy sheets. Further, the process window was broadened by the optimization of rivet and FSBR process and thereby increases its industrial relevance. Recently, Wang et al., (2016) explored failure modes in FSBR lap shear joining of dissimilar materials (Al, Mg, and Carbon fiber reinforced polymeric composite). Li et al., (2016) achieved the marine atmospheric corrosion behavior of Al-Mg joints at a severe marine test surroundings.

As reviewed above, only a very few research papers discussed the joining of dissimilar materials using FSBR process. The dissimilar alloys sheets have been increasingly employed as alternative materials in the aircraft and automobiles to reduce the weight and to enhance the performance. However the high cost of alloys, the different combination dissimilar of alloy sheets are likely to be tested in aircraft and trucks. Therefore, dissimilar joining of alloys sheets is a key enabling technology for wider adoption of lightweight bodies in aircraft and automobile applications. Hence, the joining of dissimilar alloys using FSBR process with different combination need to be studied. This research deals with the FSBR of similar and dissimilar metals of copper sheets and aluminum alloy sheets. Copper and its alloys are the most important engineering materials because of their good corrosion resistance, outstanding electrical and thermal conductivity, attractive appearance, good strength, ductility and ease of fabrication (Brinas & Wayman, 2003). Aluminum alloy sheets are known for their greater ductility and larger thermal conductivity, (Min et al., 2014).

In this research paper, different combination of similar and dissimilar joints of Cu – Cu, Al 5052 – Al 5052, Cu – Al 5052, Al 6061– Al 6061, Cu – Al 606 (1.5 mm) were fabricated using the FSBR process with spindle speeds of 1110, 1750 and 2750 rpm. In FSBR process, first alloy sheet is placed on top side and second alloy sheet is placed on the bottom side. The tensile tests are conducted to determine the mechanical properties of the joints and the microstructure of the interface has been studied to understand the behavior.

2. Experimental details

2.1 Materials and chemical combinations

The materials used in the experimental work and their chemical composition are given in the Table 1.

| Material | Chemical composition |
|----------|----------------------|
| Al 5052  | Mg-2.8%, Cr-0.35%, Cu-0.1%, Fe-0.4%, Mn-0.1%, Si-0.25%, Zn-0.1%, Al-96% |
| Al 6061  | Mg-1.2%, Cr-0.35%, Cu-0.4%, Fe-0.7%, Mn-0.15%, Si-0.8%, Zn-0.25%, Al-96.2% |
| Copper   | Fe-0.001%, Zn-0.0001%, Cu-99.99%, Pb-0.005%, Ag-0.0025%, As-0.0005%, O-0.0005%, Sb-0.0004%, Te-0.0002% |
2.2 Experimental method

The FSBR joints are fabricated using a Computer numerical control (CNC) machine with spindle speeds of 1110, 1750 and 2750 rpm. The size of the test pieces of aluminum alloy and copper sheets are 25.4 mm X 100 mm, along the lengthwise and transverse directions respectively. The thickness of both sheets is 1.5 mm. For rivet insertion, one coupon is placed on top of the other with a 40 mm overlap as shown in Figure 1. The two coupons are clamped on the work piece fixture. The coupon surface is perpendicular to the direction of the rivet insertion and the rivet insertion point should be at the centre of the overlapped section, i.e., midwidth and midlength. A commercially available Aluminium 5052 rivet with a shank diameter of 4 mm is used for conducting the tests. A specially made work piece fixture of mild steel plate is used to avoid the slippage of the work piece during the riveting process.

