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COMPARATIVE STUDY ON MECHANICAL PERFORMANCES OF CIRCULAR AND FLAT GEOMETRY WELDS IN FRICTION STIR WELDING OF ALUMINIUM ALLOY

This study is to find the extent of variation in mechanical properties between plate and pipe welds fabricated out of the same FSW process parameters. Common thickness of 3 mm along with similar tool specifications is used to fabricate the weld. Process parameters of tool rotational speed 2000 rpm and weld speed 94 mm/min that was defined as optimal for pipe weld is used as common process parameters. Welds are analyzed for hardness and tensile properties. Yield strength and ultimate tensile strength varied about 8.1% and 11.2% respectively between plate and pipe welds. The hardness of the stir zones varied about 11.6% between plate and pipe welds.

Keywords: FSW, aluminium pipe, aluminium plate, tensile test, hardness test

1. Introduction

1.1. Friction Stir Welding

Aluminium alloys are employed in various forms among which plates and pipes are most common. In recent days, the joining of aluminium alloys is carried out using Friction Stir Welding (FSW) process, owing to its high weld strength yielding capacity. To join butt joints, Friction Stir Welding (FSW) is a strong solid-state process. The FSW is an ongoing method established in 1991 by The Welding Institute and is being utilized to weld aluminum amalgams of various arrangements which were hard to weld and consequently were confined to constrained use [1]. Due to non-liquefying and re-hardening of metal in FSW, bending was low and the weld is liberated from porosity. A non-consumable, turning plain drill i.e. pin, is carried into contact with the plates to be joined. As the drill moves along the joining surface, heat is produced and underneath the solidus temperature, the joints are framed [2]. At the point when the shoulder comes into contact with the outside of plates, the temperature increases because of the heat created, and the pin of the shoulder blends in the joining surface permitting the streaming of the material rear of the pin. As the drill passes, the metal cools and a prepared zone is delivered [3].

FSW of Aluminum Alloy (AA) plates is one of the rigorous research areas that is being exploited for the past two decades, since the advent of this joining technology. The process parameters of FSW process such as tool pin profile and tool geometry [4], tool rotational speed [5], weld speed [6], axial load [7], tool tilt angle and tool offset are experimented to obtain an optimal condition for successful and quality welds. Tool material study is another area where it is tested for suiting high strength materials like steel [8], whereas for AA high-speed steel will suffice. FSW of AA pipes is another area in which researchers are taking shape from laboratory level studies. The past decade has traces of studies involving attempts to employ FSW for joining pipes [9]. The process parameters for pipe welding are the same as for plates which is an obvious factor, except for welding fixture. All the experimental studies related to the FSW of pipes invariably involve the development of their fixtures to facilitate the welding process [10]. The reason being, the fixtures are dependent on the dimensions of the pipe (diameter, thickness and length) selected for the study [11]. Moreover, there are high chances that the design of the fixture influences the process outcomes. The process parameters for plates and pipes being same, there are high chances that optimal conditions of plate being employed for pipes also. The objective of study is to determine this extent of variation, which might help researchers and industries to increase the quality of welding process.

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2. Materials and methods

FSW process is best suited for joining AA materials since it's a solid-state process. 6063-T6 series of AA is a widely used material for industrial, automobile, and aerospace applications due to its good welding characteristics. AA 6063-T6 materials are used for this study and its composition (as received) is shown in Table 1. The mechanical properties of plate and pipe materials received as such are shown in Table 2. AA 6063-T6 is procured both in pipe and plate forms, having a common thickness of 3 mm. The process parameters which were defined optimal for welding AA 6063-T6 pipes are considered as common process parameters in this study [12]. Both pipe and plate are welded using these common process parameters. The dimensions of plate and pipe and their FSW process parameters are given in Table 3. The tool has a pin length of 2.8 mm and shoulder diameter of 7 mm.

