Evaluation of FSW Process Parameters of Dissimilar Aluminium Alloys

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Abstract

Friction stir welding (FSW) is relatively a new welding technology applied to join weldable Aluminum alloys and non- weldable Aluminum alloys that are widely used in many industrial applications such as aerospace, marine, automotive, and other industrial applications. In present research, dissimilar AA2024-T3 and AA6061-T6 Aluminum alloys of 3mm thickness was butt joined by using friction stir welding. The experimental study to optimize the welding parameters on tensile strength and bending test was carried out by Taguchi's L9 orthogonal array. Experiments have been employed based on four welding parameters, namely, the tool traverse speed, rotational speed, tilt angle of tool and tool geometry. ANOVA technique and signal to Noise ratio were used to determine the most significant parameter that affects the mechanical properties of the weldment. X-ray radiographic, microstructure, microhardness tests have been conducted to demonstrate that samples subjected to the optimum welding parameters gave good quality and no defects have been observed.

Keywords: FSW, aluminium alloys, dissimilar alloys, Taguchi Techniques, ANOVA, S/N ratio.

1. Introduction

One of the most important advantages of Friction stir welding as a new welding process compared with many traditional welding processes is its ability to weld dissimilar alloys and most specifically with combinations that are not compatible with other conventional welding processes. The joining process occurs below the melting point of the welded alloys and this helps in avoiding most problems associated with fusion welding of materials in addition to key advantages that are metallurgical, environmental and energy benefits [1]. The importance of joining dissimilar alloys (extensively Aluminium alloys) using FSW has grown up as a result for engineers strive in reducing weight and improving performance of the welded structure. Among these alloys are Aluminium heat treatable alloys such as AA6061 and AA2024, which are considerably stronger, its corrosion resistance is fair, their formability and weld ability vary from excellent to impossible depending upon both the alloy and its temper, some of them exhibit tensile and yield strength superior to those of low-carbon steel making their weight/strength/stiffness ratios very suitable for special critical applications that need qualified mechanical properties like aerospace, marine, pipelines and storage tanks industries. Although friction stir welding of similar and dissimilar aluminium alloys have been studied and experimented during the past two decades [2-6], not much study have been implemented regarding FSW of dissimilar aluminium alloys of 2024-T3 to 6061-T6 alloys. In particular [7-8] were two studies that explained material flow and microstructural evolution associated with the FSW of 2024 and 6061 aluminium but neither of the two has taken into account the mechanical properties of the dissimilar material FSW joint. [9] Used optical microscopy with serial sectioning to investigate the influence of tool geometry on material flow during friction stir welding of dissimilar 2024 and 6061 aluminium alloys. Regarding optimization, [10] Utilized statistical methods to optimize the friction stir welding process parameters of dissimilar AA2024 and AA6061 aluminium plates of 5mm thickness. The study investigated five different tool designs to analyse the influence of rotation speed and traverse speed over the microstructural and tensile properties. As a powerful tool for optimization, Taguchi method was used by many authors to optimize the process parameters of the friction stir welding process, C. Vidala (2008) [11] used Taguchi method with an orthogonal array of L9 (34) to conclude the optimal FSW parameters that enhance mechanical behaviour of (AA2024-T351).The study optimized parameters such as vertical downward forging force, travel speed and pin length. C. Thaiping (2009) [12] evaluated the optimum operating parameters of friction stir welding for joining dissimilar metals (AA6061 & SS400), the four process parameters that were considered are tool rotation speed, transverse speed, and tool tilt angle with respect to the work piece surface and pin tool diameter. M. Nourani et al. (2011) [13] used as an efficient methodology that combine between Taguchi optimization method and a temperature-field finite element model to optimize the process parameters of friction stir welding of 6061 aluminium alloy. The main goal of the study was to to minimize the heat affected zone (HAZ) distance to the weld line in the joined parts. S. Gopi and K. Manonmani (2012) [14] studied the influence of shoulder profile and shoulder penetration on joint strength of friction stir welded AA6082. Experiments are conducted for various combinations of spindle speed, welding speed, pin profile, shoulder penetration and shoulder profile at five levels in Taguchi's orthogonal array. Most published previous papers that selected dissimilar aluminium alloys (6xxx & 2xxx) focused on study of microstructures and mechanical properties without using optimization statistical methods as a tool to improve total behaviour of the welded structure. Moreover, not much or almost no study used optimization techniques to find out the optimal process parameters that might be used to join AA2024 and AA6061 aluminium alloys using FSW. Based on this fact, the aim of the current paper is to determine the optimal process parameters of friction stir welding for dissimilar AA6061& AA2024 using statistical methods.

2. Experimental Procedure Design

As a methodology, the design of experiments has become effective since it maximizes the knowledge obtained from experimental data, eliminate redundant observation and reduce the time and resources to make experiments. In this paper the parameters determination for optimum design using Taguchi's procedure is done by implementing the design of experiment principles. In addition, the trial conditions under the effect of the signal to noise ratio is carried out to attain consistency of performance. As steps, the design of an experiment may involve the following:

2.1 FSW Parameters Identifying and their Levels

The design procedure is started by determining the vital process factors effect on the performance characteristic. For FSW, there are several parameters that may have significant effect on weld quality such as: tool rotation speed in clockwise or counterclockwise direction, tool traverse speed along the line of welding, the angle of spindle or tool tilt with respect to the work piece surface, the insertion depth of pin into the work pieces (also called target depth), tool geometry and joint design. In addition, preheating or cooling can also be effective for some specific FSW processes [1]. The parameters selected for this work are : rotation speed (550,950,1500)rpm ,traverse speed (40,60,80)mm/min ,tilt angle (1,2,3)degree ,and three pin profile (cylindrical ,cylindrical thread , triangle). In fact the process of values selection were based on the previous concluding remarks obtained by past researches that ensure a maximum tensile strength and good quality (free defect) will be obtained as a result for this selection . The parameters and their levels are shown in Table [1].

