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Application of Image Processing to Radiographic Image for Quantitative Assessment of Friction Stir Welding Quality of Aluminium 2024 Alloy

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Abstract

This work is an attempt to utilize X-ray radiographic image for evaluating friction stir welding process quantitatively rather than qualitatively. The X-ray image from radiographic test is quantified by applying image processing to estimate defect area in terms of number of pixels and compared with mechanical properties of weld joint. Taguchi method is used to design the experiment with input process parameters rotational speed, welding speed and tool offset value. The area of defect from X-ray image and tensile strength of weld joint possess inverse relation. According to Taguchi method, the process parameters that produce minimum area of defect and maximum tensile strength are found to be rotational speed of 1000rpm, welding speed of 80mm/min and tool offset at 0mm from center line. The ANOVA result depicts that welding speed is the dominating parameter for both area of defect and tensile strength followed by rotational speed and tool offset.

Keywords: Friction Stir Welding, Non-destructive testing, Image processing, Aluminium, Taguchi, Radiography.

1. Introduction

Friction Stir Welding (FSW) is an emerging and promising solid state welding technique used for joining most structural alloys[1]. The FSW process does not melt the material subjected for joining and the whole process is accomplished in solid state through mechanical stirring[2]. The non-melting of material in FSW offers many advantages that include low heat affected zone, elimination of cracks, lower distortion, higher joint strength, absence of fumes and spatters and energy efficiency. These benefits make FSW the preferred process over conventional fusion welding[3,4]. Though FSW has been initially developed for joining Aluminium and low melting-point materials, later the process has been extended for joining refractory metals and other metals with high fusion temperatures[5]. Despite of its advantages, the strength of weld joint in FSW process highly depend on the process parameters such as tool rotational speed, welding speed tool geometry, tool tilt angle, etc. Improper choice of these process parameters lead to weld defects and poor quality of weld joint[6]. The common defects observed in FSW joints are tunnel defect, worm hole, kissing bond, pin hole and piping defect[7,8].

The above-mentioned defects severely affect the quality and strength of weld joint that lead to rejection of the product. Hence, it is imperative to study the defect formation mechanisms in Friction Stir Welding for developing defect-free joint. Leal and Loureiro[9] investigated the internal defect formation during FSW in various aluminium alloys such as 5083, 2024 and 6063. The occurrence of voids, cracks and tunnels in the weld joint was the result of injudicious selection of welding process parameters. Kim et al.[10] identified three fundamental causes for defect formation in FSW. These authors reported that both the insufficient and excess heat input during welding leads to defect build up in weld joint, which adversely affect the strength of the weld joint. These three types of defect formation can be eliminated by controlling tool rotational speed, welding speed and axial force. Shirazi et al.[11] also reported that high quality of FSW joint in aluminium 5456 can be obtained only through selection of optimum tool rotational speed and welding speed. The weld joints tend to have defects while selecting the tool rotational and welding speed outside the optimum values. Shojaeefard et al.[12] applied Taguchi method to optimize the process parameter for obtaining maximum tensile strength and hardness during Friction Stir Welding of aluminium 1100 alloy. Welding speed is the dominating process parameter that affected the ultimate tensile strength, hardness and grain size of weld joint. Vijayan et al.[13] adopted Taguchi method to optimize process parameter in FSW of dissimilar aluminium-magnesium alloy. Further the statistical operation ANOVA was performed to find the significant factor and percentage of contribution of each factor.

It is not possible to identify internal flaws such as cracks, voids, tunnels and imperfections in friction stir weld through conventional testing techniques. These flaws can be identified and characterized by non-destructive testing (NDT) techniques[14]. Non-Destructive Testing (NDT) techniques apply the principles of physics to evaluate material characteristics and internal defects without affecting the serviceability of material. Along with the above-mentioned advantage. NDT also provides highly reliable, safe and cost-effective operation. In view of these benefits, NDT plays a vital role in many industries like aerospace, railway, petrochemical, power plants and pressure vessel industries[15]. Further in NDT, it is possible to explore the whole area of the material that is to be checked for quality, unlike in destructive testings such as tensile test and bending test, where only a small area is selected for testing[16]. There are many types of NDT available for testing materials, among which the following tests like X-Ray Radiography, Ultrasonic Testing, Magnetic Particle and Liquid Penetration Testing are most widely used in industries. However, each technique has specific merits and demerits based on application and working methodology[17]. The X-ray Radiography is the most commonly used NDT technique in industries for inspecting weld joint because of its cost-effective nature and ease of operation. Besides, the presentation of internal weld defect as photo image made X-ray Radiography preferable over other NDT methods[18,19]. Further, the X-ray radiographic test can able to detect the internal defects of weld joint with more accuracy and can produce same result at any number time[20]. In spite of this, only a few researchers have carried out studies on X-ray Radiographic inspection of FSW joint to identify the internal defect and voids. Sudhagar et al.[21] investigated various types of discontinuities developed during friction stir welding of AA2024 alloy using X-ray radiographic technique. Nataka[22] used X-ray Radiographic technique to discover the presence of internal defects in friction stir welded copper and brass sheet. The weld joint without internal defect was used for mechanical and microstructural analysis. Similarly, Park et al.[19] also used X-ray Radiography to detect the generation of voids and lack of bonding during joining of 60% Cu - 40% Zn brass through FSW. The joints which qualified in radiographic test were further studied for microstructure and mechanical properties. Caligulu et al.[18] investigated the AISI 4340-2205 steel joint prepared by friction welding using X-ray Radiography. These authors reported that x-ray radiography results revealed the extent of flashes produced under different welding conditions and could optimize the best welding parameter with minimum flashes.