TABLE 1

Chemical Composition (wt%) of AA 6063-T6

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Remainder	0.4	0.35	0.10	0.10	0.60	0.10	0.10	0.10

TABLE 2

Mechanical properties of AA 6063-T6 (Pipe and Plate)

Property	Pipe	Plate
Yield Strength (MPa)	215	214
Ultimate Tensile Strength (MPa)	240	243
Elongation (%)	10	12
Micro Vickers hardness (VHN)	82	83

2.1. FSW of pipe

To weld the pipes using the FSW process, a special rotary fixture is developed indigenously and employed as shown in Fig. 1. This rotary fixture is retrofitted with an existing vertical milling machine (VMM). The rotary fixture is made responsible for delivering the circular feed i.e., weld speed. This developed fixture is designed to deliver the required weld speed of 0.6 rpm. The tool rotational speed of 2000 rpm is delivered through the spindle head of the VMM. The plunge depth is controlled by the vertical feed available in the VMM. This pipe welding process utilizes a special form of a mandrel. The mandrel used here has the three main parts: two collets at the ends to hold the pipe to be welded in a stable position and one ring in the center to provide the support to the weld region like a backing plate. Three welds are made using the same process parameter to keep a check on the consistency of the process.

TABLE 3

Workpiece dimensions and FSW process parameters

Description	Parameter	Pipe	Plate
Pipe and plate dimensions	Length	75 mm	50mm
	Outer diameter	50 mm	—
	Width	—	50 mm
	Thickness	3 mm	3 mm
Parameters	Tool rotational speed	2000 rpm	
	Weld speed	0.6 rpm	94 mm/min
	Tool pin profile	Taper cylindrical	
	Tool tilt angle	0°	
	Axial load	1 kN	

2.2. FSW of plate

FSW of plates is an established process, which has dedicated CNC machines along with all sorts of controllers. One such machine, FSW 3T-300-NC was used to fabricate the welding. The toe camps are fabricated to suit the plate dimensions and used to hold the plate to the base of the CNC bed as shown in Fig. 2. The controls are set to the required values as prescribed in Table 3 and weld is obtained. Similar to pipe welding, three welds are fabricated in plate also, to ensure consistency of the process parameters.

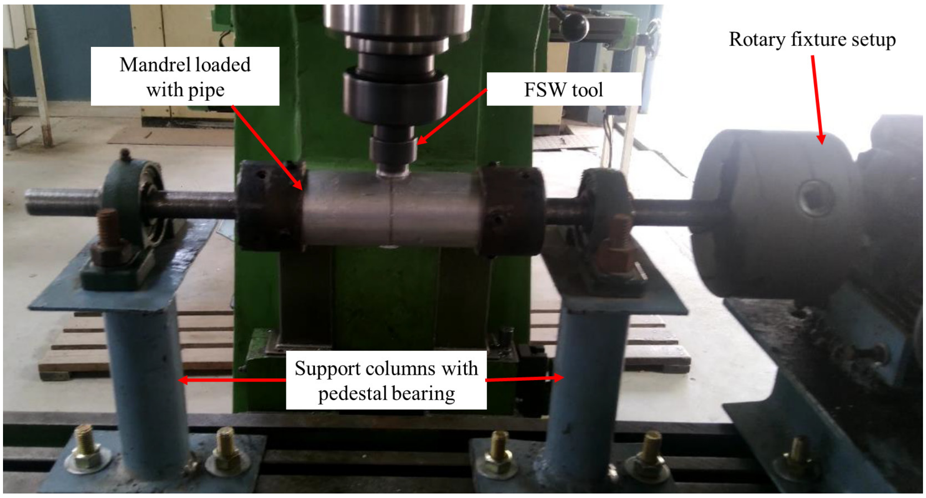

Fig. 1. Experimental setup for FSW of pipe

Fig. 2. Experimental setup for FSW of plate

2.3. Testing of welded pipe and plate

Both pipe and plate after welding, are subjected to various tests to study their performance. Initially, pipe weld and plate weld is tested using the radiography process for any flaws. Radiography test is a powerful and most commonly used test procedure used to identify the internal flaws. For this study, ASTM E1032-12 standard is followed to perform radiography test. For pipe welds, the Double Wall Single Image (DWSI) technique is used to obtain the radiography results [13]. After ensuring the welds are defect-free, mechanical tests are performed. For evaluating the mechanical performance of the welds, tensile and hardness are performed. As per the ASTM E8M-04 standard, tensile test is conducted. Tensile tests are carried out in the Electronic Tensometer machine with sub-specimen size as indicated in ASTM standards. During tensile testing, all specimen showed necking stage before reaching breaking point. The location of failures are observed to be mostly in the TMAZ zone. The hardness of the weld region is tested using micro Vickers hardness tester. The procedure prescribed in ASTM E384-17 is used to measure the hardness values. An indentation load of 300 g was used for a time period of 15s. All three specimens are tested for yield strength, ultimate strength, and microhardness values. Finally, microstructure study is performed to read the microstructural attributes that contribute to their performance characteristics. An Inverted metallurgical microscope is used to carry out the microstructure studies. The samples are cut along the weld cross-section and ASTM E3 standards are used to prepare the surfaces. Using different grades of emery sheets, cut surfaces are polished and velvet cloth added with diamond paste is used at last to complete the polishing process. As per ASTM E407 standards, the polished surface of the samples is etched for about 20 seconds using Keller's solution to reveal the grain boundaries.