2.2 Designing the Matrix Experiment (OA) and Data Analysis Procedure

After the FSW parameters and levels were determined, the orthogonal array L9 (34) was selected as the appropriate array. Basically, the use of orthogonal array L9 (34) reduced the number of experimentation to 9 tests; instead the original number of 81 tests. Once the orthogonal array was selected, a number of repeated observations (trials) representing the uncontrolled parameters was carried out. In this study, two tests were carried out to evaluate the quality of dissimilar butt joints alloys. The first one is transverse tensile test performed in order to evaluate the tensile strength of the weld joints; three samples were tested and the ultimate tensile strength (UTS) was chosen to analyse optimum and process performance characteristic. The second test used is bending test; this test is suitable for evaluating strength of brittle materials, where the evaluation of the tensile result is not sufficient since the failed areas are not included in the specimen gauge length and it is so much susceptible to defects near the surface of the weld bead, such as root flaws. As a consequence, three trials were conducted to find the mean values well used to investigate the relative effect of the proposed parameters. The measured values of both tensile and bending trials are exhibited in Table [2].

3. Performance Prediction

In order to confirm the optimum conditions, a performance prediction for the output friction stir welded joint should be implemented and to do that mission, each control factor must be evaluated to estimate the influence of parameters on the resulted response. In fact, results analysis is carried out to find out the following:

- The optimum parameters design.
- Influence of individual factors.
- Performance at the optimum condition
- Relative influence of individual factors.

3.1 S/N Ratio and (ANOVA) Analysis

Analysis of variance (ANOVA) has the function of investigating and identifying the most significant parameters that affect the resulted quality characteristic and therefore it is commonly applied to the results of the experiments. To perform the complete analysis, Taguchi proposes two different approaches. The first is the standard in which the results of a single run or the average of repetitive runs are processed through the main effect and ANOVA (raw data analysis). The second approach, which Taguchi mostly applied for multiple runs, is to use the signal-to-noise (S/N) ratio for the same steps in the analysis. To analyze experimental data, the signal-to-noise ratio needs to be calculated for each experiment conducted. In the current study, the S/N ratio is chosen to follow the principle of (larger is better) in order to maximize the response. The mean squared deviation (MSD) and S/N ratio are computed through using the following relations [16]:

$$MSD = \frac{1}{N}\sum_{i=1}^{n}\left(\frac{1}{y_{ij}^{2}}\right) \quad (1)$$

$$S/NRatio=-log10(MSD) \quad (2)$$

In which, y_{ij} is the total number of trials, n is the number of trials, i is trial number, and j is the experiment number. The range (Rank Δ) is calculated using the equation below:

$$\text{Rank } \Delta = \text{Max } S/N - \text{Min } S/N \quad (3)$$

After finding the optimum parameters, the data were plotted to find the intersection between the levels and the diagrams constructed for FSW process parameters and to give the information about how significant the effect of each controlled parameter on the quality. Finally the data were also analyzed by (ANOVA) to compute the sums of squares, degrees of freedom and percentage contributions.

3.2 Optimum Performance Prediction

To predict the optimum performance characteristics of tensile strength and maximum load for bending at selected levels of significant parameters, the estimated mean of response characteristics were calculated as in the equations below [17]:

Ultimate Tensile Strength (UTS) = average UTS (AUTS) + (optimum RS level - AUTS) + (optimum TS level – AUTS) + (optimum TA level- AUTS) + (optimum PG level – AUTS) (4)

Max Load for Bending = average load + (optimum RS level - average load) + (optimum TS level – average load) + (optimum TA level- average load) + (optimum PG level – average load) (5)

4. Experimental Work

4.1 Materials Specification, Machine and Fixture

The two dissimilar materials selected to be joined by friction stir welding process were Aluminium 2024-T3 and Aluminium 6061-T6 and both have a 3mm thickness. Each specimen that designed to be joined by FSW has been cut by a sheet metal cutter to the dimensions of (75mm width and 150mm length). These dimensions have been chosen due to the dimensions of the work table and the design of the clamping system. In this study the conventional "Turret Milling Machine Model: MDM 4VS/4HS/4 S" with a designed fixture that suits with dimensions of specimen has been used to perform the joining experiments as shown in figure (1 a&b).

4.2 Tool Material Specifications and Geometry

The conventional aluminum alloys tools made of tool steel has sufficient strength to carry out the temperature of material melting point without tool wear, twist or break. In this study the tool steel (R18) was selected and the chemical composition are shown in table [3].

Regarding tool geometry, the shoulder diameter has been selected to be (18 mm), the pin diameter and length was (6mm, 2.8mm) respectively. It has been chosen three pin profiles that give good mechanical properties as have been remarked by the literature. The 1st was the conventional cylindrical pin profile, 2nd the cylindrical threaded pin profile and 3rd is the triangular pin profile. Type of pin design was chosen according to most popular type used in friction stir welding researches which produce good quality stir weld, and easily machined [18]. The specification was shown in Figure 2.

4.3 Steps of Experimental Work

After finishing the preparation of the two plates (AA2024 &AA6061) by cutting them in required dimensions, the two specimens were fixed by clamping system (fixture). The AA2024 was chosen to be the advance side because it has strength higher than AA6061, and the edge of each specimen should be facing to avoid any gap between them. The four parameters (rotation speed, traverse speed, tilt angle, pin geometry) were selected and the machine adjustment to make nine tests that are represent the orthogonal array (L9) was made. Powered the machine and the vertical axel was downward to touch the centre of two specimens and the pin penetrate , waited a minute until the plate has been soft and then stirred the pin horizontal to the end of specimen then eliminated the tool upward, figure 3 shows the dimensions and layout of the final specimen.

4.4 Mechanical Tests

In the current study two types of mechanical tests (destructive and non-destructive) that are used to evaluate the condition or the quality of a weld process were carried out. The destructive involved: microstructure, tensile, bending, and micro hardness while the non-destructive included the radiographic test.

4.4.1 Destructive Testing

The main function of destructive testing is to determine service life and to detect design weaknesses that may not show up under normal working conditions. A number of destructive weld tests are used to determine weld integrity or performance. The current paper carried out tests like microstructure, tensile, bending, and micro hardness.