At present, the industries demand new technological methods for assessing quality and properties of weld joint[23]. The current NDT methods applied to evaluate the weld joint quality do not meet the industrial demands as they fail to directly correlate the NDT-results with the quality of the welded joint[24]. From the literature study, it has been found that the X-ray radiographic technique is only used for identification of internal defects in FSW joint. There is lack of report on utilizing X-ray image to select the best process parameters for FSW. This work is an attempt to fill this gap by directly employing X-ray image for process parameter selection by applying image processing technique. Further, the relation between the size of defect in X-ray image and tensile strength is created.

2. Methodology

Friction Stir Welding of 4mm thickness aluminium AA2024 alloy was carried out using Vertical Machining Centre modified for required purpose. The chemical composition of aluminium AA2024 alloy is given in table 1. The FSW tool made of heat-treated H13 tool steel with shoulder diameter of 20mm was employed for welding base material. The stir pin was designed with a tapered profile with root diameter of 6mm and length of 3.8mm. The parameters which mainly affect the FSW process are tool rotational speed, welding speed and tool offset. The rotating tool generates heat underneath the rotating tool and helps in plasticization of base material. The traverse speed of the rotating tool governs the amount of heat deposited on to the work piece. In this study, the input parameters are varied with three levels each and Taguchi Orthogonal Array Method was adopted for designing the experiments. Taguchi method is a statistical technique that is widely in engineering analysis. This method can produce a unique and powerful solution to industrial problems in economic way. This method reduced the number of experimental trials to be performed by efficiently selecting the necessary trials from full factorial design without compromising the result[25]. Table 2 gives the input process parameters and their values. The rotating tool offset from center line towards advancing side is indicated with a positive sign and offset towards opposite side is indicated with a negative sign. The ranges of input process parameters were selected based on literature study and pilot experiments. Pilot experiments had showed that tool rotational speed below 600 rpm and welding speed above 120 mm/min were not able to join the metals. Likewise, tool rotational speed above 1000 rpm and welding speed below 60 mm/min were found to produce excessive amount of flash during welding. The steps and methods adopted in this study and experimental setup are represented pictorially in in fig 1a&b.

Table 1: Chemical Composition of Aluminium AA2024 Alloy

Elements	Al	Cu	Mg	Mn	Others
%	93.33	3.85	1.66	0.48	0.68

Table 2: Input Process Parameters

Parameter	**Level I**	**Level II**	**Level III**
Tool Rotational Speed (rpm)	600	800	1000
Welding Speed (mm/min)	80	100	120
Tool Offset (mm)	-1	0	+1

After welding experiments, all the specimens were visually inspected for locating surface defects. Subsequently, the specimens were subjected to X-ray Radiography test to reveal the internal defects that might have occurred during welding process. The radiographic test was conducted by following the standard ASTM E94 [26] using the Yxlon radiographic machine. A 150kV X-ray radiation source was used for testing the weld joints. The radiographic images of weld joints were captured through single wall single image technique in a D4 type film. The weld samples were exposed to the radiation for a period of 30 seconds for revealing internal discontinuities. The defect image captured in X-ray film was digitized using a charge coupled device camera. The X-ray film was placed on film viewer which illuminates light from behind. The light illumination on film makes it to clearly depict small details from X-ray film. These information from film were captured and convert into digital form through charge coupled device camera. All the images were captured at same zoom level and camera setting. The

MATLAB software package was used to generate the algorithm for digital image processing to calculate area of defect from radiographic image. Details of image processing algorithm are explained in the following section. The defect area estimated through image processing was used as response for selecting best input process parameters that gives minimum defect area.

All the weld joints were subjected to tensile strength in order to understand the effect of defect size on the strength of weld joint. Two tensile specimens were cut from each weld sample, perpendicular to direction of welding. The samples were cut using wire electrical discharge machine with the dimension specified in ASTM E8 [27] standard.

