TECHNICAL ARTICLE

Effect of Tube Preparations on Joint Strength in Friction Welding of Tube-to-Tube Plate Using an External Tool Process

S. Senthil Kumaran, S. Muthukumaran, and C. Chandrasekhar Reddy

Department of Metallurgical and Materials Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, India

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Correspondence
S. Muthukumaran,
Department of Metallurgical and Materials Engineering, National Institute of Technology, Tiruchirappalli 620015, Tamil Nadu, India
Email: smuthu@nitt.edu

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Abstract

Several developments have been occurring in the field of materials processing, and friction welding is an important metal-joining process that has varied industrial applications. Friction welding of tube-to-tube plate using an external tool (FWTPET) is a vital friction welding process which is capable of producing leakproof high-quality weld joints. In the present study, FWTPET welds have been prepared with five different tube preparations. Liquid penetrant test (LPT) has been conducted in order to detect the occurrence of surface defects. Macro- and microstructural studies have been conducted and they reveal that improper weld configuration is susceptible to defect formation. Besides, hardness and tensile strength of five different tube preparations have been presented and analyzed. The present study leads to the production of defect free weld joints which have numerous industrial applications.

Introduction

During the past few decades, tremendous developments have been occurring in the field of materials processing.[1] Materials processing includes various kinds of material fabrication processes among which welding is a vital metal joining technique. Welding has tremendous applications in various sectors such as power plants, automobile, electronics, aerospace etc.[2] In general, tube-to-tube sheets are welded using arc welding processes, and explosive welding process is also used in some applications.[3,4] Among the various welding techniques, friction welding belongs to the type of solid-state welding process that is capable of producing weld joints due to the heat generated by the axial force as well as the controlled rubbing of faying surfaces.[3] Friction welding process has several advantages including its capability to weld non-weldable alloys and the production of good quality weld joints.[5] A unique aspect of friction welding is that the material being welded does not melt and recast. As a milestone in the field of friction welding, the process of friction welding of tube-to-tube plate using an external tool (FWTPET) was invented in the year 2006, and a patent was granted in the year 2008 (by one of the present authors[6]). One of the interesting characteristics of FWTPET is that its capability to produce high-quality leakproof joints. When FWTPET is compared with traditional welding techniques, it is an energy efficient, environment friendly, and versatile process. Important process parameters of FWTPET include tool rotational speed, shoulder diameter, and clearance between pin and tube. In this research work, tube is prepared with five different conditions, and FWTPET welding process has been carried out. The macro- and microstructural studies have been conducted for five different weld joints, followed by the measurement of hardness and tensile strength. In order to determine the presence of surface defects, liquid penetrant test (LPT) has been conducted. The results of this study would indicate the best weld joints as well as the best weld condition that leads to the production of high-quality leakproof weld joints, which finds applications in different fields.

Experimental Procedure

Friction welding of tube-to-tube plate using an external tool process

The in-house-developed FWTPET arrangement used in the present study is shown in Fig. 1. The FWTPET configuration includes a motor, spindle, table, tool holder and supporting structure as shown in Fig. 1. FWTPET tool consists of body, shoulder, and pin as shown in Fig. 2. The tool is lowered during rotation, and heat generation occurs due to the friction when the shoulder touches the plate.[7] As the metal reaches plastic condition, it flows toward the center of the tool axis. The flow of metal occurs through the holes in the tube and it occupies the clearance between the pin and inner diameter of the tube. After certain interval of time, the tool is withdrawn. The material movement is restricted using the cylindrical pin, and forging of metal takes place between the tube and the plate. Owing to the combined effects of high pressure and temperature between the faying surfaces, a good metallurgical bonding takes place.[8–11] Both the tube and plate used in the present study are made of commercially pure aluminum and their chemical composition is shown in Table 1. Commercially pure rolled aluminum plates of 6 mm thick are cut into

Figure 1 FWTPET machine (developed in-house).