3. Results and discussion

The process parameters considered are more likely to hinder the microstructure of the plate more than the pipe. The tool rotational speed is one of important factor during comparison of welding between plate and pipe. During plate the tool rotational forces will act outwards, centrifugally, which is obvious. This force will have different impacts on plate and pipe. In plate this force will be more parallel whereas in pipe this force will be tangentially to the weld surface (curved for pipe). A total of six (3 pipes and 3 plates) welds are fabricated using common process parameters which was optimal for pipe welding alone. Fig. 3 shows the welds made in pipes and plates respectively. Pipe weld sample 1 (Fig. 3a) and sample 3 (Fig. 3c) have better weld surfaces, when compared to the pipe weld sample 2 (Fig. 3b). Plate weld sample 3 (Fig. 3f) has a better surface finish when

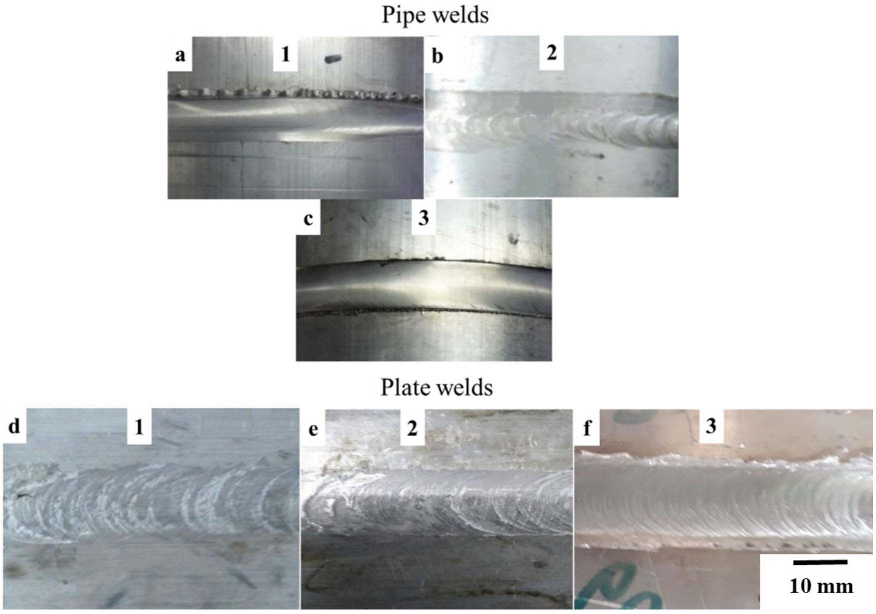

Fig. 3. Friction stir weld samples

compared to the other two plate welds (Fig. 3d and 3e). These variations in surface finish could be due to fixturing influences. All weld samples are subjected to radiography, mechanical and microstructural studies. Their corresponding results and their respective inferences are discussed below.

3.1. Radiography test results

Results of radiography test revealed void-free weld in all three weld samples of pipes and three weld samples of the plate. Fig. 4a shows the radiography results of pipe weld taken from sample 2 along with the position of actual pipe weld specimen. Fig. 4a (A) shows radiography of pipe in A position. Fig. 4a (B) shows radiography of pipe in the B position. Fig. 4a (C) shows radiography of pipe in C position. Fig. 4b shows the test results of radiography process carried out on plate weld sample 1. Radiography results of both pipe and plate show a flawless weld zone in all test result images. Even though the frictional heat generated for plate and pipe weld are different, the successful welds show zero defects, infers that proper bonding has happened in both welds for the same process parameters [14]. Thus it is confirmed that both pipe and plate welds have a successful weld joint and are of good quality. As similar results are obtained in the remaining samples also, all the weld samples are taken further for mechanical testing.