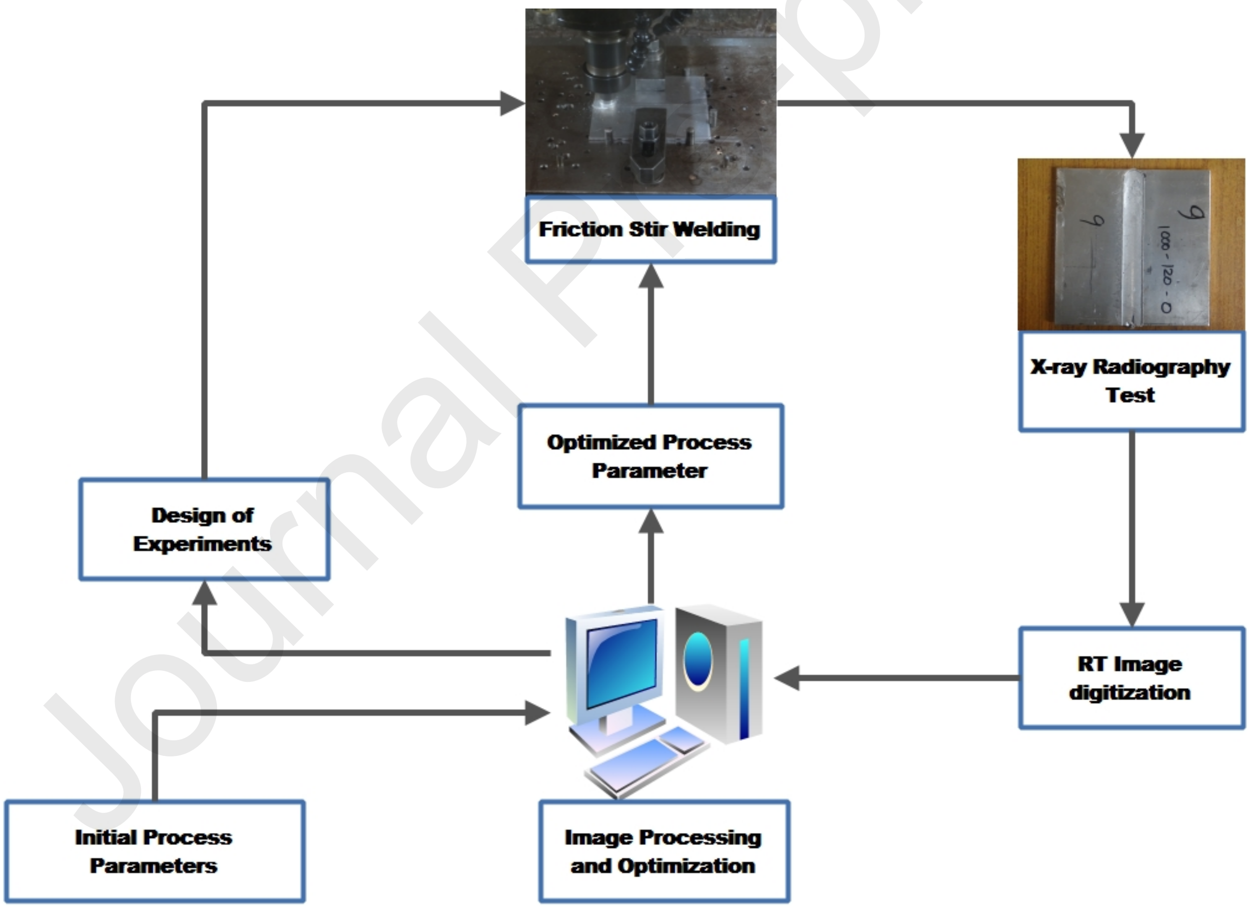


Fig 1(a) Proposed friction stir welding process evaluation method using NDT

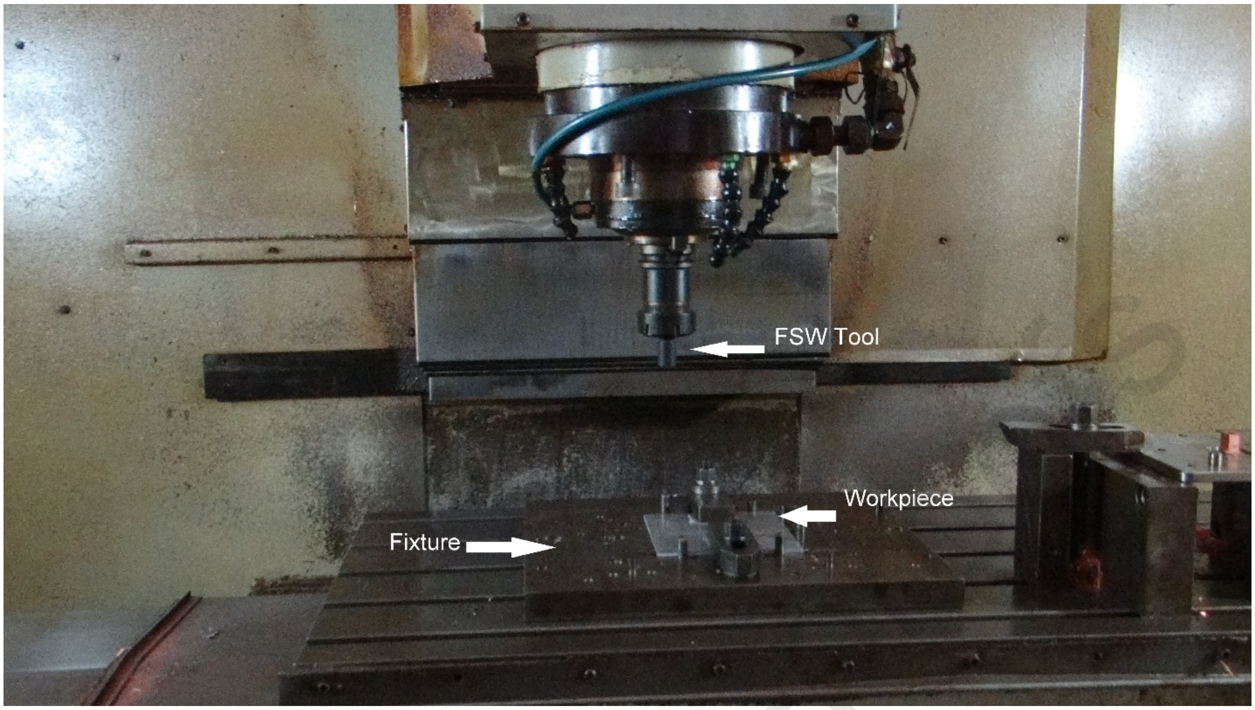


Fig1(b) Experimental setup

2.1. Image processing

Image processing is a technique in which the digital image of an object is used to extract features of the object. Various operations are involved in image processing which are illustrated in fig 2. The preliminary stage in image processing comprises grayscale conversion, noise filtering and resizing. The noises in image, caused by various uncontrollable factors were removed by applying median filtering technique. The median filter is a commonly used noise filter in digital image processing because it conserves edges while removing noise from image. In median filter, the value of noisy pixel is replaced by the median value of neighborhood pixels in the digital image. Afterwards, Region of Interest (ROI), that is the region in the image from which the required data is to be extracted, is selected. In this study, the ROI is the region showing defect in radiography image that is shown in fig 2. Subsequently Thresholding technique is used to convert the gray image into binary image. During Thresholding, intensity of all pixels in image is compared with threshold value k, the pixel value above threshold k is set to 1 and the remaining pixels are set to value 0. The binarization of image can be expressed using the equation.

$$B(x,y) = \begin{cases} 1 & if\ f(x,y) \geq k \\ 0 & otherwise \end{cases} \quad (1)$$

Where $B(x,y)$ is the binary value of the pixel in image, $f(x,y)$ is the gray scale value of pixel in image and k is threshold value. The threshold value k for each image was calculated through Otsu's method, which minimize the intraclass variance of black and white pixels.

The binary image consists of only black and white pixels. In order to measure the area of defect from binary image, the number of white pixels in the image was counted. The area of defect estimated from each image is listed in table 3. The calculated area is used as response for selecting the process parameters that produce minimum defect area and maximum strength.

