Design, Development and Performance Analysis of a Friction Welding for Dissimilar Metals

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Abstract—**Advancements in welding have been rapid in recent times and joining two similar and dissimilar metals in solid state of metal is on high demand as revealed from the literature studies. Friction Welding (FW) is one such advanced technique of uniting two parent metals at solid state. The fundamental advantage of the FW is that is more efficient in joining the dissimilar materials as this method provides outstanding weld seam with good mechanical and metallurgical properties in comparison to other welding methods. Unavailability of a FW set up in CCE is also another source of inspiration that is addressed through this project work. Selection of work holding parts, prime moving devices and design of a suitable electronic controller pose a greater challenge in making the FW set up. There is no reservation on the geometry of work pieces (such as plates, pipes and rods) that can be welded. However, in this work, round cylindrical metallic solid rods of diameter ranging from 10 mm to 20 mm are welded using FW set up. Similar and dissimilar base metals (mild steel to mild steel, stainless steel to stainless steel, copper to aluminium and copper to bronze) are welded with this process. The FW on stainless steel and mild steel rods was achieved at a rotational speed of in the range from 2100 rpm to 2400 rpm while the temperature of heat generated ranges between 950°C to 1000°C. Finally, welded pieces are subject to tensile testing on UTM in order to compare the results obtained through FW with that of conventional or other advanced welding methods so as to confirm the usefulness of this set up. The testing results show good agreement in most of the cases and in some cases, welding conditions to be improved to achieve the full efficiency and comparable mechanical property values**

Index Terms— **dissimilar metals, friction welding, joining of metals, tensile test**

I. Introduction

Joining of metallic materials one another to get required shape and strength to perform a designed operation or duty has been since mankind begun. At the very beginning, bolted and riveted joints used, particularly in shipbuilding riveted hull and the deck structures, for ships more than 100 meters long. However, riveted structures at sea became problematic due to exerted fatigue and lack of maintenance in the structure, which is in turn ended up with catastrophic accident due to failure of the rivets at the critical spots. As the technology developed, needs for more reliable and economical manufacturing process came to play an important role in the industries. The safe and the reliable design with less maintenance cost with longer operational time demand are the major assessment of the consumers to decide which design to go for. Friction Welding (FW) is an unconventional technique of uniting two parent metals. The fundamental advantage of the FW, being a solid state, is efficient in joining the dissimilar materials as this method provides outstanding weld seam with good mechanical and metallurgical properties in comparison to other welding methods. It has been found that with FW the welded assemblies have high joint strength owing to the less heat effect during the process. Particularly, for smaller diameter rods, FW results in better materials properties after welding and better outlook at the interface.

Furthermore, less deformation on the both materials' surface and the non-use of consumable items such as welding rod, arc and protective gases etc. are the advantages of the FW. It requires a force applied on the surface of two parent materials, one being fixed and the other one rotated at required speed in order to generate necessary heat for the forging. This simple and the clean welding process are the benefits of the FW in comparison to conventional welding methods available in Oman. The purpose of this attempt is to fabricate a friction welding set-up for the College that will open up research avenues and scholarly works related to FW domain. In order to reaffirm the quality of weld, mechanical properties of the weldments are measured through undertaking tensile test using UTM (Shimadzu 200 kN capacity). Further, it also contributes to academics in terms of an experimental work in the laboratory that can be demonstrated to students at higher level. Furthermore, this type of welding would bring a great opportunity to the college to introduce training and certification program for the students and staff who wish to have such training on FW.

II. Background Studies

Producing a welding machine than using an existing machine for welding and carrying out further tests poses a greater challenge and imparts a totally different altogether

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experience for students. In this work, a FW machine was built after selecting suitable parts, motors, work holding devices and designing base structure and electronic controller for process parameters control. While building the FW machine, several studies done in the past were referred and suitable design inputs and operational issues were considered. Summary of the inputs taken from the literature studies is given in the following sections.

