Original Article

Strength and hardness studies of C44300 tube to AA7075-T651 tube plate threaded and unthreaded dissimilar joints fabricated by friction welding process

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Abstract

Friction welding is an important process used nowadays especially for joining dissimilar metals in engineering and allied industries. The joining of dissimilar materials is different from the conventional materials and needs proper care and technology advancement. The objective of the present research is to investigate the strength of friction welded joints in the absence of backing block. Two conditions of tube and tube plates with thread pair and without thread pairs are considered for the experimentation. The effect of process parameters on the strength has been arrived. Microstructure at the weld joint interface indicates the high level of refinement at the weld zone. Scanning Electron Microscopic (SEM) images are used for investigating the intermolecular bonding of the tube and tube plate. Micro cracks are observed at the interface. Absence of backing block is the cause for the defect. Energy Dispersive Analysis (EDX) and X-Ray Diffraction (XRD) test are used for analyzing the material properties and quantification of crystalline phases.

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1. Introduction

Industrial sectors like power plant equipment manufacturers are involved with welding fabrication process. Different welding techniques like arc welding and gas welding are being employed to join the components. Though these techniques are highly versatile, there are some limitations like restricted suitability, limited process parameters, non-economic and process hazard. These noticeable limitations restrict wider applications. Conventional welding processes are not suitable to join similar/dissimilar non-ferrous metals at higher production levels. To overcome these difficulties, friction welding process is placed in the front line to take a prime role in fabrication. Friction Welding of Tube–Tube Plate using External Tool (FWTPET) is an economical, eco-friendly and a wider input variant method. FWTPET is a superior process to make a joint...
on dissimilar metals [1]. Many challenges are ahead for the industries to join dissimilar metals to get optimum process parameter for better joint strength. Continuous attempts are being made to optimize the process parameters to join tube and tube plate of different materials. Friction welding optimization has been carried out by the researchers to maximize the output and they followed different techniques for optimization [2–6]. Palanikumar [7] has used Taguchi and response surface methodology for optimization of process parameters in machining. Radhakrishnan et al. [8] has claimed that joining of dissimilar metals with threaded profile has more compressive strength than unthreaded pair joint. This authors made the experimentation on threaded and unthreaded pair welded joint with backing block and evaluates the mechanical properties and proved that threaded pair has more strength than unthreaded. Friction welding of tube to tube plate using external tool is a recent technique and invented by Muthukumaran [9] and patented. FWTPET technique is highly focused by researchers because of its scope and potentiality. Friction welding technique is eco-friendly, economical and it has wider capability. Muthukumaran et al. [10] and Lakshminarayanan et al. [11] have claimed that the high level of joint strength and refinement of microstructure are obtained at the joint interface. No consumable material is involved in this technique. Friction welding is a solid state welding process. Materials under the tool are converted into a semi-solid state and flows towards centre of the tube [12–14]. Parent metals are fuses and made to bond together by the application of compressive force. No oxidation takes place during friction welding. A high degree of leak proof joint can be achieved across and along the tube and tube plate.

In the present work, admiralty brass (C44300) tube and aluminum alloy (AA7075–T651) plate is chosen as base metal. Admiralty brass is extensively used in the tubing of steam condensers, salt or brackish water condenser, evaporator, heat exchanger and distiller tubing. An alloy of aluminum is largely used for all fabrication work. Aluminum alloy is largely used in fabrication by its attractive mechanical properties of a high potency to heaviness ratio, good corrosive resistance and glassy appearance, more versatile and is an important non-ferrous alloy extensively used in the fabrication process. Welding of dissimilar metals is a challenging task because of its non coincidence physical, mechanical and metallurgical properties at ambient temperature and elevated temperature. Bekir et al. [15], Mumin Sahin et al. [16] and Mahadeva swamy et al. [17] have made dissimilar metal joining and have analyzed the properties of the weld. Aluminum alloys cannot be welded successfully by using any other welding except friction welding technique. A consistent attempt is being made to identify the optimum process parameters in friction welding for an efficient joint. An attempt was made to join these two non-ferrous metals by friction welding process without a backing block. Pandiarajan et al. [18] made an investigation on steel group dissimilar welded joint without backing block following Taguchi and Analysis of Variance (ANOVA) technique. Selvamani et al. [19] have optimized the process parameter variables in friction welding using Response surface methodology effectively.