![Illustration of test specimen](image1)

The steps involved in the FSBR process cycle is shown in Fig. 2.

| Step Description                                                                 |
|----------------------------------------------------------------------------------|
| Advancing the blind rivet until it is 2 mm away from the work pieces             |
| Accelerating the spindle to the pre-set rotation speed                           |
| Holding the spindle for 9s to developing the frictional heat                      |
| Advancing the rotating rivet into the work pieces at a pre-set rate               |
| Continuing to advance the rotating rivet into the work pieces until maximum penetration |
| Stopping the spindle advance                                                     |
| Holding the rivet in position for another 5s while continuing to rotate the spindle |
| Stopping the spindle                                                            |
| Upset the blind rivet by using upsetting plate and fastens the joint.            |

Fig. 2 Steps in the friction stir blind riveting process
Five set of different joint combinations of experiments from Cu, Al 5052, and Al 6061 were fabricated and the combinations are shown in Table 2 with spindle speeds of 1110, 1750 and 2750 rpm. The feed rate does not have significant influence in the joining process (Goa et al. 2009) and hence it is kept constant. The similar and dissimilar joints for various combinations obtained from the FSBR process are shown in Figure 3.

Table 2 Combinations of different joints

| Position of sheet metal | Combination 1 | Combination 2 | Combination 3 | Combination 4 | Combination 5 |
|-------------------------|--------------|---------------|---------------|---------------|---------------|
| Top Metal               | Al 5052      | Al 6061       | Cu            | Al 6061       | Al 5052       |
| Bottom Metal            | Al 5052      | Al 6061       | Cu            | Cu            | Cu            |

Fig. 3 Different combinations of similar and dissimilar alloy joints

2.3 Tensile test

The tensile tests are carried out on a 40 tonne universal Instron 5582 testing machine at a crosshead speed of 5mm/min with a room temperature. The spacers are used in the tensile tests to keep the joint parallel to the tensile axis which will prevent the bending. The gripping area on both ends was 25.4 x 25.4 mm².

3. Result and discussion

The effects of the similar and dissimilar FSBR process parameters upon the lap-shear strength and the results obtained from the tensile tests result are compared for the different combinations.

All FSBR processes rely on frictional heat generation resulted from the interaction of the rivet and joining material. The frictional heat leads to softening the material, thereby allowing sufficient stirring, which subsequently causes mechanical interlocking where material flow acts as an additional bonding mechanism to riveting itself. In some cases, metallurgical bonding between the rivet and work materials can also occur. Thereby, improved mechanical properties of FSBR joints are usually seen when compared to conventional riveting method.

Figure 4 shows the ultimate tensile strength of the joints for various material combinations with different spindle speeds. Within the experimental region, the tensile strength attains the maximum value at a spindle speed of 1750 rpm for both similar and dissimilar cases. It shows that the lower spindle speed (1110 rpm) may not provide sufficient frictional heat to induce proper bonding between the sheets. Though the higher frictional heat is induced at 2750 rpm, it may encourage grain coarsening which may reduce the strength of the joint. In similar joints, Al 5052 – Al 5052 and Al 6061 – Al 6061 combinations showed better results except Cu – Cu. Due to insufficient bonding, the poor result is exhibited by Cu – Cu. In the case of dissimilar metals, the Al 6061 – Cu joint exhibited better strength compared to its counterpart Al 5052 – Cu. This is due to the reason that the rivet penetrates the Al 6061 – Cu sheet and merges with the parent metal completely when compared to the other combinations.
3.1 Joint Efficiency

The efficiency of the riveted joint is defined as the ratio of the strength of riveted joint to the strength of base metal. Normally the efficiency of the single riveted lap joint is 45% - 60%, V.B.Bhandari (2013).

$$\text{Joint efficiency} = \frac{\text{Strength of riveted joint}}{\text{Strength of base metal}}$$