An experimentation work (Koyama, 2002) was done in which FW process was used for evaluating the properties of a brazed joint made up of Al-Si-Mg-Bi brazing alloy. This was followed by Harmeet et al. (2014). He mentioned that Aluminum alloy 6066, is broadly used in ship building, aircraft industry, small boat building and for piping etc. In his paper, MIG, a conventional arc welding and FW were compared in order to analyze the tensile stress on a butt weld which was made on Al 6066. It was observed that locations effected by the high temperature during welding process on MIG was more than that of FW. This was then concluded that the FW exerts less temperature than MIG. Most importantly it was noticed welding with MIG cause more deterioration on the materials than FW which is in turn weak mechanical properties and les tensile stress. Therefore, it was determined that FW was found very effective welding process which provides advanced tensile strength. W is preferable because with FW unique characteristics of the metals are almost not changed. It has been evidently noted that by friction stir welding problems like porosity, cracks due to solidification and crack liquation are eliminated. Hence, friction stir welding presented less defects tolerable differences in materials. It is however worth to mention that one of the unique characteristic of the friction stir welding is being able to join the alloys which were previously said to be not weldable.

In accordance with Mukuna at al., (2013) friction based welding (stir / non-stir), known as solid state welding, are found better due to its effectiveness and not presenting usual complications such as cracks of solidification as appears on the conventional welding methods. However, FW appeared to be much better especially for the concept of joining the dissimilar parts, Al and Cu materials where almost no intermetallic composites are created. Friction stir welding uses no consumables materials and reduces the environmental impact due to lass exposure to the toxic, hazardous gases that generated by the conventional welding methods.

In reference to Khourshid (2013), friction based welding processes are mostly applied to join the aluminium alloys in marine, aerospace and automotive industries as well as many other manufacturing filed. As the friction stir welding a process that joins the materials below the melting temperatures without the filler materials. The original material properties are maintained and the heat at the weld seam is lesser in comparison to the conventional welding. The design of the tool plays an important role as this is the part only in contact with the work pieces. The material of the tool must be able to withstand the generated heat during the rotation in order to execute the job perfectly. Two aluminium pipes were welded by rotating the tool which was fixed on the drill machine. The duty of the tool is to generate heat by friction on the work piece till the plasticity forms on the materials. Thereafter, the tool moves traversal on the weld seam to join the pipes.

As per Akinlabi et al. (2013), aluminium of AA 6082 presented good welding. However, AA 5083 indicated increase in temperature and very weak welding when both materials were welded under same conditions. Similarly, different materials were tested by friction stir welding such as Al and Mg and so on. It was then determined that with two differently configured tool with a pin and without pin the results vary one another. As the tool without pin provides higher UTS and better ductility in comparison to the tool with pin. The Al and Mg nugget size in terms of grain increase as the speed of tool’s rotation increase. In addition, friction sir welding was tested on the Ti and Al combination and result indicated that at the weld seam higher tensile strength formed in contrast to Al – Mg combination. However, it was also recommended that friction stir welding on Ti and Al may have great advantages in aerospace and another industry, therefore this is to be studied.

In respect to Lammlein at al. (2011) friction stir welding is an efficient metal joining method that provides remarkable strength and good integrity weld in particular on aluminum. It is a promising welding method due to its being a solid state where temperature of the process is not exceeding the melt point of the materials.

In the all the above research works, researchers used the existing FW machine on different materials to make welded joints and experimental tests were further carried out on them to analyse their joint characteristics mechanically as well as micro-structurally. In the present attempt, the authors have designed and manufactured the FW machine and further tests were carried for the purpose of validation of the results obtained with that of standard conventional welding methods.

As a result of the review of literature, core principles of the friction based welding and its advantages is familiarized. One of the fundamental ideas gained from the literature is its difference from other methods in terms of material properties in post welding process. The means of setting up the FW is also decided based on the information and the samples given by the previous studies. Therefore, literature studies are an important medium for the present work as reference to an extent possible.