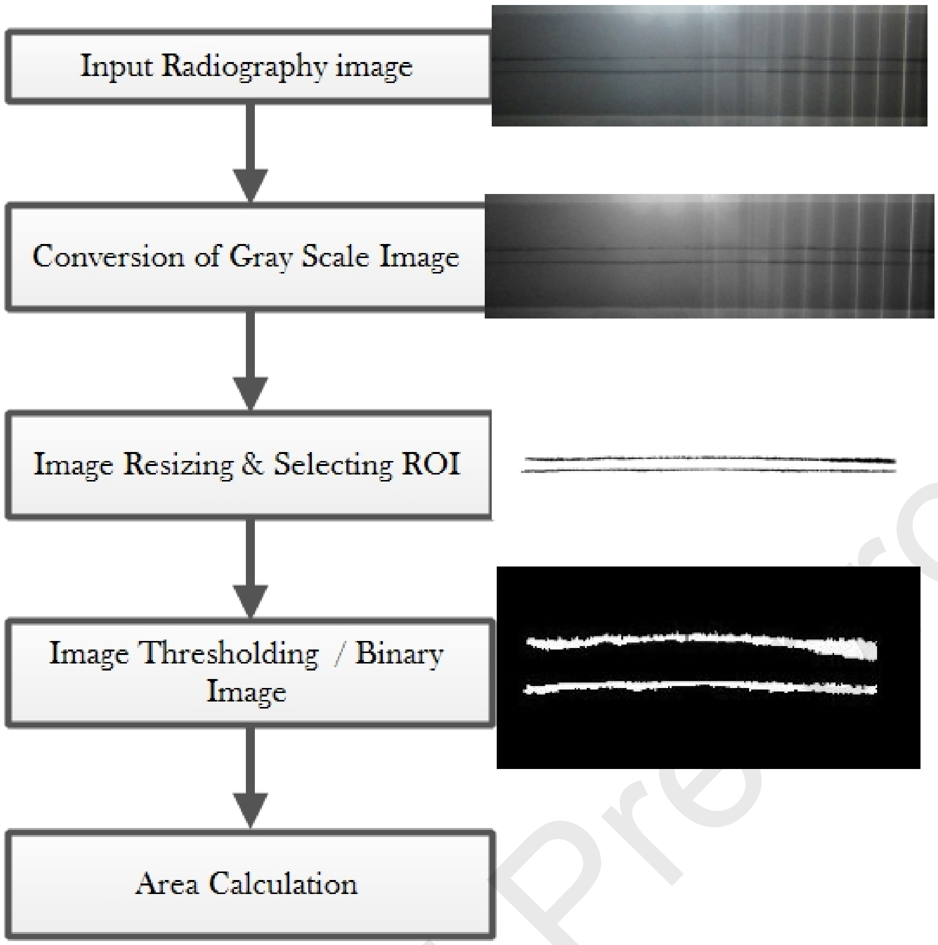


Fig 2 Steps involved in image processing

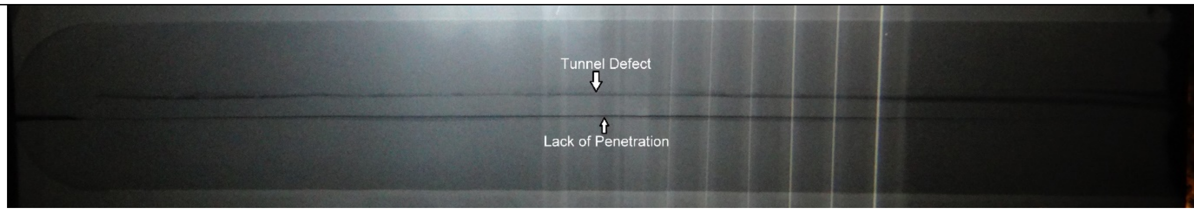
3. Result and Discussion

3.1. Radiography Test

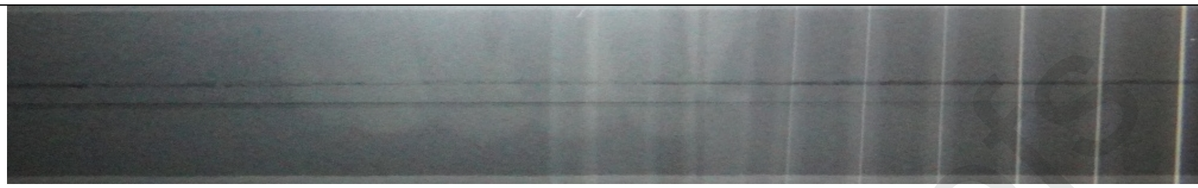
X-ray Radiography Test is used to expose the defects formed internally during welding process. In Radiography Test (RT), the lack of material inside work piece is indicated as dark spot in X-ray film. In all RT image the topside is advancing side and bottom is retreating side. The fig 3 shows the RT image of various weld joints produced at different welding conditions. Cross-sectional samples of weld joints were prepared to identify the type of defects and the common defects observed were tunnel-hole defect and lack of penetration. In image 3a, two dark lines appeared in which the top line represents tunnel hole inside joint and bottom line represents lack of penetration as it presents along butt line of joint. The insufficient heat generated by the rotating tool may be the reason for formation of tunnel defect inside the weld joint. Due to insufficient heat generation less material is plasticized by the rotating tool which is not enough to fill the gap produced by the stirring pin. The tunnel defect occurs in advancing side because the material is transported from retreating side to advancing side [28].