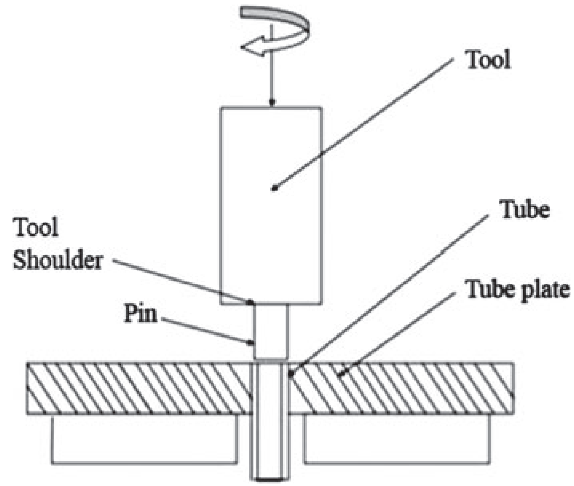

Figure 2 FWTPET setup.

Figure 3 Backing block used in FWTPET process.

the required size (50 mm × 70 mm) using a power hacksaw and 19-mm external diameter tubes have been cut into required sizes. Then 19-mm-diameter holes are drilled in the center of the plates. Tool used in the present study is made of tool steel for fabricating FWTPET joints. In the present study, tool rotational speed and the tool feed rate (axial movement) are 1030 rpm and 0.2 mm/min, respectively. The backing block employed in FWTPET process is shown in Fig. 3.

Table 1 Chemical composition of parent metal

	Element									
	Al	Si	Fe	Cu	Mg	Mn	Ti	Zn	Cr	V
%	Bal	0.0006	0.0007	0.0013	0.0021	0.0001	0.0001	0.0002	0.0001	0.0001

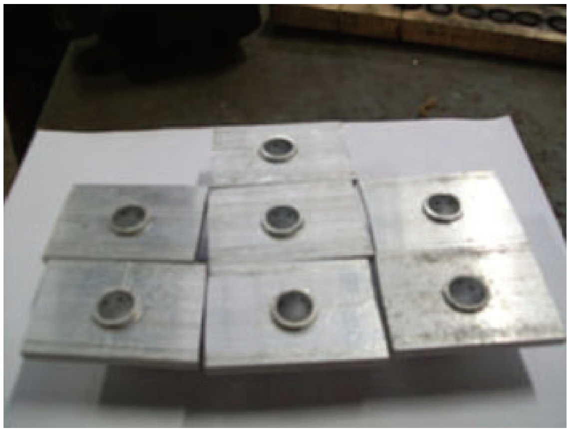

Figure 4 Assembly of tube-to-tube plate before FWTPET process.

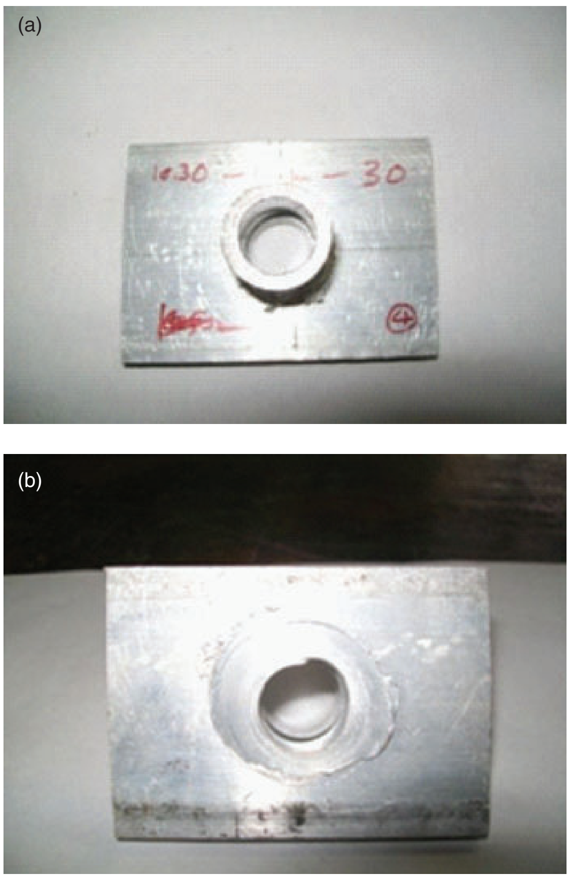

Figure 5 (a) Top view of a tube-to-tube plate welds. (b) Bottom view of tube-to-tube plate weld joint.