In this study, different pairs of the Admiralty brass (C44300) tubes and Aluminium Alloy (AA7075–T651) tube plates are paired and two principal profiles are decided. One is without threaded pair and another is with threaded pair. Threaded pairs are prepared with different pitch values 0.5 mm, 1 mm and 1.5 mm. In this experimentation, M35 High Speed Steel tool is used. Tube and tube plates are placed in position by holding device and friction welding process is carried out. No backing block is used in this work to support the tube and tube plate. The tool is clamped in the spindle and permitted to rotate and lowered towards the tube and tube plate. Axial compressive force is applied on the tube and plate and heat generation occurred between the rotating tool and stationary tube and tube plate by friction. Due to rotational rubbing action on the tube and plate, plastic deformation occurs and metal flow takes place towards to the centre of the tube and enters in the annular gap between tube and plate. Tool pin resists metal flow further into the centre of the hole and is forced into the annual gap and forging action takes place. To study the cause of input parameters on mechanical properties, compression test was conducted on all 16 samples by using compression testing machine. Micro hardness test was performed to evaluate the hardness of the joint at different zones. Microstructure of the samples was gathered to study the micro structural formation at weld Interface using the optical microscope. SEM with EDX was conducted to find the molecular bonding and chemical composition level in the joint. XRD test was taken to evaluate the crystalline phase and quantification.

2. Material and methods

In the present investigation, tube samples are designed with outer diameter 22 mm, inner diameter 18 mm and 41 mm length. Two conditions of profile are designed one without thread (WOT) and another with thread (WT) having different pitches of 0.5, 1.0, and 1.5 mm. The profile and dimension of the tube without thread and with thread are provided in Fig. 1. The chemical composition of C44300 is given in the Table 1.

In this study, AA7075–T651 is chosen as tube plate. Since aluminum alloy has higher thermal conductivity rank, less weight, excellent corrosion resistance and low cost, aluminum is being given first priority than copper in fabrication appli-
cations. 70 mm × 50 mm × 6 mm thick aluminum plates have been designed for welding. A central hole of 22 mm diameter was made carefully on the plate without thread and with thread in the hole. Thread has different pitch values of 0.5, 1, 1.5 mm. The design profile of the tube plate with dimension is shown in Fig. 2. The chemically composing elements for AA7075–T651 is given in Table 2.

M35 High Speed Steel tool is used in this experimentation. 40 mm diameter unhardened round is turned using NC turn carefully. Front pilot pin, shoulder and shank sizes are designed as per the requirement. Tool Shoulder diameter 30 mm and 40 mm length is made in turning machine. Frontal pilot diameter of 17 mm and length 20 mm is designed. The overall length of the tool is 140 mm. The tool is hardened to retain good hot hardness and to prevent sticking action with base metals at high temperature during welding. Geometry and dimension of the tool is shown in Fig. 3. The chemical composition of M35 tool material is shown in Table 3.

FWTPET is a special process which plasticizes the metal by the action of compressive axial load and rubbing. It makes the metal to flow and bond with adjacent metal. In-house high capacity vertical milling machine is used in this work to weld the tube and tube plate. The tool is fitted in position firmly with the spindle and ensures the concentric rotation. Mechanical and chemical cleaning is done on the tube and plate to ensure the cleanliness in the weld area. Tube and tube plate sample is placed in position without backing block under the tool. Sixteen samples of tube and tube plates are welded. The axial compressive force (forging force) is given to the work and tool makes the work to flow [20,21]. Tube to tube plate Friction welding without backing block is shown in Fig. 4. Sixteen pair assembly of tube and plate are produced as shown in Fig. 5. All 16 pairs are welded by friction welding. Post weld inspection work is carried out on all samples. Small amount of bend is being observed in the tube plates. This effect is realized due to the absence of backing block. The metal throw was observed on the rear side of the plate after weld which indicates that the plasticized metal was penetrated through the annular gap between tube and tube plate. Bonding of metals is also taken place between tube and tube plate after solidification of the metal in the weld zone.

The responses considered for the present investigation is compressive stress, which has been measured by using compression testing machine and the other response considered is hardness, which has been studied by using Vickers hardness tester.

3. Results and discussion

Copper based alloy 70-30 brass (C44300) is extensively used in the field of power plant to fabricate heat exchangers. C44300 brass is prioritized as third largest metal and is being used to fabricate heat exchangers. Admiralty brass possesses good thermal conductivity property hence it is chosen for the friction welding study. Aluminum alloy is abundantly used in all fields including aerospace engineering. Aluminum alloy is the best alternatives for ferrous group materials. Aluminum alloy possess multi-dimensional suitability in all engineering fields. In this work, the effect of process parameters on strength of C44300 tube to AA7075-T651 tube plate threaded and unthreaded dissimilar joints fabricated by Friction welding process is investigated.