The lack of penetration is created in joint when the rotating tool is not positioned properly. The lack of penetration shown in RT image (fig 3a & fig 3b) is formed when the rotating tool is positioned at advancing side of joint. The lack of penetration is not found when the rotating tool is positioned at butt line or at retreating side of joint, which is shown in fig 3c & fig 3d. Figure 3d shows the image of weld joint 4, where the size of dark line in RT image is reduced when compared with RT image of weld joint 3 (fig 3c). This indicates that the weld joint 4 possesses smaller sized tunnel hole than weld joint 3. As seen from table 3, the weld joint 4 had been produced with higher tool rotational speed and lower welding speed than weld joint 3. The increase in tool rotational speed increases the heat generation due to friction between tool and workpiece. Further at higher tool rotational speed, the stain rate of work material will be more, resulting in extra plasticization of material for transportation [29]. The slower welding speed results in higher heat input to the work-piece due to longer contact time between tool and workpiece [30]. The same trend of defect size is observed from RT image of weld joint 6 & 8 shown in fig 3a & fig 3b.

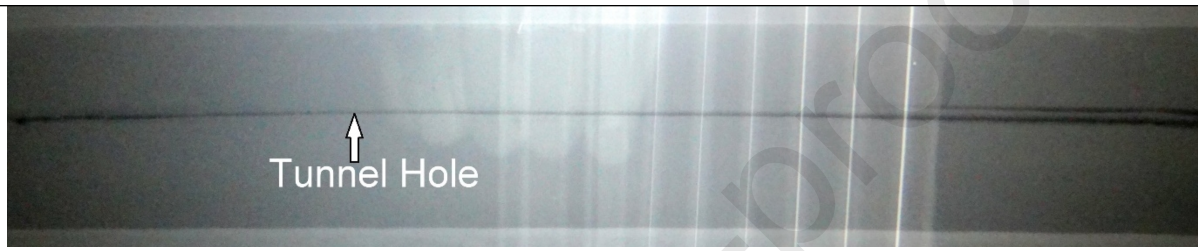
a)



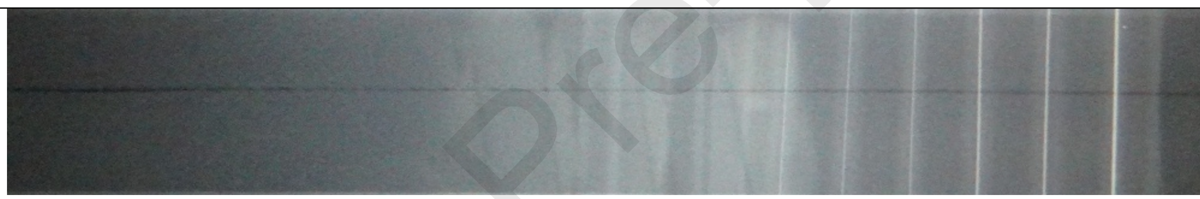
b)