The assembly of the work piece is fixed on the machine table with the fixtures, and the tool has been fixed to the spindle. FWTPET assembly and the joints after performing welding are shown in Figs. 4 and 5

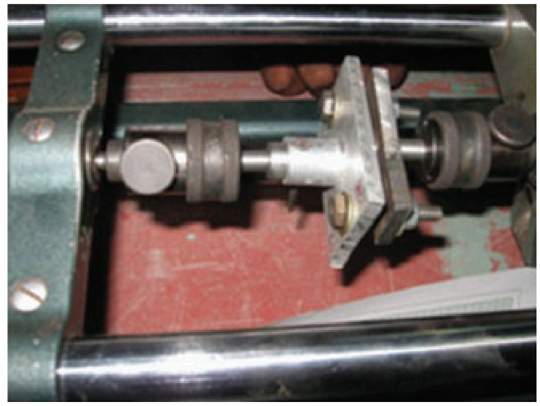

Figure 6 Tube-to-tube plate joint loaded in a tensometer.

respectively. Joints are prepared for tensile test and the tests have been conducted using a tensometer. A tensile test specimen fixed in the tensometer is shown in Fig. 6.

Experimental investigation of five different tube conditions

Five different conditions used in the present investigation are as follows:

1. Drilling holes of 2 mm size on the circumference of the tube.
2. Drilling holes of 3 mm size on the circumference of the tube.
3. Drilling vertical slots of 3 mm width and 6 mm length on the circumference of the tube.
4. Drilling horizontal slots of 3 mm width and 6 mm length on the circumference of the tube.
5. Drilling vertical open slots of 3 mm width and 6 mm length on the circumference of the tube. The above-mentioned five types of tube preparations are shown in Figs. 7–11. The five patterns of

Figure 7 Small hole preparation on the tube (preparation 1).

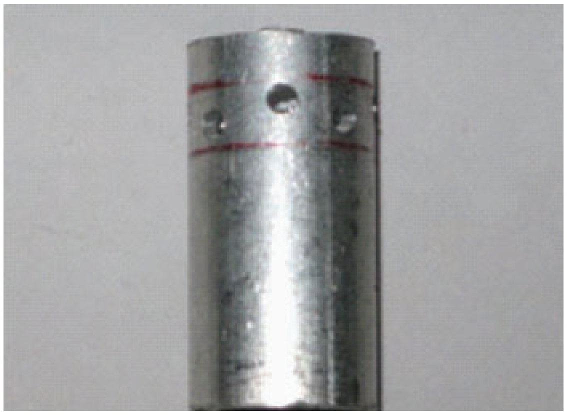

Figure 8 Big hole preparation on the tube (preparation 2).

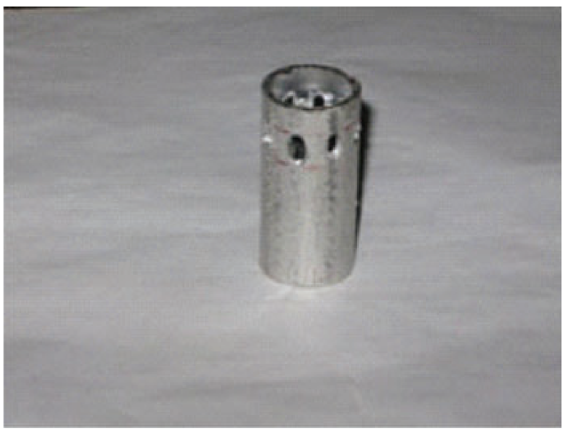

Figure 9 Rectangle vertical slot preparation on the tube (preparation 3).

Figure 10 Rectangle horizontal slot preparation on the tube (preparation 4).