III. Materials & Methods

This section deals with the design and the fabrication of the FW in conjunction with the components used and their specifications. The drawings of the set-up, mechanically and electrically are demonstrated in this section. FW set-up which was first drafted for Friction Stir Welding (FSW) during the research phase and later the design has been changed from FSW to FW concept to a rotating work piece concept due to unavailability of the required materials for the FSW tool and the complications for fabricating the fixture for this type of FSW setup. The difference between two is, with a tool, the both work piece is fixed but FSW tool rotates. For FW, there is no need of tool. Both workpieces are clamped on both chucks, one end is fixed the other end rotates. Having the design changed facilitate better progression on fabrication of set-up as the required components can easily be accessed and obtained in Omani market. As well as the proper fixture issue solved by removing the FSW tool. Although previous design changed, with revised design there were also some challenges faced later on.

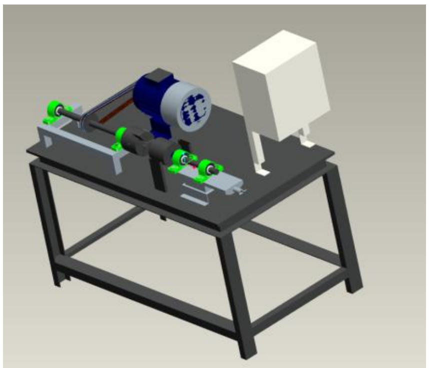

Figure 1 CAD Model of Friction Welding Set Up

2D and 3D design drawings are prepared by using Pro-Engineer Wildfire 4.0 software. The materials were purchased from Oman market. Literature studies have been referred to, for some of the calculations which were useful for the current design and development of the machine.

Figure 1 illustrates the CAD model of the final assembly and Figure 2 shows the physical model produced in this attempt. Table 1 presents the key parts in the FW Machine assembly made in this attempt and Table 2 lists the chemical composition of each metal being welded using this FW set up. It was learnt that the most challenging part of the design was the both chucks that could hold the cylindrical rods in alignment to achieve the welding by rotating one against to another.

One of the other challenge was to obtain the specification of the components such as chucks, bearings, shafts, breaking device, belts and the cross slider. These materials were purchased at local market and the electrical motor and the components of the control panel were fabricated later in the College workshop. As the budget of the project was tight the cost for the materials and the parts could only be affordable if the used or low cost material purchased from local market in Oman. The only parts ordered from outside of Oman were the electrical components which play an important role on this project and the variable speed device (VSD) to control the motor speed was procured from outside.

Fabrication and the setting up the movement mechanism for the fix end of the FW set-up was also a challenge. Initially a complete new design of a slider was considered however the cost to fabricate this was too high. Therefore, a purchasing a used one (which was only the available one and only one type) was the option. This was not noticed until the first test revealed that the cross slide rigidity was weak which was later modified.

Figure 2 Prototype of Friction Welding Set Up

The bearings needed to be same size as the shaft found from the scrap. This was also difficult to get the bearings same diameter. The bearings found were machined in order to slot into shaft. Installation of the bearings on the cross slide side was problematic due to required extra work on the foundation of the bearings or the slot on the cross slide. The welding could not be achieved due to ply noticed on the cross slide. The only mounting method was using bolts, but this was also extra cost for fabrication and the labor. Secondly on the same part the vibration was effecting more due to overhang of the cross slide when extended maximum towards to the rotating shaft. This has been overcome later on. The alignment of the electrical motor's pulley to the rotating shaft pulley was challenging as required alignment tools were not available. Setting up the electrical motor, cable penetration and the Programming of the VSD was a lengthy process. The motor was first tested at the workshop before installing it on the set-up.