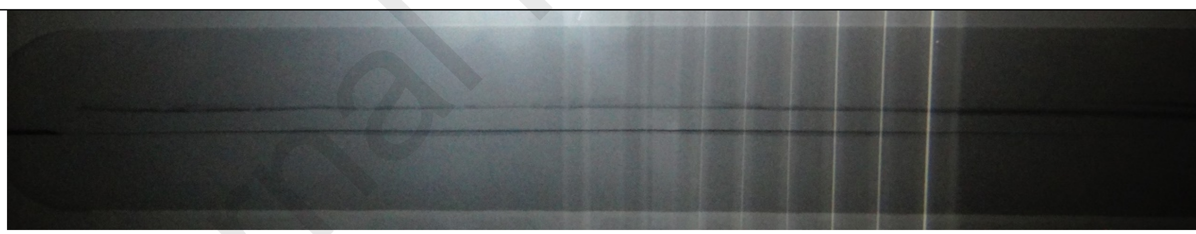
c)



d)



e)



f)

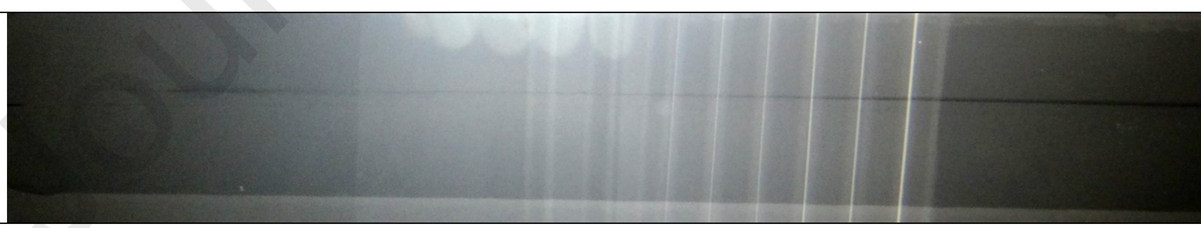


Fig 3 X-ray Radiography Image of a) weld joint 6, b) weld joint 8, c) weld joint 3 d) weld joint 4, e) weld joint 2, f) weld joint 7,

The size of defect occurred inside determines the strength of weld joint. In order to gather knowledge about effect of size of internal defect on strength of weld joint, all the specimens were subjected to tensile test. The tensile test result of each joint is listed in table 3. From the result, weld joint 7 is found to have the maximum tensile of 241.36 MPa and the corresponding radiographic image is seen to have the minimum area of defect. On the other hand, radiographic image of the weld sample 6 with the lowest tensile strength of 101.93 MPa is seen to have the maximum defect area. The above results clearly indicate the direct correlation between defect area of the weld zone with the tensile strength. The relation between tensile strength and area of defect is depicted in fig 4. It is clearly seen that tensile strength varies inversely as the area of defect. In other words, the larger the area of defect in a weld joint the lower is the corresponding tensile strength.

3.2. Selection of best Process Parameters

The area of defect obtained from RT image through image processing is recorded in table 3. From the result it was found that maximum defect area of 2016.30 pixel occurred for experimental trail 6 and minimum area of 968.75 pixel is obtained for experimental trial 4. The aim of the study is to minimize the formation of defect during Friction Stir Welding and maximizing tensile strength of joint, hence the method 'smaller is better' is selected for area of defect and 'larger is better' is selected for tensile strength for calculating S/N (Signal-to-Noise) ratio in Taguchi analysis. The following formula is used for calculating S/N ratio.

$$\text{(Smaller is better)}\ \frac{S}{N} = -10\log\left(\frac{\sum y_i^2}{n}\right) \quad (2)$$

$$\text{(Larger is better)}\ \frac{S}{N} = -10\log\left(\frac{\sum (1/y_i^2)}{n}\right) \quad (3)$$

Where y is the measured response value and n is number of test

The main effect plot for S/N ratio of area of defect and tensile strength is given in fig 5a & 5b. The plot fig 5a depicts that increase in tool rotational speed decreases the area of defect formation. This may be because of more heat generated at increased tool rotational speed that leads to better weld quality [7]. Further the increase in rotational speed increases the strain rate of aluminium which produces enough plasticized material to close the pore created by stirring pin of tool [31]. The opposite trend is observed for welding speed, as increase in welding speed generates more area of defect. At higher welding speed the tool travels quickly, hence the time of contact between workpiece and tool is less. The lesser time of contact results in lower heat input per unit volume of material which causes defect in joint [4]. In Taguchi method the best set of process parameter can be identified from main effect plot. It is evident from fig 5a that tool rotational speed of 1000 rpm, welding speed of 80 mm/min and tool offset at 0 mm (at the center of butt line of joint) are the best process parameters which produce lower defect area. Similarly, it can be seen from fig 5b that the parameters that yield the lowest defect area give the highest tensile strength of the weld joint. This clearly shows that the strength of joint directly depends on the size of the internal defect formed.