Figure 11 Rectangle vertical open slot preparation on the tube (preparation 5).

holes/slots are prepared using a bench drilling machine and files. In order to remove the oxide film on the faying surfaces, both the tubes and tube plates are cleaned with wire brushes and washed in acetone solution before welding. The tubes are assembled into the tube plate, and the process parameters used in the present investigation are tool rotational speed, shoulder diameter, feed rate, and pin clearance whose values are 1030 rpm, 30 mm, 0.2 mm/min and 1 mm, respectively.[7] For all five preparations, the welding has been carried out using the above-mentioned process parameters.

Liquid penetrant test

Conditions 1 and 5 are subjected to LPT. Initially, the samples are cleaned using a cleaner. Penetrant is applied on the weld surface of samples. Then the samples are dried using a drier. Next, the penetrant has been removed with the help of the cleaner. Developer has been spread on the weld surface. After certain time, the developer absorbs the penetrant from the area where crack has occurred.

Macrostructure studies

After the completion of welding, the tube-to-tube plate joints are sliced for macrostructural studies. The rough scratches on the surfaces have been removed using a belt grinder. The fine scratches have been removed using emery sheet of different grades and further polishing is carried out using alumina and diamond paste using a disc-polishing machine.

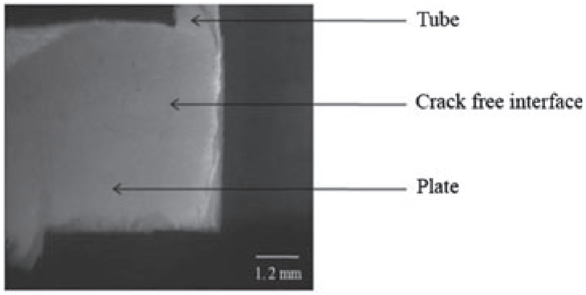

Figure 12 Condition 1.

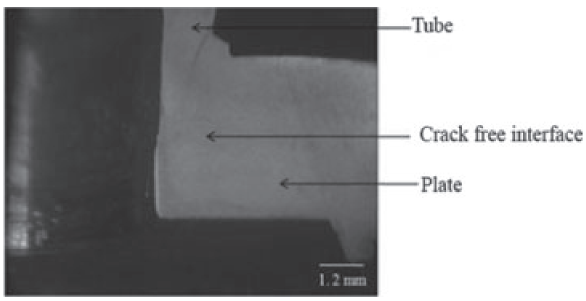

Figure 13 Condition 2.

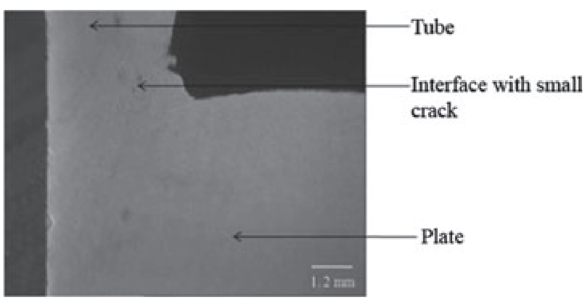

Figure 14 Condition 3.

This is followed by the etching the macrostructures using tucker's reagent (composition: 4.5 mL HNO_3, 2.5 mL H_2O, 1.5 mL HCl, 1.5 mL HF). Then the samples have been washed, dried, and observed under a macroscope. The macrostructural observation pertaining to the five different weld conditions are shown in Figs. 12–16, respectively.

Microstructural studies

The microstructural aspects of the friction welded joints are studied through optical microscopy. The integrity of joints has been analyzed through the micrographs at the weld zone. The Keller's etchant has been used for microstructural studies (composition:

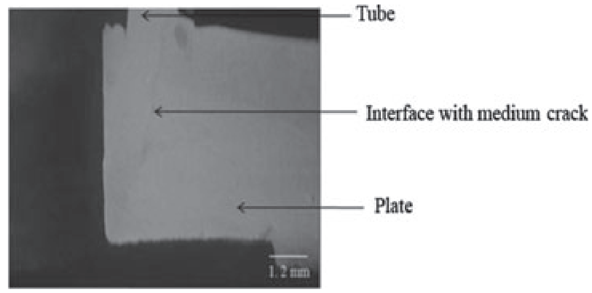

Figure 15 Condition 4.