Starting with microstructure test, this test is usually implemented to locate welding problems such as crack initiation, when used for failure analyses. In this study nine samples were cut out from welded joint specimens and mounted to facilitate the grinding process. The grinding process involved using abrasive silicon carbide papers for four minutes, at a speed of 600 rpm and using water for cooling. Polishing for materials was carried out using polishing machine used with diamond suspensions with grain size of (0.05 μm); samples were polished for five minutes for each grain size. The samples were then cleaned by running under cool water followed by acetone cleaning and then dried using compressed air. The samples were etched by etchant reagent used for Aluminum alloys (Killers' reagent (composition: 95ml water, 2.5ml HNO3, 1.5ml HCL, 1.0ml HF)), the regent stay on the sample surface for 10 second and then cleaned by water and dry. For the tensile test, a universal testing machine (WDW-200E) has been used and the specimens were prepared to be suitable for gripping into the jaws. The standard tensile test used in this study has been chosen according to (ASTM E8M-04). The shape and dimensions of the tensile specimen is shown in figure 4. Concerning bending test, it is most commonly used to find liner fusion defects that open up in the plate surface during the testing procedure. In this work the bending specimens were cut with dimensions (width=20mm, length =150mm) as shown in figure 5. The last test in the group of destructive tests carried in this work is micro hardness test. In this study the digital micro hardness tester has been used to measure Vickers hardness with 0.49N load at 15 second. The test involved first, measuring the base metal hardness which was (A)(137HV for AA2024) & (B)(107HV for AA6061). 2nd step is to abrasive 1mm of samples thickness and take 18 point of micro hardness test vertical to weld line from the (C) 2024 edge to (D) 6061 edge. The illustration of these steps is shown in Figures 6.

4.4.2 Non- Destructive Testing (NDT)

Non-destructive testing (NDT) used to inspect an object, material or framework without disabling its future usefulness. It's often required to verify the quality. The commonly used tests are dye-penetrate testing and fluorescent-penetrate testing, magnetic particle testing, ultrasonic testing, and radiographic testing. In this paper radiographic testing was used to examine the interior of the weld region. It gives a permanent film record of defects that is relatively easy to interpret. It's a slow and expensive method of non-destructive examination but it is a positive one for detecting porosity, inclusions, cracks, and voids in the interior of castings, welds, other structures.

5. Results and Discussion

The results of joining dissimilar aluminum alloy plates of AA2024 and AA6061 with thicknesses of 3mm using friction stir welding process are sectioned into three parts. The first part deals with the optimization of FSW process parameters of tensile strength and bending tests, in which the experiments were designed using Taguchi method with an L9 orthogonal array. In the second part, the radiographic (X-ray) tests are discussed. Finally, the third part explains the microstructure and micro hardness results.

5.1 Optimization of FSW Process Parameters

Welding processes can have various effects on the base metal, and knowing of how welding parameters impact the mechanical properties of welds is a truly significant. In fact, the mechanical properties of welded joint are the major factors that determine the welding quality. Consequently, the aim of the welding process designer is to optimize the mechanical properties in order to produce excellent welded joints. To accomplish this purpose, the experimental techniques that include statistical design of the experiment and Taguchi techniques were used to improve the quality of welded components.

5.1.1 Optimized Process Parameters for Tensile Strength (S/N Ratio and ANOVA Analysis)

Tensile strength is one of the most important mechanical properties especially in joining dissimilar components. It simply plays a major role in deciding weld quality. In this study three trials of the tensile strength were run by using the Taguchi method and orthogonal arrays L9 (34). In fact, the data were analysed and identified to determine the optimal levels for all the control factors. In order to evaluate the influence of each selected factor on the response, the 9 mean and S/N ratios were calculated as shown in table [4].

From the data above, the effect of this factor is used to determine the range (Rank Δ), which is the larger the R value for a parameter. The larger the effect the variable has on the process. This is because the same change in signal causes a larger effect on the output variable being measured. The results are tabulated as shown in Table [5]. Through analyzing S/N ratio for various process parameters, the optimal level of process parameter is the level of the highest S/N ratio. The plotted diagram constructed for FSW process parameters are shown in Figure 7. The diagrams of the S/N ratio may also be used to determine the optimal set of parameters from this experimental design. It can be noticed from the S/N plot that the tilt angle and travel speed are the most important factors affecting the response; the minimum value of response is at the highest level. Rotation speed has a less relevant effect, while pin profile plot show the lowest effect among those factors. The main effects plot for S/N ratios suggests that those levels of variables would minimize the weld defects. The summery of best parameter settings for the FSW joint is shown in Table [6]. To analyze the effects of the welding parameters in more detail, analysis of variance ANOVA was conducted to inspect the importance of the process parameters that affect the tensile strength of FSW joints. The F-test named after Fisher is used to determine which parameter has a significant effect on tensile strength. Usually, the change of the process parameter has a significant effect on quality characteristics, when F is large. The percentage contribution results are shown in Table [7]. The analysis of variance indicates that tilt angle has the greatest effect on the response followed by traverse speed and then by rotation speed. Pin geometry did not have major effect and the design must change. The models indicate that not all the studied parameters significantly affect the response. Now, after the significant process parameters and their levels have been selected as rotation speed (level 1) =550 rpm, traverse speed (level 1) = 40mm/min, tilt angle (level 3) =3, pin geometry (level 1) = cylindrical, the optimum value of (UTS) was predicted. The mean of the response from equation (4) is

Ultimate Tensile Strength (UTS) =159+ (166-159) + (165-159) + (165-159) + (162-159) = 181MPa.

5.1.2 Optimized Process Parameters for Bending Test (S/N Ratio and ANOVA Analysis)

The bend test is a simple and inexpensive qualitative test that can be used to evaluate both the ductility and soundness of a material. It is often used as a quality control test for butt-welded joints. In order to calculate the mean and S/N ratio to find the optimum levels that maximize ductility, the data set in orthogonal array L9 (34) were analyzed .The bending results are shown in Table [8].The previous steps for tensile strength were repeated to find the rank Δ and the best levels are tabulated as shown in Table [9]. The Rank Δ values show that traverse speed has the highest value, then followed by the rotation speed, tilt angle and pin profile. It is observed that large S/N ratio corresponds to better quality characteristics. The best results are shown in Table [10]. The plotted diagrams that represent the response effect and optimum levels are shown in Figure 8. To analyze the effects of the welding parameters in more detail, analysis of variance ANOVA was carried out and the results are shown in table [11]. The results from the ANOVA for bending show that the traverse and rotation speed had the great effect on response, while the tilt angle and pin profile did not have that effect, and that is not similar to the results obtained from tensile strength [17]. The optimum value of maximum load for bending was predicted after the significant process parameters and their levels have been selected as rotation speed (level 1) =550 rpm, traverse speed (level 1) = 40mm/min, tilt angle (level 3) =2, pin geometry (level 1) = cylindrical. The mean of response from equation (5) is,

max load for bending =0.56+ (0.79-0.56) + (0.8-0.56) + (0.64-0.56) + (0.62-0.56) = 1.17 KN