Table 3: Experimental trials with output response

SlNo	**Rotational Speed (rpm)**	**Welding Speed (mm/min)**	**Tool Offset (mm)**	**Estimated Area of defect (pixels)**	**Tensile Strength (MPa)**
1	600	80	-1	1598.80	136.1±2.6
2	600	100	0	1623.63	142.98±0.9
3	600	120	1	1956.90	115.15±2.6
4	800	80	0	968.75	201.9±2.4
5	800	100	1	1447.50	157.21±1.5

6	800	120	-1	2016.30	101.93±1.6
7	1000	80	1	998.80	241.36±3.8
8	1000	100	-1	1510.80	157.87±1.7
9	1000	120	0	1345.90	168.6±2.1

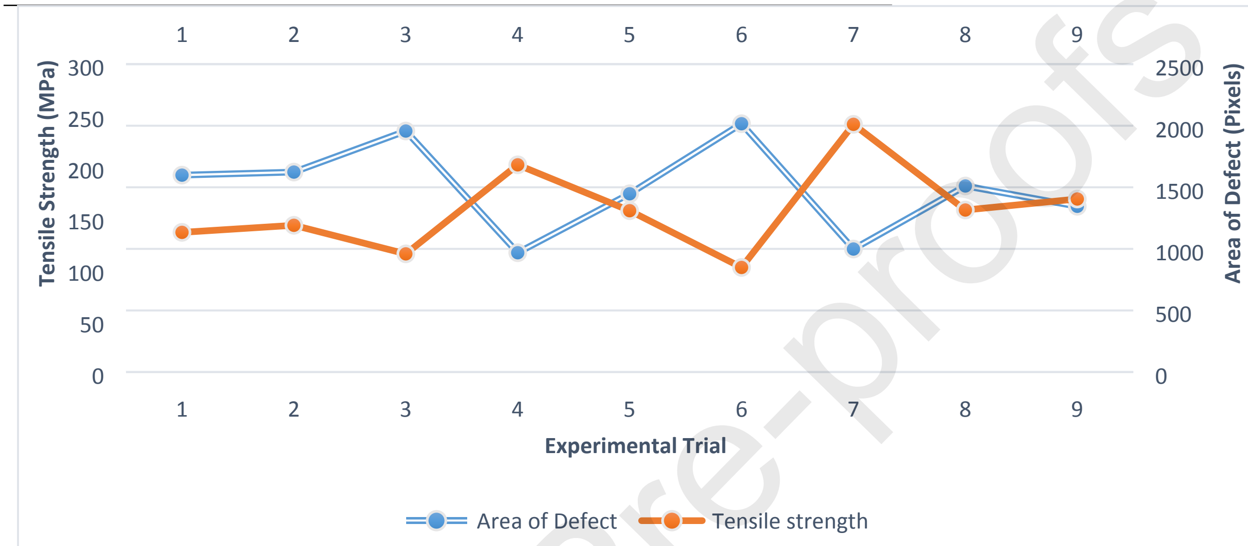
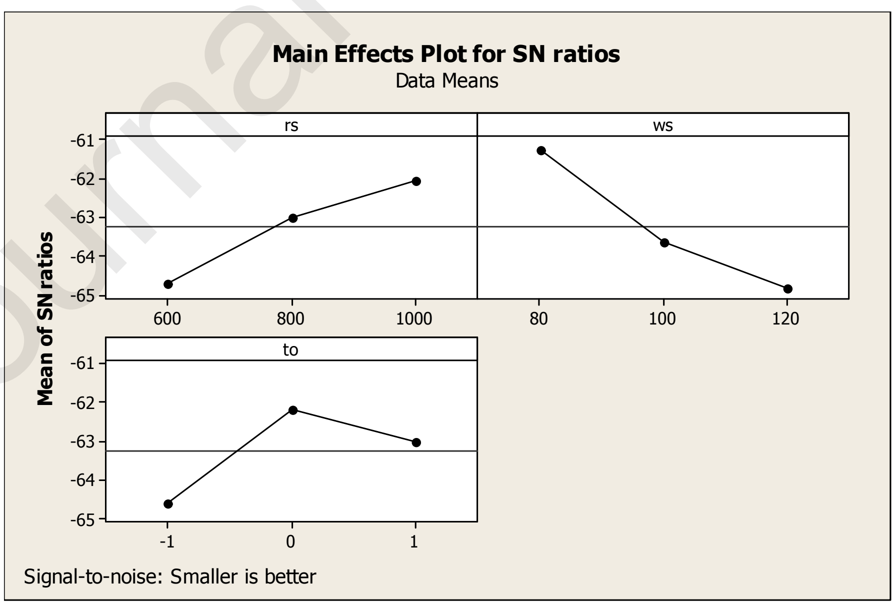
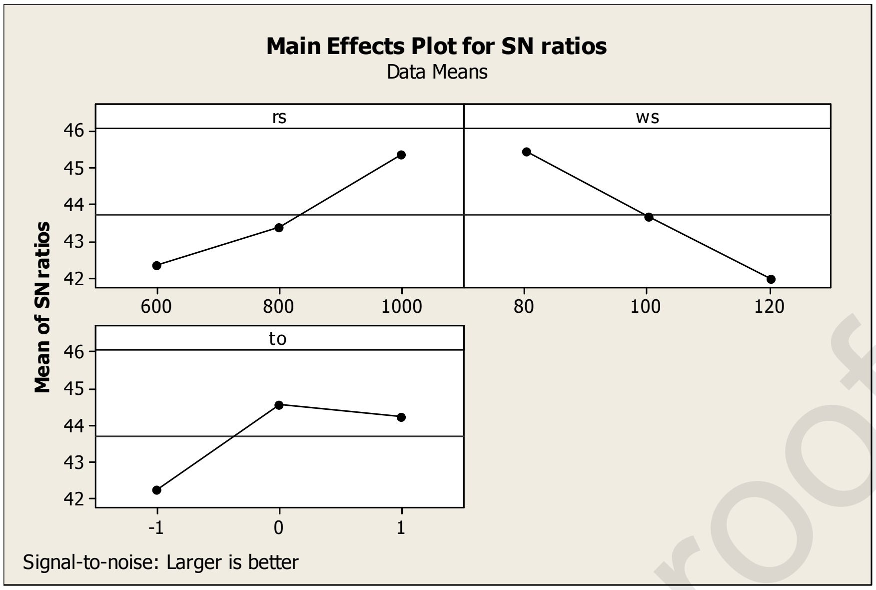