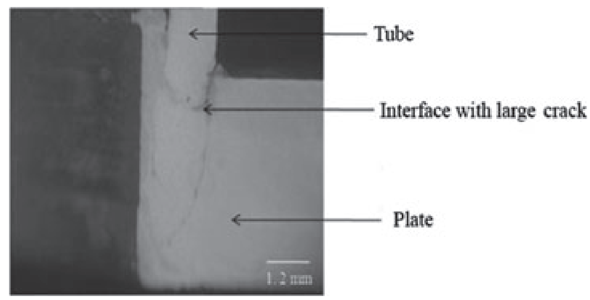

Figure 16 Condition 5.

2 mL HF, 3 mL HCl, 5 mL HNO_3, 190 mL distilled water).

Prediction of hardness and tensile strength

The hardness has been measured for the welds obtained with five different tube preparations using Vickers hardness tester. The hardness has been measured at three different positions in tube, as well as in the tube plate and three different positions in weld interface area, and the results are shown in Fig. 17. Then the average of those values have been taken and presented in Table 2. The tensile test sample (prepared from condition 1) before and after testing is shown in Figs. 18 and 19, respectively. Some of the specimens have fractured away from the joint as shown in Fig. 19, and the maximum tensile strength has been achieved by the FWTPET process. Table 3 shows tensile strength for five different weld conditions.

Results and Discussion

On the basis of the macrostructural observation, it is found that the weld conditions 1 and 2 can produce defect free welds, whereas the remaining weld conditions 3, 4, and 5 are susceptible to defects as shown in Figs. 12–16. Weld condition 5 is more prone

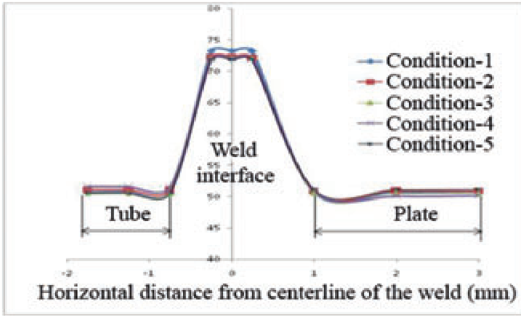

Figure 17 Vickers hardness traverse along the bond line of a typical weld.

Table 2 Hardness measurement for different weld conditions

S.No	Weld condition	Tube (H_v)	Base metal (H_v)	Interface (H_v)
1	Condition 1	50.60	50.70	73.22
2	Condition 2	51.03	50.875	72.18
3	Condition 3	50.45	50.46	71.96
4	Condition 4	51.53	51.0	71.98
5	Condition 5	50.54	51.1	71.80

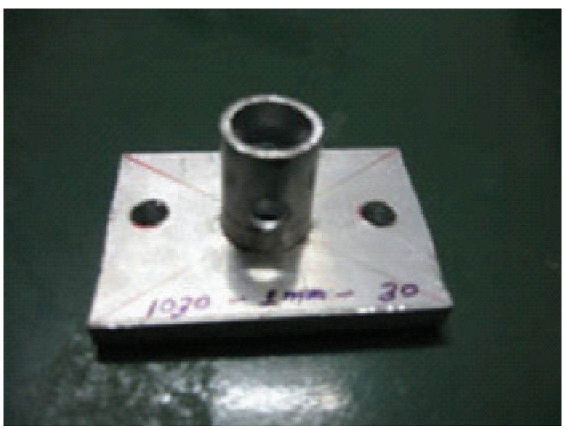

Figure 18 Tensile test sample.

to defect when compared to other weld conditions due to the insufficient bonding between tube and tube plate. The variation of hardness and tensile strength for five different weld conditions are shown in Figs. 20 and 21, respectively. On the basis of the inferences, from Figs. 20 and 21, it has been found that weld condition 1 possess both maximum hardness at the interface and maximum tensile strength. When more quantity of plate material which is in plastic condition is forced through a small hole, the tube surfaces surrounding the holes may reaches plastic condition. Hence, a better metallurgical bond is possible in the case of small holes as shown in Fig. 12. However, the strength decreases as the hole size increases as shown in Figs. 13–15. In the case of vertical open slots, poor interlocking has been achieved as shown in Fig. 16.