5.2 Radiographic (X-Ray) Results

For efficient and reliable performance, the welded component might be checked using non-destructive methods. As a method, Radiography has the function of detecting complete internal details of the weld, material transportation and defects resulted due to inadequate force applied by the tool. The results of the radiographic tests conducted on all the welded specimens are presented in Figure 9(a-i). From the x-ray radiographs presented in the figures preview it can be seen that : in samples 1, 4, and 7, no defects are observed, in sample 2 the defects found are mainly voids which is more likely to exist at the start of the weld where nib plunges or at the end of the weld where tool is withdrawn due to inadequate frictional force that lead to additional material removed from both ends, in sample 3 circular pressure mark at the start of the weld is observed, the pressure mark indicates the change of microstructure of the material under the shoulder of the tool at the beginning of the welding process and a severe deformation of the material without reaching the plastic state. Sample 5 shows long tunnel defect running along the weld that results from insufficient weld temperatures due to low rotational speeds or high transverse speeds. In samples 6&8, the weld is characterized with incomplete fusion of both materials joined and wormhole defect was also notice. The increasing of the weld travel speed increases the frequency of voids, and the highest lack of penetration. With regard to tool rotational speed, it is evident that the extent of mixing is directly related to the medium rotational speed. Thus greater penetration and a more consolidated weld is achieved. In sample 9, the long tunnel defects which may be surface or subsurface were observed. A lack of penetration result if the pin is not long enough or the tool rises out of the plate; then the interface at the bottom of the weld may not be disrupted and forged by the tool [19].

5.3 Microstructure and Micro hardness Results

5.3.1 Microstructure Results

The microstructure of welds produced during friction stir welding of dissimilar Aluminium alloys and using four different weld parameters: tool rotational speed, traverse speed, tilt angle and pin profiles were investigated. The obtained results show to a high extent that the microstructure of the dissimilar joint is dependent on the position within the weld zone. Different microstructures are observed while moving across the width and depth of the weld zone. In fact, all the investigated microstructures can be classified into three different regions namely unmixed region(a), mechanically mixed region(b,c) and mixed flow region(d) as illustrated in Figure 10. A through-section view of the friction stir weld shows a well formed stir zone with a lamellar pattern created by dark and bright lamellae as was also detected. The microstructure for the nine experimental tests using different magnifications is shown in Figure 11(a-i). The images of figures 11(a, b, d, f) show joints of good quality because no defects were adjusted confirming the complete weldability of the two alloys at the solid state. The BM, the HAZ and the TMAZ are also clearly identifiable.. For figures 11(c, e, g, and h), internal defects and absence of mixing zone were observed, due to high generation of frictional heat and amount of plasticized material. The figures also show that volume of plasticized material and interaction of tool is low due to the decompose of mixed flow region. The formation of different lamellae are due to the existence of non-chemical mixture of BM's; some elements in the chemical composition of the welded alloys are responsible for the appearance of certain regions for instance the bright regions of the picture are due to the presence of peaks of copper while peaks of Si are responsible for the dark regions of the picture, this leads to the conclusion that dark lamella originates from AA2024 alloys and the bright lamella from AA6061 [20]. The differential flow behaviour of each material that is associated with the type of the pin used in the joining process is one of the reasons that cause such observed pattern. The separating between every lamella and their size is identified with the utilized weld pitch (tool rotation divided by the welding speed).

5.3.2 Microharness Results

Micro hardness test is usually used to evaluate the strength of the weld. It simply gives indications about hardness status around heat affected zone (HAZ). . It can assist in evaluating the brittleness of the weld and confirms that the weld has the desired strength. In addition, the test can provide information about the metallurgical changes caused by welding. In order to apply this test, a number of measurements in a given sample are made at a given distance from the sample edge or from top of the weld. For the current study, the micro hardness for the nine experiments from (S1 - S9) was measured and plotted. The data shows that micro hardness values are higher in advanced side AA2024 than retreating side AA6061; lower values are in edges where the mixing happens and the lowest values are in the center of joint line, and the values from edge to anther are more close to each other because the temperature effect is lower than that at the surface that lead to enhancing the grain size and strength. The micro hardness graph is shown in Figure 12. For samples 1,2,4,7 the weld strength give good weld quality and free of defects, in samples 6, 8, 9 the strength higher which give weakness of samples and lead to cracks, in samples 3, 5 a decrease in HAZ hardness due to the accelerated ageing and recovering processes caused by the weld thermal cycle, in these regions hardness peaks can be observed, disrupting the declining trend of the micro hardness profiles.

6. Conclusions

This study proves that optimizing multi response parameters by using Taguchi method of experimental design can improve the performance; where the predicted values for ultimate tensile strength and maximum load gives improvement reach to 3% and the system was designed to give a specified target quality. From S/N ratio and ANOVA analysis for tensile strength test, it is found that tilt angle is the most influencing parameter which has the largest effect, and the pin geometry has the smallest effect. The S/N and ANOVA results were identical. While for bending test the S/N ratio and ANOVA analysis show that the traverse speed is the most influencing parameter which has the largest effect, and the pin geometry still has the smallest effect. From the experimental results, it is found that the optimum FSW parameters that ensure a good performance and free defects were low traverse speed (40-60)mm/min, low rotation speed (550)rpm, tilt angle of (2-3) degree and cylindrical threaded pin profile. From the X-ray results; the samples subjected to the optimum process parameters values have no defects and are of good quality. The microstructure and micro hardness results show a good flow pattern in which three basic zones appeared.