3.2. Tensile strength of pipe and plate welds

After ensuring that all the welds are free from flaws, they are subjected to tensile tests. Table 4 shows the summary of all the tensile test results comprising of both pipe and plate welds. The yield strength of pipe weld is averaged around 145.12 MPa, whereas the ultimate strength is 167.35 MPa, similar to the results found in the literature [12]. On the other hand, yield strength of plate welds averaged around 133.34 MPa and its ultimate strength is 148.57 MPa. The tensile results on a big picture show that the strength of pipe welds are higher when compared to the strength of plate welds, under-considered common welding parameters. The yield strength of plate welds is 8.1% lower than the yield strength of pipe welds, whereas the ultimate strength of plate welds is 11.2% lower than pipe welds. Thus the process param-

TABLE 4

Results of tensile test for pipe and plate specimens

Sample		Yield strength (MPa)		Ultimate strength (MPa)	
Pipe weld	1	145.12	Average = 145.12	167.35	Average = 167.35
	2	144.87		167.22	
	3	145.37		167.47	
Plate weld	1	133.08	Average = 133.34	148.47	Average = 148.57
	2	133.02		148.52	
	3	133.92		148.73	

a. Pipe weld

b. Plate weld

Fig. 4. Radiography test images of pipe weld (sample 2) and plate weld (sample 1)

eters which are defined as optimal for producing higher strength in pipe welding gave a lower weld strength in the plate. Also, pipe welds experience a 13.3% plastic deformation state, whereas the plate welds have a plastic deformation state of 10.3%.

3.3. Hardness of pipe and plate welds

The cross-section of welds is subjected to the micro Vickers hardness test. The results obtained through hardness tests are presented in Fig. 5. The hardness values presented are the average of results gathered by every three samples of pipe and plate welds. The hardness plot of both pipe and plate welds show a similar curve type [15], whereas the latter shows higher curve values as shown in Fig. 5. The (–1, 0, 1) hardness plots corresponding to the either side from the weld centre, refer to the stir zone of the FSWed region. The stir zone of the plate welds has a hardness of 60.6 HV, whereas that of pipe welds is 53.6 HV. The hardness of plate welds is 11.6% more when compared to that of pipe welds. This factor is the reason for the decline of the tensile strength, which also corresponds to a similar ratio.

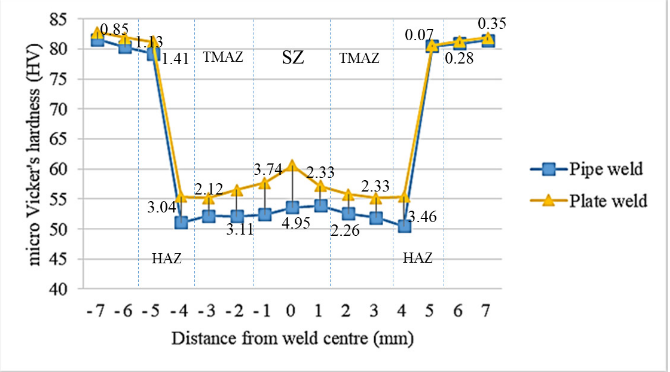

Fig. 5. Results of Hardness test (with standard deviation)

3.4. Microstructure attributes

The microstructure of the various zones of pipe and plate welds are shown in Fig. 6a and 6b respectively. There is a clear differentiation in the three major zones namely, Stir Zone (SZ), Thermo-mechanically Affected Zone (TMAZ), and Heat Affected Zone (HAZ) in both pipe and plate welds. The zone formation in pipe weld looks similar to that of in the plate weld. The difference lies in the shape and size of the grains in each zone, except HAZ. The HAZ in both the welds are found to be similar and share the common characteristics of a usual HAZ found in the literature [16]. The major differences occur in the TMAZ and SZ between pipe and plate welds. Fig. 6a shows the TMAZ of pipe weld which has the combination of both coarse and elongated grains. But in the TMAZ of plate welds as shown in Fig. 6b, highly deformed and elongated grains are found. Also, the TMAZ of pipe weld is a little larger than the plate weld. This is due to the preheating offered by the pipe fixture, which conducts the heat across the weld cross-section of the pipe. This results in the increased flow velocity of the material, thus helping breaking down the grains at the TMAZ as well as like in SZ [17]. This phenomenon is absent during welding of the plate, hence, the TMAZ of the plate weld is only left with