3.1. Compression test

Muthukumaran et al. [21] have investigated the mechanical and metallurgical properties of AA 6061 tube and tube plate of similar metals and claimed the better joint strength.
Table 3 – Chemical composition of tool material-M35 (by wt. %).

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>W</th>
<th>Co</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.079</td>
<td>0.042</td>
<td>2.055</td>
<td>5.590</td>
<td>0.169</td>
<td>0.032</td>
<td>0.082</td>
<td>0.193</td>
<td>90.550</td>
<td>0.193</td>
<td>90.550</td>
</tr>
</tbody>
</table>

Fig. 4 – Tube–Tube Plate Friction welding process without backing block.

Fig. 5 – Sixteen pairs of tube and tube plate.

Table 4 – Compressive strength of fabricated pairs.

<table>
<thead>
<tr>
<th>Experiment no.</th>
<th>Rotational speed (rpm)</th>
<th>Rubbing depth (mm)</th>
<th>Pitch (mm)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>545</td>
<td>0.25</td>
<td>0.0</td>
<td>19.904</td>
</tr>
<tr>
<td>2.</td>
<td>545</td>
<td>0.50</td>
<td>0.5</td>
<td>25.825</td>
</tr>
<tr>
<td>3.</td>
<td>545</td>
<td>0.75</td>
<td>1.0</td>
<td>37.818</td>
</tr>
<tr>
<td>4.</td>
<td>545</td>
<td>1.00</td>
<td>1.5</td>
<td>43.857</td>
</tr>
<tr>
<td>5.</td>
<td>730</td>
<td>0.50</td>
<td>0.0</td>
<td>15.923</td>
</tr>
<tr>
<td>6.</td>
<td>730</td>
<td>0.75</td>
<td>0.5</td>
<td>35.828</td>
</tr>
<tr>
<td>7.</td>
<td>730</td>
<td>1.00</td>
<td>1.0</td>
<td>39.808</td>
</tr>
<tr>
<td>8.</td>
<td>730</td>
<td>0.25</td>
<td>1.5</td>
<td>33.838</td>
</tr>
<tr>
<td>9.</td>
<td>950</td>
<td>0.75</td>
<td>0.0</td>
<td>13.933</td>
</tr>
<tr>
<td>10.</td>
<td>950</td>
<td>1.00</td>
<td>0.5</td>
<td>33.838</td>
</tr>
<tr>
<td>11.</td>
<td>950</td>
<td>0.25</td>
<td>1.0</td>
<td>55.732</td>
</tr>
<tr>
<td>12.</td>
<td>950</td>
<td>0.50</td>
<td>1.5</td>
<td>58.838</td>
</tr>
<tr>
<td>13.</td>
<td>1320</td>
<td>1.00</td>
<td>0.0</td>
<td>12.904</td>
</tr>
<tr>
<td>14.</td>
<td>1320</td>
<td>0.25</td>
<td>0.5</td>
<td>36.885</td>
</tr>
<tr>
<td>15.</td>
<td>1320</td>
<td>0.50</td>
<td>1.0</td>
<td>47.818</td>
</tr>
<tr>
<td>16.</td>
<td>1320</td>
<td>0.75</td>
<td>1.5</td>
<td>48.828</td>
</tr>
</tbody>
</table>
Tejonadha Babu et al. [22], discussed the mechanical properties of AA6061–T6 weld with filler metal of commercial aluminium in their research work. Rajabharathi et al. [23], made investigation of parameters impact on the properties of magnesium alloy tube-tube plate welds and they concluded that rotational speed influences more on mechanical properties. All these researchers are undertaken the similar metals and investigated the behavior of the joint. The significant of this work is the metals are dissimilar having various geometric profile and also no filler material being used. Compressive strength of the joint is evaluated by conducting compression test. This test was conducted using a hydraulically operated compression testing machine. All samples were subjected to compressive force and strength of each sample was found. Samples to be tested with compression test have been placed in position under the ram and base. Less compressive strength was noticed in all unthreaded pairs. Table 4 shows the compressive strength of all 16 samples. Referring the experimental order nos. 1, 5, 9 and 13, the compression values are: 19.909 MPa, 15.923 MPa, 13.933 MPa and 12.904 MPa, respectively. The lesser compressive value is due to rubbing depth. This order of result indicates that the strength of the unthreaded pair joint is inversely proportional to the rubbing depth. Samples of pitch (p) = 0.5 mm records higher compression strength than the first case as given in the experimental sequence 2, 6, 10 and 14. The increase in compression value indicates that the weld joint made in threaded profile is stronger than unthreaded profile joint. Subsequently, pairs having higher pitch values (p = 1.00 mm) gives better joint strength when rotational speed is minimum. Less strength was recorded at high rotational speed. Compressive Strength of 1.00 mm pitch are recorded as 37.818 MPa, 39.808 MPa, 55.732 MPa, 47.818 MPa with the rotational speeds of 545 rpm, 730 rpm, 950 rpm, 1320 rpm, respectively (experimental sequence 3, 7, 11, 15). Compressive strength of the pairs having pitch value (p = 1.5 mm) recorded as 43.857 MPa, 55.732 MPa, 58.838 MPa, 48.828 MPa for the rotational speeds 545 rpm, 730 rpm, 950 rpm, 1320 rpm, respectively (experimental sequence 4, 8, 12, 16). The compressive strength of the joint for same pitch value at different rotational speed was analyzed within the experimental sequence (2, 6, 10 and 14), (3, 7, 11 and 15), (4, 8, 12 and 16). A sample of pairs after subjecting to compression test is shown in Fig. 6. Joint strength gets decreased when rubbing depth increases. Fig. 7 shows the compression test results in graphical form.