IV. DESIGN OF EXPERIMENTS

Once fabrication of FW set up was done initially, trail experiments conducted on this set up revealed a good understanding. Following parameters were required to be relooked in order to complete the set up without any welding defects. They are as follows:

- Speed of the chucks

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- Force Applied during welding
- Temperature generate
- Vibration levels during the welding

Table 1 Key Parts in the FW Machine Assembly

Sn.	Parts	Specifications	No
1	Chucks	20 x125 x100 mm; SS; Center locking	2
2	Shafts	ϕ31.2 mm; MS; 580 mm	2
3	Bearings	P207; 31.2 mm; MS	4
4	Breaking Device	100 x 150 mm; MS	1
5	Electrical Motor	3 ϕ, 2HP, 2850 rpm	1
6	Cross Slide	CI, 3800 x 20 mm	1
7	Belts	'V' Type A 1219.2 mm	2
8	Table	MS, 1350 x 1250 mm	1
9	Pulley	100 mm (shaft) & 65 mm (Motor), 'V' Type A	2
10	Metric Bolts	M13 – M20	28 pcs
11	Infrared Camera	FLIR E8, 50 Hz	1

TABLE 2 Chemical composition of materials used

Aluminum					
Al	Mn	Fe	Si	Cu	Zn
Balance	1.0 – 1.5	< 0.7	< 0.6	0.05 – 0.2	< 0.1

Mild Steel					
C	Si	Mn	S	P	Fe
0.16-0.18	0.4	0.7-0.9	0.04	0.04	Balance

Stainless Steel							
C	Si	Mn	S	P	Cr	Ni	Fe
0.03	1	1.5	0.04	0.04	10.5	1	Balance

The final FW set up is made free from any errors and non-conformities in the above parameters. However, due to restrictions on the availability of the materials and the cost of specimens for required diameters were limited the design to cope with all required parameters. It has been noted with the initial design that there are three major forces acted on the both work pieces. Those were in the direction of X, Y and Z. X directional force was due to cross slide motion towards to rotating work piece, Y directional force acting on when two work piece touched each other before the welding and Z directional force due to centrifugal effects of the rotating shaft. There have been several more tests conducted on different materials including the pipes. However, those are not mentioned here as their results were not efficient to take to UTM test. All above tested specimen has been taken to UTM for the stress analysis. The results will be discussed in the next section. Above tests indicated that as the diameter reduces, better test results are obtained. This is due to force applied is manageable manually at the cross slide side. Furthermore, by reducing the size the length of the welding time reduces as well.

The test conducted on two different locations, college workshop and in the external workshop. The electrical current is very important for the FW set-up as it was experienced that due to unstable of current, the process did not succeed several times. Second of all the force applied at the spindle of the cross slide is very important. This plays an important role of the entire process. However, owing to manually integrations on the FW set-up, some of the parameters could not have been achieved as desired. The speed of the welding (WS) for different materials could be calculated by following formulae (Siddiqui et al, 2015).

$$WS = \frac{WL}{t}$$

WL, is welding length and t, is the time. The weld seam length would be all around the same dimension as the diameter of the specimens.

V. RESULTS AND DISCUSSION

The reliability and accuracy of the welding machine is to be verified using the appropriate laboratory experiments. In this work, the dissimilar butt-welded assemblies are taken to UTM for mechanical testing. In doing so, initially, the mechanical properties such as Ultimate Tensile Stress (UTS) and % elongation are measured for individual constituents and then for the welded assemblies. This would give us an idea on how the welded assemblies could perform under mechanical loading. It is to be noted that FW set-up fabricated in this project is prototype and the welding is done repeatedly on a number of specimen to correlate the results. It is expected that the results are comparable to those obtained with conventional welding methods or other published data from literature sources Figure 3 through 7 indicates the results obtained from the UTM testing for 10 mm diameter SS with 10 mm diameter MS specimens welded on FW set-up.

The results of the UTM tests for the specimen used are tabulated and shown in Table 3.