Fig 4 Comparison of Tensile Strength and Area of Defect



a)



b)

Fig 5 Main effect plot for S/N ratio a) Area of defect b) Tensile strength

rs - tool rotational speed, ws - welding speed and to – tool offset

Analysis of Variance (ANOVA) is performed to evaluate the significance of each process parameter on output response[25]. Table 4 shows the ANOVA result for area of defect from X-ray image at 95% confidence level. It depicts that all input process parameters significantly affect the area of defect since the F-test value of each parameter is larger than standard value. Further the P-value also confirm the same since all the parameters have P-value less than 0.05%. The percentage of contribution of each parameter on response can be calculated using Seq SS. Welding speed contributes 48.69% on defect formation during Friction Stir Welding followed by rotational speed with 27.69% of contribution and finally tool offset contributes 22.51% on defect formation. The percentage of contribution of error in experiments is very less i.e. 1.08%.

Table 5 shows the ANOVA result for tensile strength at 95% confidence level. The P-value of all the input parameters are less than 0.05 which indicates that all input process parameters have significant effect on tensile strength. The percentage of contribution of each parameter on tensile strength are rotational speed contributes 34.83%, welding speed contributes 43.51% and tool offset contributes 20.97%. Error contributes 0.6% on tensile strength, this indicates that very small errors occurs during experimentation. Analysis of variance clearly shows that welding speed is the most dominating parameter that affects the weld-quality, followed by rotational speed and tool offset in that order.

Table 4: Analysis of Variance for Area of defect, using Adjusted SS for Tests

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**% contribution**
Rotational Speed	2	293686	293686	146843	25.50	0.038	27.69
Welding Speed	2	516328	516328	258164	44.83	0.022	48.69
Tool Offset	2	238767	238767	119384	20.73	0.046	22.51
Error	2	11516	11516	5758			1.08
Total	8	1060297					

Table 5 Analysis of Variance for Tensile strength, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% contribution
Rotational Speed	2	5111.6	5111.6	2555.8	51.6	0.019	34.83
Welding Speed	2	6384.9	6384.9	3192.5	64.46	0.015	43.51
Tool Offset	2	3078.5	3078.5	1539.3	31.08	0.031	20.97

Error	2	99.1	99.1	49.5			0.6
Total	8	14674.1					

DF – Degrees of Freedom, Seq SS – Sequential Sum of Square, Adj SS- Adjusted Sum of Square, Adj MS – Adusted Mean Square, F – F test

4. Confirmation Test

According to Taguchi method, the best process parameter that produce higher tensile strength and lower defect is tool rotational speed of 1000rpm, welding speed of 80mm/min and tool offset at 0mm from center line. In order to validate this finding, an experiment was conducted with these input process parameters and the weld joint was subjected to radiographic test and tensile test. From the X-ray radiographic image of the weld joint shown in fig, it has been found that the size of tunnel defect gets reduced compared with other previous experiments. Further the tensile strength of weld joint was 288.9±1.2MPa which is far higher than the tensile strength of previous experiments. This confirms that process parameter obtained through Taguchi method would produce better result.

Fig X-ray Radiographic image of weld joint produced at best process parameter from Taguchi method.

5. Conclusion

The major conclusion arrived through this study are as follows.

- Radiographic image can be used for quantitative assessment of FSW process by applying image processing technique.
- The size of the internal defect possess inverse relation with tensile strength i.e. larger the internal defect size, lesser the tensile strength of weld joint.
- By Taguchi method, the process parameters that yield minimum defect size in weld joint and maximum tensile strength are tool rotational speed of 1000 rpm, welding speed of 80 mm/min and tool offset at 0 mm from centre line.
- ANOVA was used to predict the dominating process parameter for defect size formation and tensile strength. It was found that the welding speed contributes 48.69% on defect size formation followed by tool rotational speed and tool offset contribute 27.69% and 22.51% respectively. For tensile strength welding speed, tool rotational speed and tool offset contributes 43.51%, 34.83% and 20.97% respectively.
- ANOVA test result confirms that the proposed method for quality assessment in FSW using radiographic image is reliable and can be implemented in industries.

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Conflict of Interest and Authorship Conformation Form

Please check the following as appropriate:

- o All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

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- A novel method is proposed to select best FSW parameter using X-ray radiography.
- Image processing is applied to extract area of defect from X-ray image.
- The tensile strength is inversely proportion to size of internal defect.
- Taguchi method is used to study the effect of FSW parameters on defect size.