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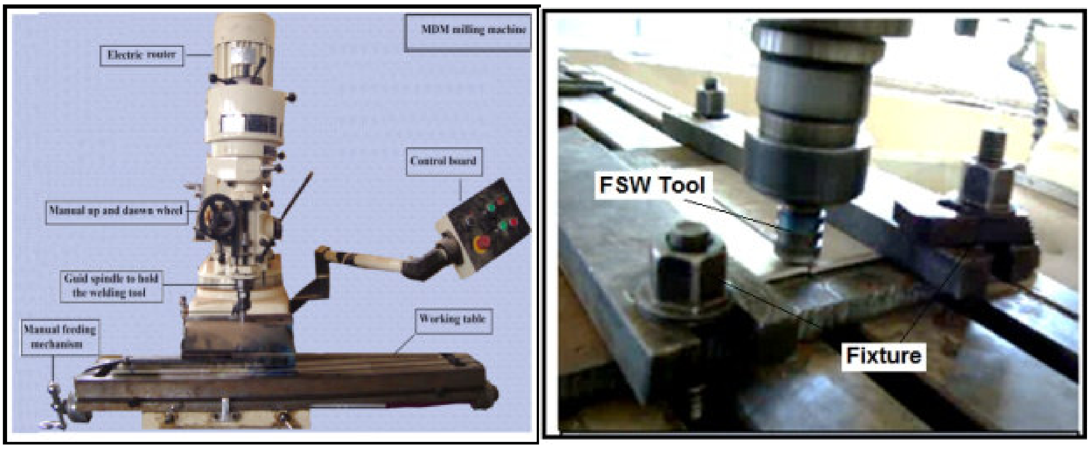
Table [1] Parameters and their Levels of FSW

Parameters	Level 1	Level 2	Level 3
Rotation speed (RS) [r/min]	550	950	1500
Traverse speed (TS) [mm/min]	40	60	80
Tilt angle (TA) [degree]	1	2	3
Pin Geometry (PG) [profile]	Cylindrical flat	Cylindrical threaded	Triangle

Table [2] Transverse Tensile and Bending Tests Trials

No.	RS rpm	TS mm/min	TA degree	PG	Tensile tset trials			Bending test trials		
					T1 MPa	T2 MPa	T3 MPa	T1 KN	T2 KN	T3 KN
1	550	40	1	Cyl	140	175	173	0.98	0.9	0.93
2	550	60	2	Thr	175	177	179	0.78	0.67	0.77
3	550	80	3	Tri	131	172	172	0.69	0.69	0.69
4	950	40	2	Tri	145	171	169	0.64	0.85	0.84
5	950	60	3	Cyl	151	176	175	0.45	0.48	0.63
6	950	80	1	Thr	90	125	175	0.11	0.11	0.11
7	1500	40	3	Thr	158	179	175	0.6	0.84	0.7
8	1500	60	2	Tri	90	173	178	0.13	0.11	0.11
9	1500	80	1	Cyl	125	172	171	0.4	0.4	0.4



-a- -b-

Figure1. a-MDM milling machine, b- Fixture of butt FSW

Table [3] Chemical composition for tool steel material

Elements	C%	Si %	Mn%	Cr%	Mo%	V%	W%
Tool steel	0.8	0.5	0.5	4.4	1	1.4	17

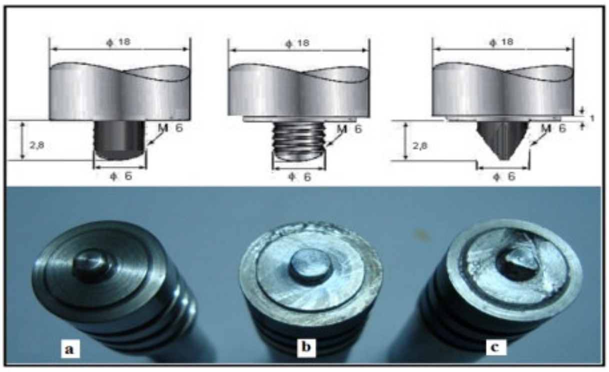
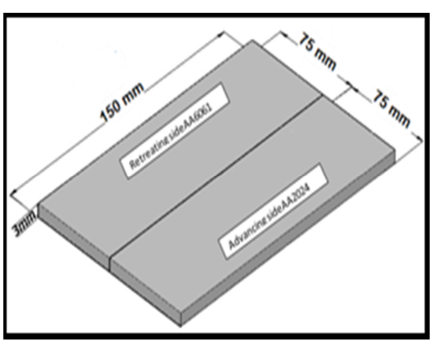
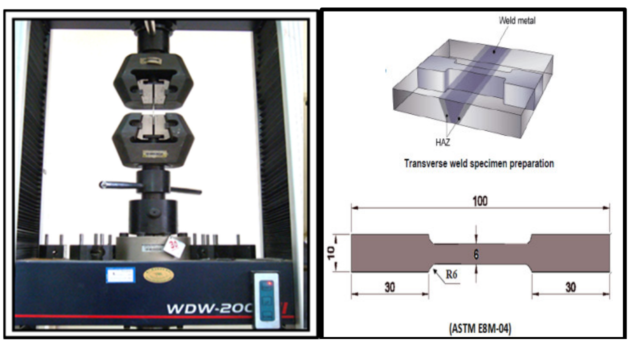


Figure 2. Pin geometry types: a) Cylindrical, b) Cylindrical Threaded, c) Triangle





-a- -b-

Figure 3 Specimen shape and dimensions FSW process

Figure 4 a. Tensile machine WDW-200E b.Tension Test welded by Samples

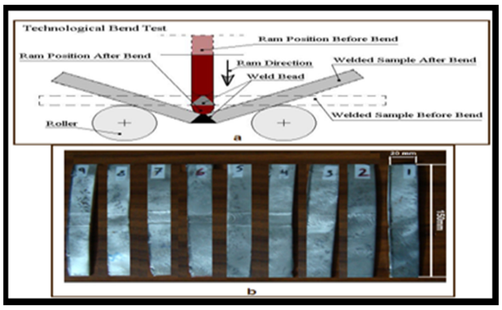


Figure 5. a. Schematic of three points bending
b. Nine bending specimens before test.

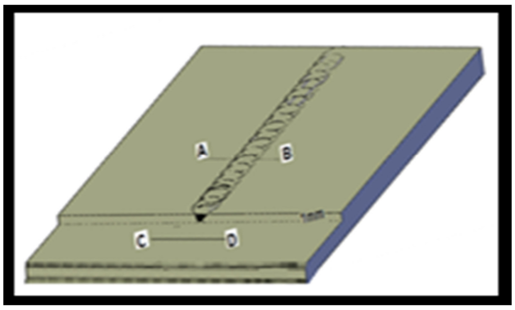


Figure. 6 Outline for micro hardness

Table [4] The mean values for tensile strength and S/N ratio results

No.	RS rpm	TS mm/min	TA degree	PG	Mean MPa	S/N ratio
1	550	40	1	Cyl	163	18.3
2	550	60	2	Thr	177	38.9
3	550	80	3	Tri	158	16.6
4	950	40	2	Tri	162	20.9
5	950	60	3	Cyl	167	21.4
6	950	80	1	Thr	130	9.5
7	1500	40	3	Thr	171	23.6
8	1500	60	1	Tri	147	9.3
9	1500	80	2	Cyl	156	15.2