| Combinations     | Average Joint Strength in N/mm² | Base metal Strength in N/mm² | Joint Efficiency in % |
|------------------|---------------------------------|------------------------------|-----------------------|
| Al 5052 Vs Al 5052 |                                |                              |                       |
| 1110 RPM         | 165.75                          | 210-260                      | 63.75                 |
| 1750 RPM         | 176.25                          |                              | 67.79                 |
| 2750 RPM         | 159                             |                              | 61.15                 |
| Al 6061 Vs Al 6062 |                                |                              |                       |
| 1110 RPM         | 168.75                          | 260-310                      | 54.44                 |
| 1750 RPM         | 173.25                          |                              | 55.89                 |
| 2750 RPM         | 161.25                          |                              | 52.02                 |
| Cu Vs Cu         |                                |                              |                       |
| 1110 RPM         | 121.5                           | 180-260                      | 46.73                 |
| 1750 RPM         | 134.25                          |                              | 51.63                 |
| 2750 RPM         | 113.25                          |                              | 43.56                 |
| Al 6061 Vs Cu    |                                |                              |                       |
| 1110 RPM         | 170.25                          | 260-310 & 180-260            | 54.92                 |
| 1750 RPM         | 181.5                           | 180-260                      | 58.55                 |
| 2750 RPM         | 163.5                           |                              | 52.74                 |
| Al 5052 Vs Cu    |                                |                              |                       |
| 1110 RPM         | 165                             | 210-260                      | 63.46                 |
| 1750 RPM         | 169.5                           | 180-260                      | 65.19                 |
| 2750 RPM         | 157.5                           |                              | 60.58                 |

*Joint efficiency is estimated based on higher base metal strength.

The table 3 shows the joint efficiency of various combinations based on base metal strength. In all the cases the joint efficiency is almost within the preferred level.
### 3.2 Error Bar Chart

Error bars are graphical representations of the variability of data and used on graphs to indicate the error or uncertainty in a reported measurement. They give a general idea of how precise a measurement is, or conversely, how far from the reported value the true (error free) value might be. For each condition, 3 samples have been used. The average values and error bar for each condition is shown in the following figure 5(a - e).

Fig. 5(a) Error bar chart for Al 5052 Vs Al 5052

Fig. 5(b) Error bar chart for Al 6061 Vs Al 6061

Fig. 5(c) Error bar chart for Cu Vs Cu

Fig. 5(d) Error bar chart for Al 5052 Vs Cu

Fig. 5(e) Error bar chart for Al 6061 Vs Cu
3.3 SEM Analysis

Fig. 6 Sample specimens of FSBR joints

Fig. 7 Illustration of sample specimen for SEM analysis
Fig. 8 SEM images of similar joints

Fig. 9 SEM images of dissimilar joints
The FSBR joints prepared at 1750 rpm are cut with a low speed precision diamond saw and cold mounted by epoxide. Before SEM (Scanning electron microscope) observation, the observation area is polished to inhibit charging and improve the spectroscopy. The prepared samples are shown in Figure 6. The microstructure images were acquired by a VEGA3 TESCAN, the voltage was set as 20 kV for SEM backscattered electron (BSE) and SE images, and was 10 kV for EDS scanning.

The SEM images of similar joints are shown in Figure 8 (a-c) and dissimilar joints are shown in Figure 9 (a&b). The joint is placed vertically as shown in Figure 7, it is classified into three regions: (i) Top of the joint (ii) Riveted region (iii) Bottom part of the joint. The second region is important one to concentrate as it indicates the penetration and blending of the rivets with the parent metal.

In similar joints 8 (a-c), the rivet penetrates properly in the metals of all combinations. In the case of Cu – Cu (8.c) combination, there is a cleavage in the joint (i & ii) due to improper bonding which leads to the reduction in strength. While considering the dissimilar metals 5052 - Cu (9.a), the penetration of rivet causes a bending of the aluminum sheet which can be seen zone (I & III). In the case of 6061 - Cu (9.b) combination, the rivet penetrates and blends with both the parent metals and a uniform II region indicates this. This is the reason for the joint strength is better in 6061 - Cu combination.

4. Conclusion

The following conclusions can be made from the results obtained from this study.

- As a proposed joining method FSBR has been proven to be a quick process for making similar and dissimilar joints of Aluminum alloys and Copper.
- In the case of similar combinations, both the aluminum alloys showed better strength than Copper.
- The aluminum alloy and copper dissimilar joints can be made using FSBR and Al 6061 – Cu exhibited better strength.
- FSBR with spindle speed of 1750 rpm is found to be a suitable choice for making the joints with in the experimental works.

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