Figure 19 Fractured tensile test sample.

Table 3 Values of tensile strength for different weld conditions

S.No	Tube condition	Tensile strength (MPa)
1	Condition 1	77.58
2	Condition 2	67.23
3	Condition 3	54.82
4	Condition 4	51.72
5	Condition 5	49.65

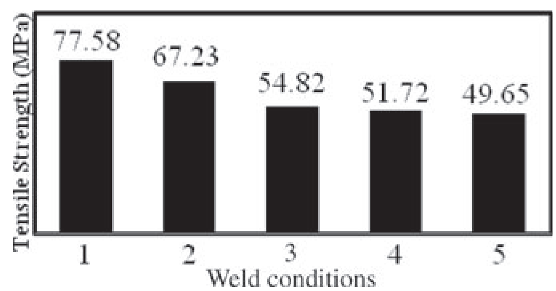

Figure 20 Tensile strength for five different weld conditions.

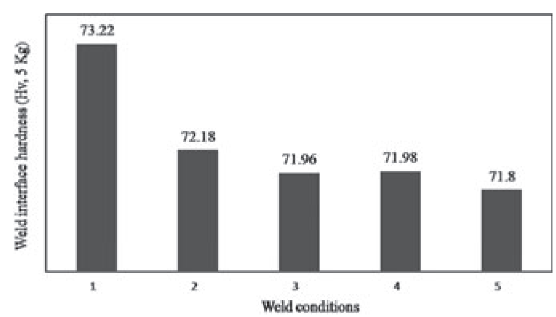

Figure 21 Hardness for five different weld conditions.

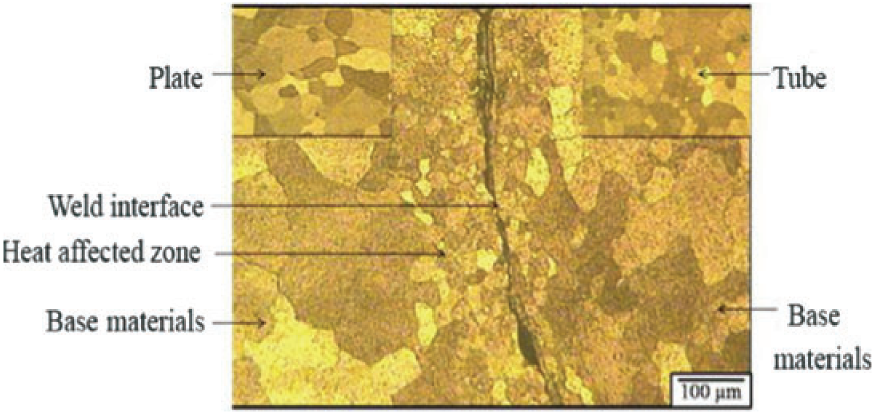

Figure 22 Condition 1 (microstructure of weld joint obtained by FWTPET process showing crack free interface).

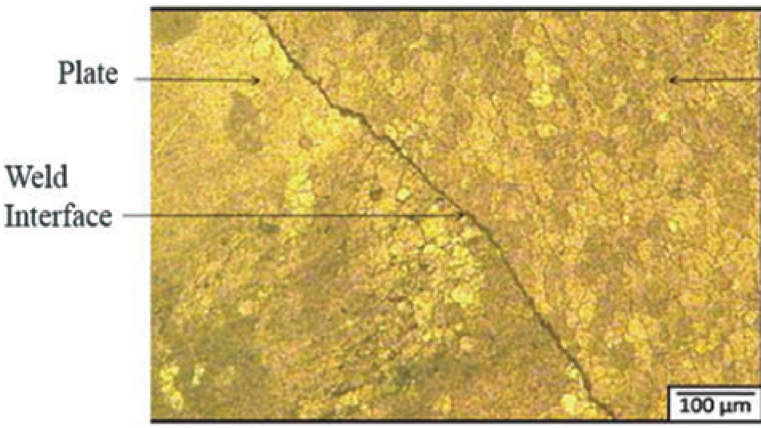

Figure 23 Condition 2 (microstructure of weld joint obtained by FWTPET process showing crack free interface).