Table [5] Rank Δ results for tensile strength

		S/N Ratio			
parameters		RS	TS	TA	PG
levels	L1	24.6	23.2	12.3	24
	L2	16	20.9	13.7	18.3
	L3	17.3	13.7	23.2	15.6
Δ		8.6	9.5	10.9	8.4
Rank		3	2	1	4

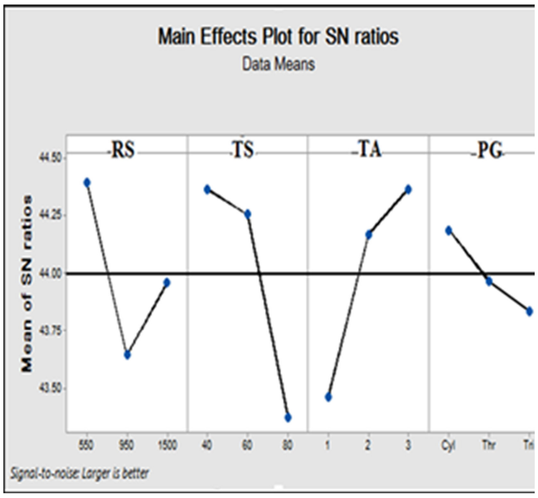


Figure 7. S/N ratio diagrams

Table [6] Best setting of combination parameters

Factor	Parameters	Levels
Rotation speed (rpm)	550	1
Traverse speed (mm/min)	40	1
Tilt angle (degree)	3	3
Pin geometry	Cylindrical	1

Table [7] ANOVA for FSW process parameters

Parameters	DF	S_A	S_T	F	P_A%
Rotation Speed	2	258	1552	0.6	16.3
Traverse Speed	2	549	1552	1.64	34.87
Tilt Angle	2	685	1552	2.37	44.75
Pin Geometry	2	61	1552	0.12	4
Total	8				99.93

Table [8] Mean values S/N ratio results for bending

Samples No.	RS (rpm)	TS (mm/min)	TA (degree)	PG	Mean N	S/N ratio
1	550	40	1	Cyl	940	59.5
2	550	60	2	Thr	740	57.4
3	550	80	3	Tri	690	56.7
4	950	40	2	Tri	770	57.7
5	950	60	3	Cyl	520	54.3
6	950	80	1	Thr	110	40.8
7	1500	40	3	Thr	720	57.1
8	1500	60	2	Tri	120	41.5
9	1500	80	1	Cyl	400	52

Table [9] Rank Δ results for bending test

		S/N Ratio			
parameters		RS	TS	TA	PG
levels	L1	57.86	58.1	50.76	55.26
	L2	50.93	51.06	52.2	51.76
	L3	50.2	49.83	56.03	51.9
Δ		7.66	8.266	5.27	3.5
Rank		2	1	3	4

Table [10] Best setting of combination parameters

Parameters	Parameters	Levels
Rotation speed (rpm)	550	1
Traverse speed (mm/min)	40	1
Tilt angle (degree)	3	3
Pin geometry	Cylindrical	1

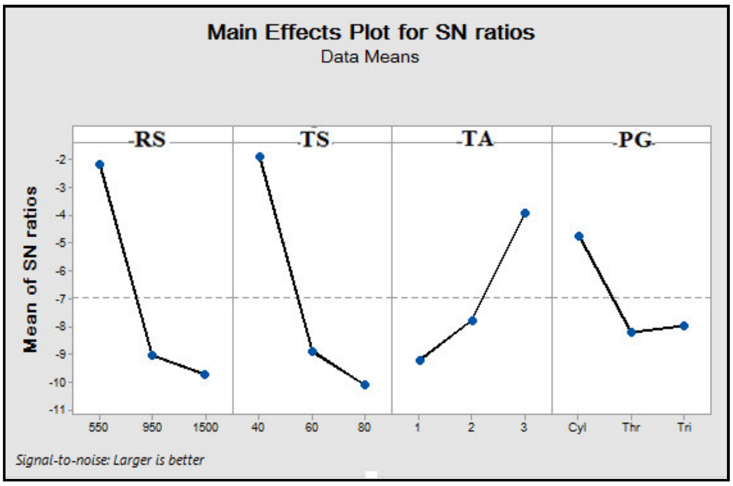
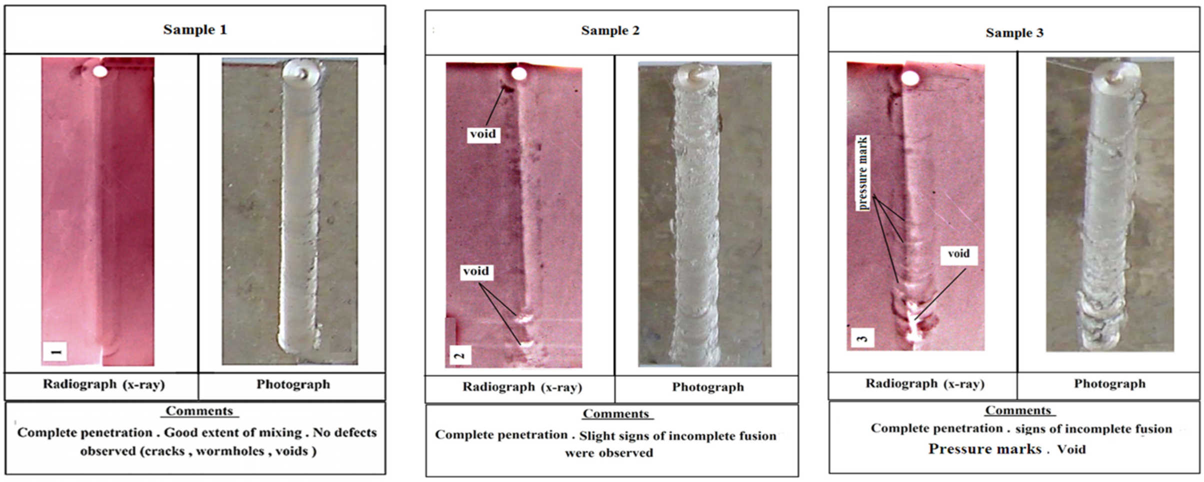