3.2. **Hardness test**

Micro hardness test was conducted using Vickers hardness testing machine. Hardness at Base Metal zone (BMZ), Heat Affected Zone (HAZ) and Welded zone (WZ) of the tube and tube plate hardness have been measured. Predetermined force value of 1 kgf load and time duration 30s of penetration was set to measure Hardness values. Samples are tested with same preset force value and duration. Hardness of C44300 tube and AA7075-T651 plate of samples are plotted as shown in Fig. 8. Central vertical line in the graph refers to the joint interface of the weld. The right of the vertical line refers to the different zone of the tube and left of the line refers to the plate material. The graph reveals that the hardness values of the base metal zone for tube and plate record less valves and it gets increased gradually towards HAZ. Hardness at HAZ and WZ is increased drastically. It indicates that micro structural
formation occurs from course to fine refinement in the weld zone. While comparing the WZ and HAZ the hardness value attains more at WZ than HAZ, which reveals that finest refinement can be achieved by welding process. Kannan et al. [24] narrated in his research about hardness of the joint on Copper tube and Aluminium 2025 plate stating that the weld zone has higher hardness than WAZ and base metal. The joint interface attains a high value of hardness and this high value of the joint leads to better mechanical and metallurgical properties.

3.3. Microstructural analysis

Morphological analysis is carried out on weld joint samples to analyze the microstructure at the weld zone and heat affected zone and base metal zone. Weld samples are taken randomly to study the microstructure formation. Toumpis et al. [25] have analysed the fatigue performance of low alloy steel. Subramani et al. [26] narrated and concluded that the strength of the joint is enhanced in welded joint without SiC. Micro structural morphology of tube and tube plate material, Heat Affected Zone (HAZ) and Weld Zone (WZ) and interface of the joints are observed by Refs. [27–33]. The grain size of aluminium is comparatively smaller than brass material grains. The base admiralty brass consists of copper and zinc is the main constituent. Substitution alloy formation exists in brass. Aluminium alloy is a precipitated hardened alloy. The microstructure of admiralty brass (tube material -C44300 and tube plate material AA7075-T651 are present in Fig.9(A) & (B).

Fig. 10 shows the microstructure observed for the joint which are made (a) without thread and (b) with thread at the tool rotational speed 530 rpm. Fig. 10(A) indicates admiralty brass (tube material) and Fig. 10(B) indicates aluminium (plate material), the brass section of the joint material shows course grain. The interface between the brass and aluminium are clearly seen in the picture. The grains observed in the joint interface also differ from the original material viz., brass and aluminium used in the present investigation. The figure clearly indicates that the joint formation is better with thread.

Since the penetration of the material in the joint is comparatively better.

Fig.11(a) and (b) shows the joints formed without thread and with thread respectively fabricated at a speed of 730 rpm. Fig. 11(a) shows the microstructure, which is taken at a magnification of 100×. Fig. 11(a) in some region fine grain structures are observed. Whereas other regions the surface is not uniform. Crack towards the aluminium region also observed in the figure which weakens the joint. Fig. 11(b) shows comparatively better interface and alignment, grain refinement and grain growth also observed in the figure. Fig. 12 shows the microstructure observed for the joining of brass and aluminium with respect to the tool rotational speed of 950 rpm. The observation of the joint in the interface produces better fine grain when compared to the other samples considered. The joint interface observed for 950 rpm is said to be uniform and the joint is intact. Fig. 12(b) shows the joint observed for a threaded specimen. The joint observed here is throughout uniform and good joint is observed. The joint interface observed also uniform and has good grain refinement, which indicates that the joint observed in the particular speed is good and the joint strength observed is said to be intact.