Hence, a defective weld with a poor tensile strength is achieved as shown in Fig. 16.

Typical micrographs of different zones in the welded joint have been presented in Fig. 22. The friction welded joints have been sectioned perpendicular to the bond line and observed using an optical microscope. Typical micrographs showing different morphology of microstructure at different zones of the friction welded joints have been presented and analyzed. Compared to base metal, the changes in microstructures are observed obviously at weld zone interface. The grains at base metal (plate and tube) are relatively coarser. Fine grain structure has been observed in the weld zone interface. In solid-state welding, especially in friction welding, due to severe deformation, the refined grain structure is observed at the weld zone which resulted in improved properties. An investigation of tube preparation with different microstructural conditions has been depicted in Figs. 22–26. On the basis of the microstructures, from Figs. 22 and 23, it has been found that conditions 1 and 2 possess better metallurgical bond at the weld interface. The weld interface clearly shows that there is no crack due to more quantity of plate materials passes through small hole on the faying surface of the tube. But in the cases of conditions 3 to 5, the cracks have been observed at the interface due to poor metallurgical bond between the tube-to-tube plate as shown in Figs. 24–26. The reason for the crack formation at the interface is due to the big slot occurring on the faying surface of the tube, and the strength of the tube is also affected because more quantity of tube material has been removed from the faying surface. The high quantity of plate material is required to compensate for filling the slot of the tube as well as high pressure and temperature are necessary to fulfill the interlock between the tube-to-tube plate. For this reason, the crack got propagated at the interface and also less quantity of plate material gets occupied at the slot of the tube and also affects the strength of the FWTPET process. Hence, conditions 1 and 2 possess better weld strength between tube-to-tube plates. The photographs depicting the application of developer for conditions 1 and 5 are shown in Fig. 27(a and b). LPT reveals that condition 1 is best as there is no occurrence of cracks, whereas condition 5 reveals the presence of crack. Hence, LPT could be used

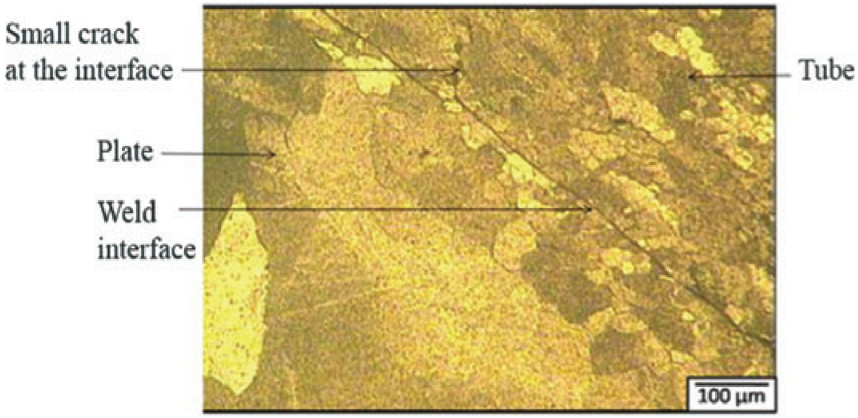

Figure 24 Condition 3 (microstructure of weld joint obtained by FWTPET process showing interface with small crack).

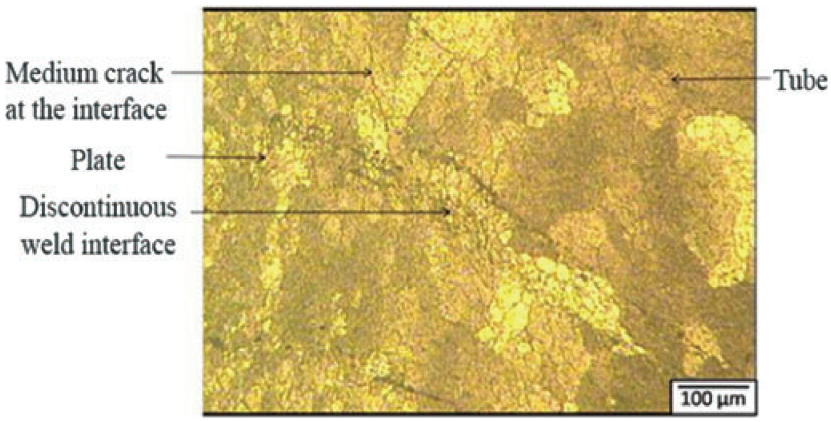

Figure 25 Condition 4 (microstructure of weld joint obtained by FWTPET process showing interface with medium crack).