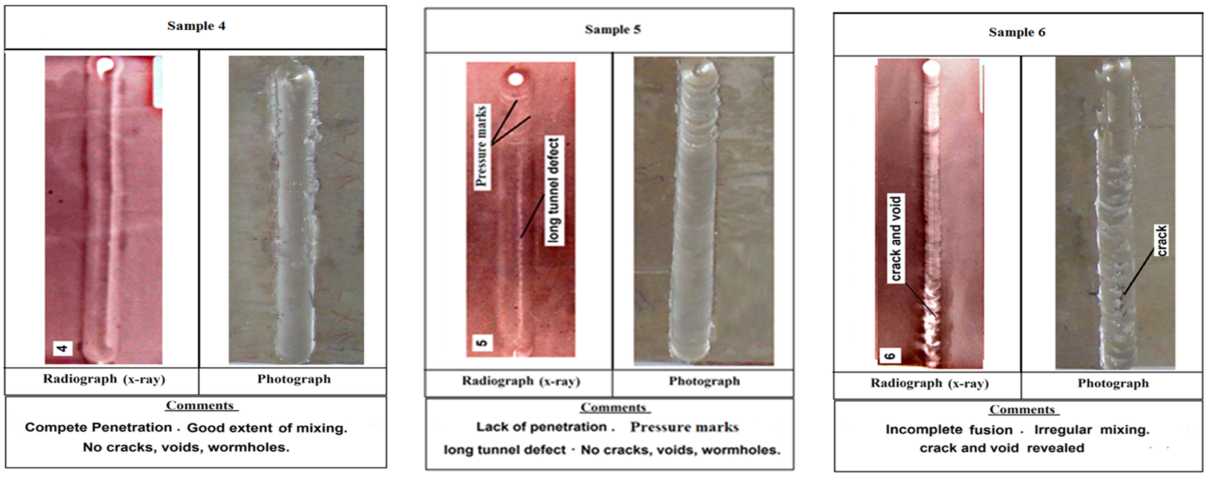
Figure 8. *S/N* ratio diagrams

Table [11] ANOVA for FSW process parameters

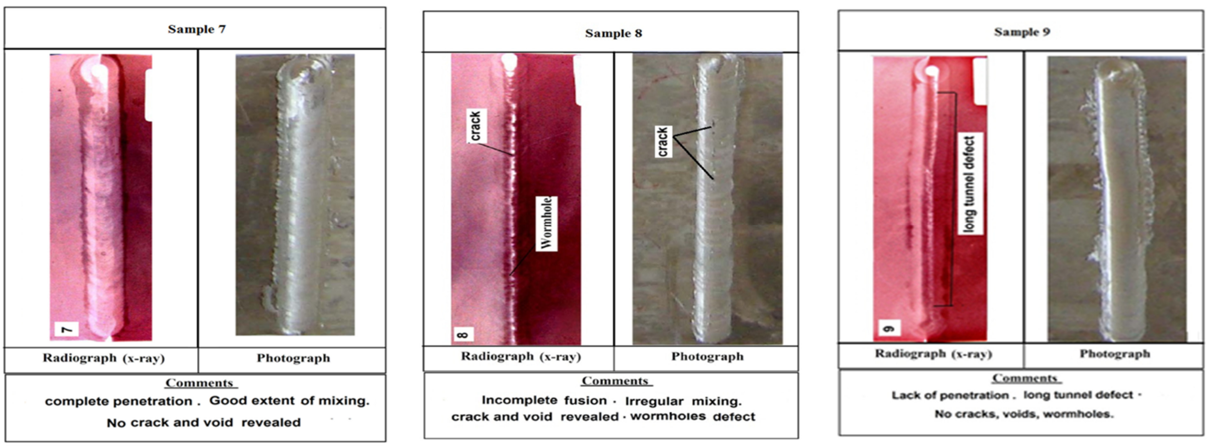
Parameters	FD	SA	ST	F	PA (%)
Rotation Speed	2	0.2493	0.6866	1.71	36.3
Traverse Speed	2	0.2942	0.6866	2.25	42.85
Tilt Angle	2	0.1251	0.6866	0.67	18.22
Pin Geometry	2	0.018	0.6866	0.009	2.63
Total	8				



a. 550 rpm, 40mm/mi 1deg. b. 550 rpm, 60 mm/min, 2deg c. 550 rpm, 80mm/min, 3deg.

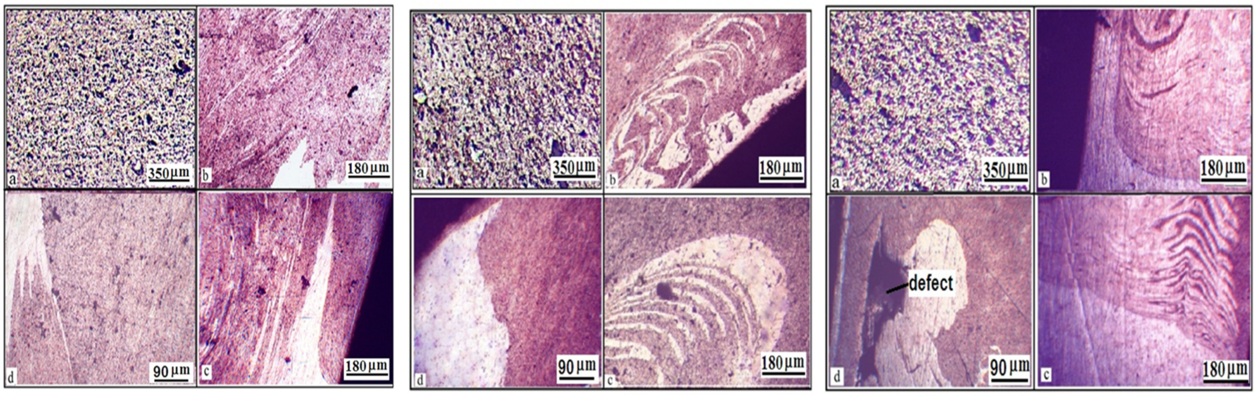


d. 950 rpm, 40mm/min, 2 deg e. 950 rpm, 60mm/min, 3deg f. 950 rpm, 80mm/min, 1 deg