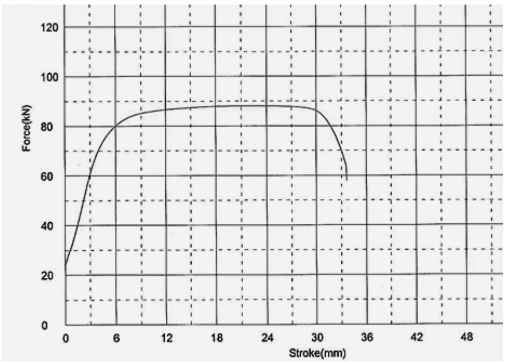

Figure 3 Stress – Strain Curve for SS ø10 mm rod

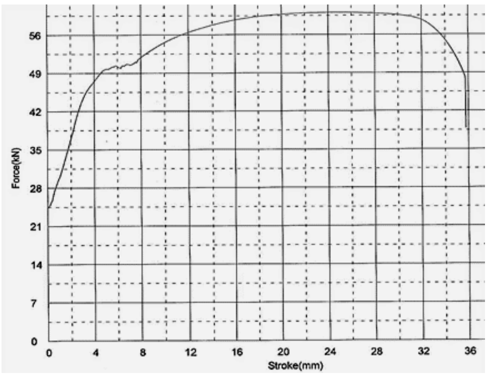

Figure 4 Stress – Strain Curve for MS ø10 mm rod

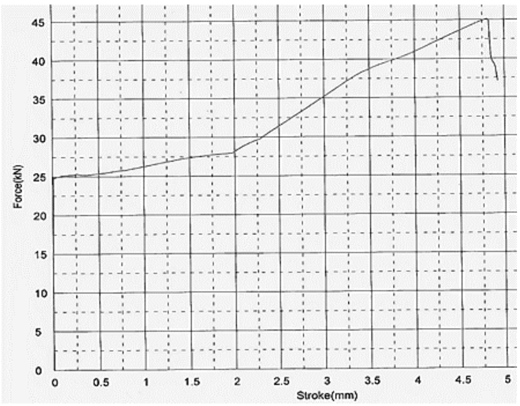

Figure 5 Stress – Strain Curve for MS-SS ø10 mm rod1

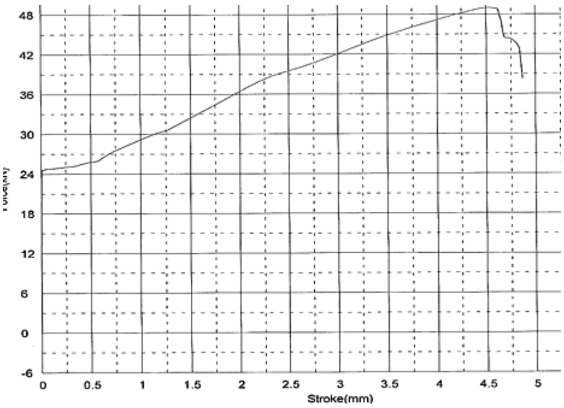

Figure 6 Stress – Strain Curve for MS-SS ø10 mm rod2

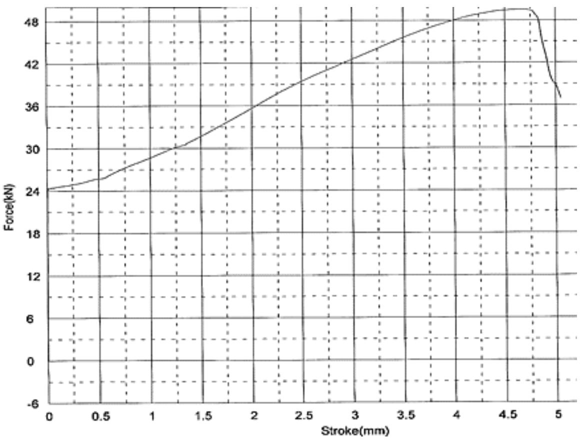

Figure 7 Stress – Strain Curve for MS-SS ø10 mm rod3

The results obtained from the tensile tests with UTM reveal that the UTS values are comparable with that of individual UTS values. In fact, the values are getting better from specimen 3 to specimen 5 because of improved welding procedures. For Sl. No 3, there was no edge preparation done and the speed of the chuck was kept at 1600 rpm. For the specimen Sl No. 4, the edges were made smooth and right angle and the rotational speed was increased to 1880 rpm while the force given to keep the specimens intact was gentle. However, for the Sl. No 5, rotational speed was pegged at 2000 rpm and the pushing force was more.

Table 3 Results of the UTM

Sl No	SPECIMEN	Specimen Dimensions		YIELD FORCE kN	YIELD STRESS MPa	ULTIMATE TESILE FORCE kN	UTS MPa
		Diameter	Gauge Length				
1	Stainless Steel Rod	ø10 mm	60 mm	-	-	88.24	1123.6
2	Mild Steel Rod ø10 mm			24.48	311.63	60.07	764.86
3	Stainless Steel – Mild Steel Rod 1			24.88	316.80	45.14	574.76
4	Stainless Steel – Mild Steel Rod 2			24.66	313.93	49.05	624.52
5	Stainless Steel – Mild Steel Rod 3			24.40	310.63	49.61	631.61

This was evident in such a way that the weld seam on these specimens were different and bonding area was varying from specimen to specimen. The temperature developed at the weld seam is very crucial as it is directly effects the effective completion of the welding. However, taking into account of this prototype FW set-up, there are areas in this machine that could be improved to obtain better results and outcomes. The more robust FW set-up may be designed for future studies to conduct welding with higher diameter materials. The force applied during welding is important as it is experienced in this project, the force was applied only by the operator hand to the spindle. This effected the result of the welding parameters, However, this in future studies need to be avoided by introducing a better controllable force application with an electronically control system. In other words, it has been noted that, on this FW set-up, the smaller the diameter, better the welding results. This is due to applied force is manageable on smaller diameter and far less vibration levels. The test results indicated that, as well as during the welding process it is experienced, the 10 mm diameter is the best size for this set-up. However, maximum size can go as high as 14 mm diameter beyond which increased the vibration levels and chatter that would affect the weld geometry and bond strength of the joint.