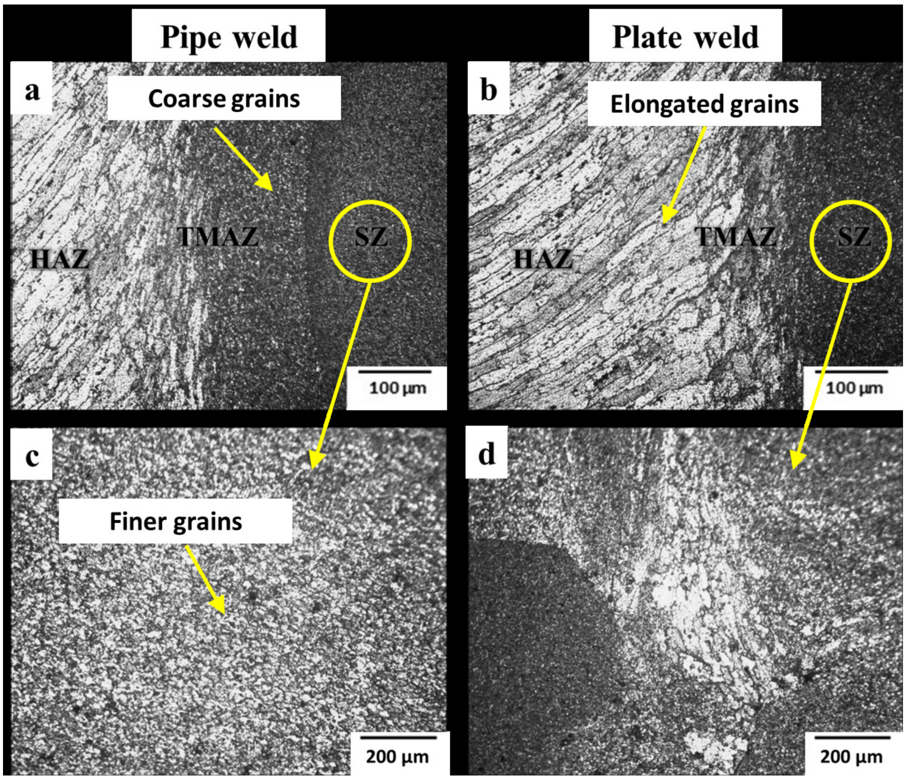

Fig. 6. Microstructure of various zones in pipe weld (sample 3) and plate weld (sample 3)

deformed grains due to tool action alone. The SZ of the pipe weld, as shown in Fig. 6c also has received the compliments of preheating, which has resulted in more finely deformed grains with uniform distribution. This decreases the grain boundaries at the SZ, thus increasing its load-carrying capacity. Whereas, SZ of plate weld has a non-uniform distribution of fine grains, which has a few coarse grains also suspended in it and is evident from the Fig. 6d. Thus, this factor has led to the increase in hardness at the SZ of the plate weld and its lower tensile strength. The more fine and uniform distribution of grains at the SZ of pipe welds have attributed to the higher tensile properties, resulting in good load carrying capacity when compared to that of plate weld.

4. Conclusion

This study has taken up to the task check for the limits in the performance variations, plates and pipes are FSWed using same process parameters. As per literature, the process parameter of tool rotational speed 2000 rpm and weld speed of 0.6 rpm (94 mm/min), which was defined as optimal for a pipe is set as common process parameters for both pipe and plate weld. Based upon this study, following conclusions are arrived:

- The welds made in pipe have a high tensile strength compare to the welds made in plate. Plate weld has a yield strength of 133.34 MPa which is 8.1% lower than that of pipe weld yield strength. The ultimate tensile strength of plate weld is 148.57 MPa, which is 11.2% lower than that of the ultimate tensile strength of pipe weld.
- The hardness of the plate welds is considerably higher than that of pipe welds. The SZ of plate welds has a hardness of about 60.6 HV when compared to that of pipe weld which is 53.6 HV. An increase of about 11.6% in the hardness values is found.

From the above statements, it is clear that with the same welding parameters for friction stir welding will head to have different weld quality in plates and pipes. Approximately 10% variations in the weld mechanical performances are found while using common welding process parameters. It is also recommended to have separate suitable and optimal welding parameters for FSW of pipes and plates respectively, even though the materials and thickness are the same. If an application finds itself suitable where the 10% variations are allowed, then the same process parameters can be employed for both plate and pipes, provided the thickness be the same. This will help in achieving time and cost savings, which will ultimately increase the economy of the welding process. This study can be further extended by experimenting with the tribological aspects as well which will help to compare the wear and tear characteristics.

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Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest

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