Fig. 13 shows the microstructure of the joint observed without and with thread for joining of brass and aluminium. The figure indicates the joint interface and the material observed, the figure also indicates fine grains in some sections. But the joint grain is not uniform as observed for 950 rpm. The same observation is made for the threaded joint also. From the analysis of the above figures it has been noted that the joint observed for threaded and unthreaded joints are better when the speed is increased, the better joint strength is observed for 950 rpm rather than 1320 rpm. The scanning electron microscope images are taken for with thread aluminium — admiralty brass welded joint at all 545, 730, 950 and 1320 rpm for image analysis. The SEM images observed for the welded samples are provided in Fig. 13.

Fig.14(a) shows the SEM microstructure of the joint at a speed of 545 rpm. In the interface there is a crack observed in the surface of the joint. The SEM Image has been observed for ×500 magnification of 50 μm size at the interface. The white patches and inter granular movement of the material is observed in the figure. The joint observed is not uniform. Surface embedment of granular is observed in few region of the interface. Fig. 14(b) shows the welded zone interface micro structure for the sample 730 rpm. The image indicates that the interface is comparatively better than the joint observed at 545 rpm. The inter granular movement is observed in the joints, also there is a rough surface formed in the interface, white patches of aluminium also observed in the fabricated weld joint. Multi layer embedment of joint is seen in the interface region. Fig. 14(c) shows the SEM microstructure of the weld zone interface. The surface observed is almost uniform when compared to the previous speed of rotation of the joint considered. The intermetallic bonding also comparatively well. The even distribution taken place at this rotational speed (930 rpm) and hence the joint is said to be uniform. The image of the specimen is having uniform surface embedment and no crack, pit, void or non uniform embedment is observed. Fig. 14(d) shows the SEM microstructure of the joint observed for a speed of 1320 rpm. The interface of the joint is not uni-
form as discussed earlier. Small pits and voids are observed in the microstructure from the analysis of the figures. It has been noted that the 950 rpm is better speed which makes the joint robust, and hence the preferred speed of rotation for the joint is 950 rpm. The EDX analysis is carried out to see the presence of different metallic element in the interface of the joint. The EDX showing the different chemical composition is presented in Fig. 15. The EDX profile is observed for the weld specimen at the speed of 950 rpm which is considered to be the best speed within the range observed for the present investigation. The analysis of the figure confirms that the welding zone having the presence of Cu, Zn, Al. Fig. 16 shows the XRD analysis of the weld zone taken at 950 rpm which is considered as optimal speed in which the smooth surface is obtained.
Fig. 13 – Microstructure (a) without thread and (b) with thread samples (at 1320 rpm).

Fig. 14 – SEM images of weld sample.

Fig. 15 – EDX showing the chemical composition.

Fig. 16 – X-Ray diffraction plot for the sample at 950 rpm.
4. Conclusions

In the present investigation, effect of process parameters on strength of C44300 tube to AA7075-T651 tube plate threaded and unthreaded dissimilar joints fabricated by friction welding process is studied and presented in detail. Based on the experimental work and analysis, the following conclusions have been drawn:

- Welding is carried out successfully without backing block. In this investigation, it is concluded that the friction welding of tube to plate with thread has more compressive strength than without threaded joint.
- Among three key parameters, rotational speed has taken the prime role to enhance the better joint strength. In this study, rotational speed of tool at 950 rpm has found to be the best speed among the range taken between 545 rpm and 1320 rpm.
- Higher hardness at weld interface was found. The sample produced at 950 rpm has more hardness value at interface than other samples.
- Microstructure study confirms the higher joint strength. Fine refinement and better bonding was seen at interface. Micro structure of other samples is found with defect but in the threaded sample produced at 950 rpm has no defect.
- SEM image of the samples are the evidence for the study of surface image of the joint. Very fine uniform embedment has been observed in the joint made at 950 rpm.
- EDX analysis has confirmed the balanced chemical composition at the interface. In over all, this investigational study claims that rotational speed influence the joint strength and threaded joint is better than unthreaded joint.

Conflicts of interest

The authors declare no conflicts of interest.

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