VI. CONCLUSION

In this attempt, fabrication of a solid state welding set up i.e., FW was successfully completed after going through and overcoming a number of challenges and limitations. Selection of suitable parts, motor, work holding devices and

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motor controller was carefully done to meet the operating conditions. Design changes took place in more than one occasion to ensure that the welding set up is free from any undesirable vibration and noise levels. The FW setup was successful tested with a range of materials right from ferrous metals to non-ferrous metals and similar metals to dissimilar metallic joints. Experimental and testing conditions reveal that this set up is very much suitable for welding circular mils steel and stainless rods of 10 mm. further redesigns were undertaken to meet the requirements from ergonomics point of view. Tensile tests were carried out on the welded specimens using UTM and the results are obtained and compared. The above project provides a lot of insights and hands on experience that will be useful to make further projects in my career. CCE does not possess a FW setup and the above model can be used as a demonstration set up for students at higher levels of study. The design and fabrication of the FW set-up has a room for further optimisation in terms of weight, cost and operational abilities which are left for other students to pursue it further. The total cost of producing the prototype amounts to more than 500 OMR and the major challenge is the selection of suitable parts and devices along controller. Testing of welding process is done progressively and the specimen welded looks very neat and free from spatter and defects. Many reference papers were used in this work in order to follow the standards and validate the results obtained. Finally, the model is kept in the workshop to be used for demonstration model for students on various manufacturing related modules. This model can be further developed by integrating it a numerical control and automation mechanisms therefore it becomes a state of art facility being developed by students in their final year project module.

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