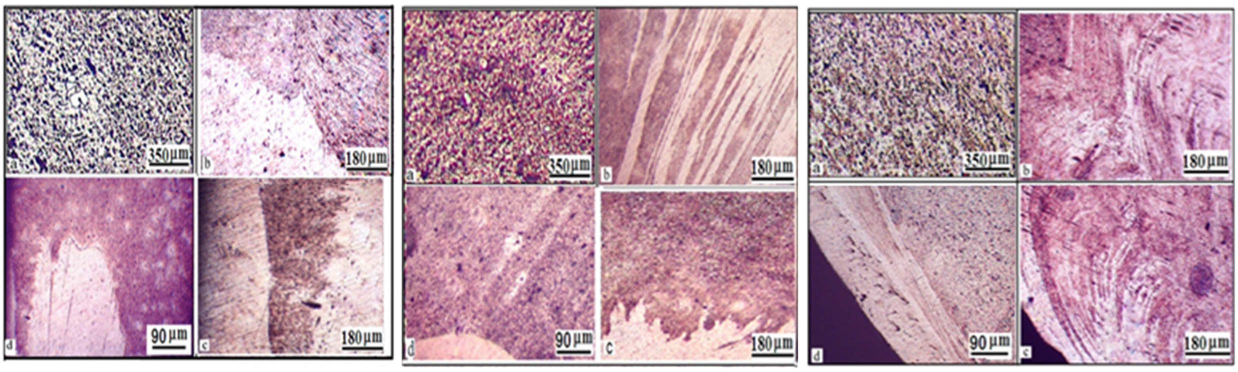


g. 1500 rpm, 40mm/min, 3deg h.1500 rpm, 60mm/min, 1 deg i.1500rpm, 80mm/min, 2deg

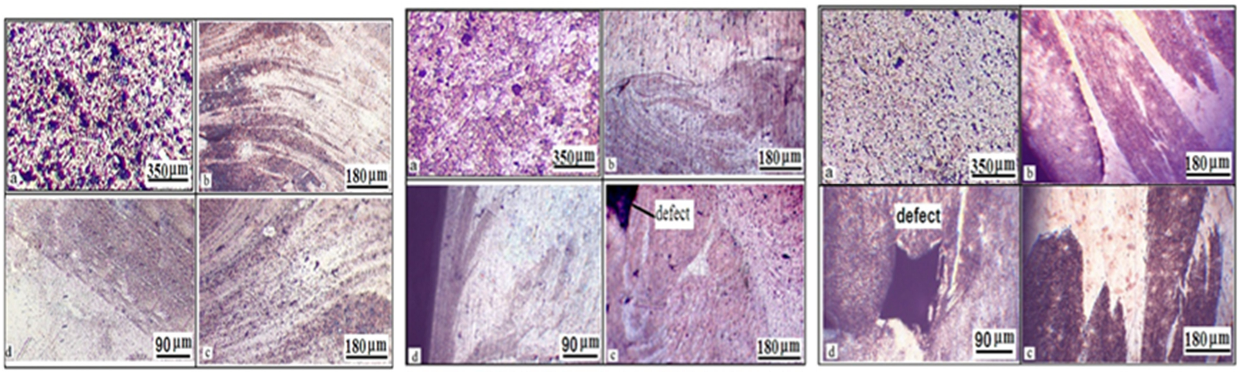
Figure 9(a-i) Photographs and radiographs of welds



a.550 rpm, 40mm/min, 1deg   b. 550 rpm, 60 mm/min, 2deg   c.550 rpm, 80mm/min, 3deg



d. 950 rpm, 40mm/min, 2 deg   e. 950 rpm, 60mm/min, 3deg   f.950 rpm, 80mm/min, 1 deg



g.1500 rpm, 40mm/min, 3deg   h.1500 rpm, 60mm/min, 1 deg   i. 1500rpm, 80mm/min, 2deg

Figure 10. Schematic illustration of FSW zon

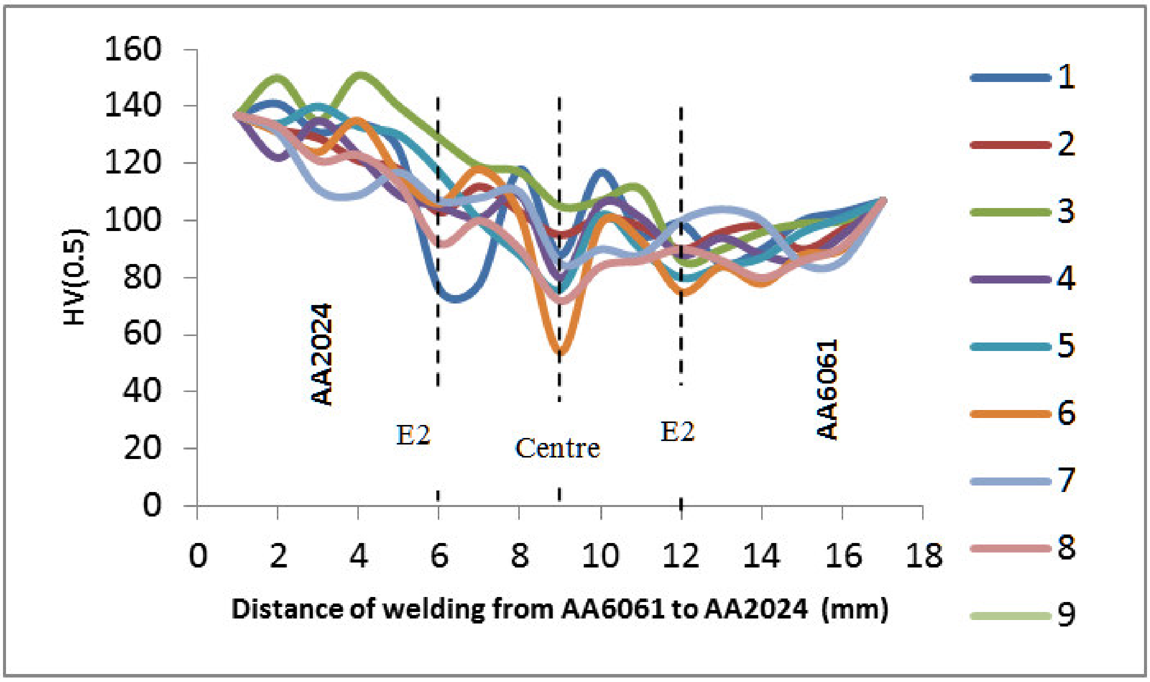


Figure 11(a-i) Microstructure in weld zone