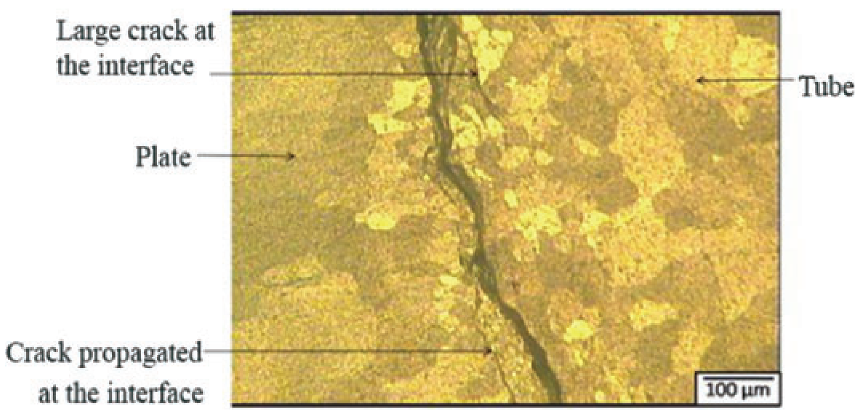

Figure 26 Condition 5 (microstructure of weld joint obtained by FWTPET process showing interface with large crack).

for supporting the results reaped from micro and macrostructural studies.

Conclusions

Solid-state welding process possess many advantages and widely used in industries. Friction welding is a solid-state joining process which is capable of joining similar or dissimilar metals. In order to reduce fabrication cost, researchers have been exploring the newer welding process to improve joint properties. FWTPET is a novel invention in this direction and has numerous industrial applications. This process is capable of producing high-quality tube-to-tube plate weld joints with enhanced mechanical and metallurgical properties. In this study, five different tube conditions have been subjected to FWTPET welding. The macro- and microstructural studies indicate that weld conditions 1 (2 mm hole size) and 2 (3 mm hole size) are defect free, whereas weld conditions 3 (3 mm × 6 mm slot), 4 (3 mm × 6 mm slot), and 5 (3 mm × 6 mm slot) are prone to defects. Further,

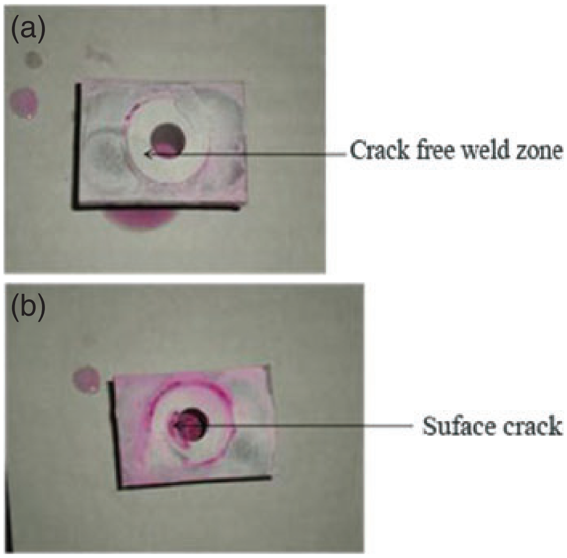

Figure 27 FWTPET sample after applying developer. (a) Sample without surface defect. (b) Sample with surface defect.

the present study indicates that weld condition 1 possess higher hardness along the interface and higher tensile strength when compared to other weld conditions. LPT has been used for checking the results generated from micro- and macrostructural studies. The present study is useful to understand the kind of weld condition that is capable of producing high-quality weld joints which has tremendous applications in industries.

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