Fatigue Life Assessment of 9mm Thickness Low Carbon Steel with Multi-Objective Optimized Welding Process

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ABSTRACT

Gas Metal Arc Welding (GMAW) is one of the popular methods in joining metal in manufacturing industries. However the transient thermal stresses and non-uniform distribution of elastic strains is produced by the weld causes residual stresses and distortion, thus affecting the fatigue performance of the welded structure. The used of Robotic Welding (RW) allows this welding process parameters to be controlled significantly to improve the welding quality. First, Multi-Objective Taguchi Method (MTM) were used to analyse optimum parameters value which started application of common Taguchi methods (L8) Orthogonal Array (OA) and Total Normalized Quality Loss (TNQL) followed by ANOVA under simultaneous consideration response factors. The value was furthermore analysed by applying Multi-Signal to Noise Ratio (MSNR). The two (2) optimize welding parameter ranges are selected to be used for fatigue life assessment on the 9 mm plate which is labelled as set A and B. Tensile test was carried out on the specimen prior to fatigue testing to know the value of yield strength and UTS of the specimens. The fatigue test was carried out on three (3) type of specimen with one sample without any welding as controlled specimen. It can be concluded that welding parameters of set A is more superior for fatigue performance of this 9 mm low carbon steel plate.

Keywords: *Fatigue Life, Optimization, GMAW*

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Introduction to Welding Process and Fatigue Assessment

Fusion welding process is joining metal by coalescing the metal by means of heat. Gas Metal Arc Welding (GMAW) is a common welding process used in many fabrication and manufacturing industries [1]. The heat generated by a welding arc from the continuous filler metal electrode and the workpiece. During the GMAW process, the heated metal expands and bend in all directions, causing distortions on the workpiece. Out of plane distortion or better known as angular distortion is one of common defect by GMAW process.

The simplicity of the GMAW process allows it to be supported by Robotic Welding (RW) to produce welding movements and speed at high precision and reproducibility. Furthermore, other welding parameters, for instance welding current, voltage, feeding rate and weaving can be control compared to conventional manual welding process [2]. The understanding of these parameters interrelationships between bead geometry and induced distortion is essential in producing sound welding process with desired welding qualities. In addition, welding defect such as Lack of Penetration (LOP) and undercut may occur due to inaccurate welding parameters.

In this study on finding the optimum welding parameters, Taguchi method can conveniently applied with orthogonal array design from Design of Experiment (DOE). Past research was carried out by focusing on single quality optimization, thus this research is carried out by applying Multi Objective Taguchi Method (MTM) to optimize multiple welding quality characteristic which is Undercut and Distortion.

When the welding process is completed, the welded component in use, is subjected to cyclic loading which will lead to fatigue failure. Therefore, Fatigue Assessment on the welding joint are essential to evaluate the fatigue life of welded component. In welding joint, the stress concentration point at the weld toe are the main contributor to fatigue failure. The compressive residual stress developed during the heating and cooling of welding process is in favour of fatigue life while the tensile residual stress will limit the fatigue endurance of a structure [3].

Experimental Setup and Parameters Optimization

The experimental study for the parameter optimization was carried out using ABB Robotic Welding System IRB 2400/16 to control the welding process parameters. Figure 1 shows the experimental setup and workpiece dimensions for optimization of welding parameters.

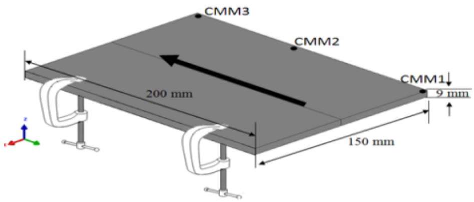

Figure 1: Experimental Setup for 9-mm Low Carbon Steel

Generally, Taguchi method is a robust technique and statistical analysis for process parameter optimization. It requires the matrix formation for DOE to experiment performed as an orthogonal array (OA) [4]. In this method, experimental data were analysed and significant parameters were identified using the Signal-to-Noise Ratio (SNR). The preferred welding process parameters for this study are Current (I), Voltage (V), Welding Travel Speed (mm/s) and width of welding weaving are presented in this study. Two levels for every factor (low and high) were established from the basis preliminary study on a series of experiments conducted. In the research, the distortion (DTN) and Undercut (UC) of the welded plates is to be kept at minimum as possible. Therefore, "smaller is better" from SNR had been applied and SNR type empirical formula is shown as Eq. (1) [5]:

$$SNR = -10 \log_{10} [QLF]$$

Then, quality loss functions (QLF) for smaller is better type is:

$$QLF = \frac{\sum_{i=1}^{n} y_i^2}{n} \quad (2)$$

y_i is the value of data response, ith is the number of experiment and n shown as the total number of experiments. In Multi-objective Taguchi Methods (MTM), each response data required to calculate the quality characteristic in order to obtain the signal to noise separately. The sum up of signal to noise ratio is known as multiple SNR (*MSNR*). The *MSNR* can be calculated using equation below [6]:

$$MSNR = -10 \log_{10} [Y_j] \quad (3)$$

$$Y_j = \sum_{i=1}^{k} w_i y_{ij} \quad (4)$$

$$y_{ij} = \frac{L_{ij}}{L_{i^*}} \quad (5)$$

where Y_j is the total normalized quality loss in jth trial, w_i represents the weighting factor for the ith quality characteristic, k is the total loss value and y_{ij} is the normalized quality loss with ith quality characteristic at the jth trial. The variation of normalizing quality loss characteristic is from zero to the maximum of 1. L_{ij} is the quality loss of quality characteristic at jth trial, and $L_{i^*}$is the maximum quality loss for the ith quality characteristic among all the experiment runs.

Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is used to develop a mathematical model and to analyse problems using a collection of mathematical and statistical technique where several variable influence the response of interest while the objective is to optimize this response. The response is also known as the performance measure or quality characteristic and the input variable is also known as independent variables. The RSM scope consists of: (1) Independent Variables or experimental strategy for exploring the space of the process, (2) Empirical statistical modelling to develop approximating relationships between yield and process variables, and (3) optimization method for finding the variables values that would produce the desirable response value. In this research, the experiment is focused on developing an approximate model between input variables (ampere, voltage, speed and waving speed) and responses (distortion and undercut) and finding the optimum parameters level. These relationships can be defined as:

$$y = f(A, B, C \dots) \tag{6}$$

Table 1 shows the variables input, factor and level for this experiment. It also shows the experimental runs, which followed the parameters ranged in OA without any repetition. For this research result of Distortion and Undercut, there are as two (2) main responses.

Table 1: Factor and Level for 9 mm Low Carbon Steel welding

Symbol	**Factors**	**Unit**	**Level 1**	**Level 2**
A	Welding current 1	A	130	150
B	Welding voltage 1	V	18	20
C	Travel speed 1	mm/s	5	7
D	Weaving width 1	mm	2	4
E	Welding current 2	A	140	160
F	Welding voltage 2	V	17	21
G	Travel speed 2	mm/s	3	5
H	Weaving width 2	mm	4	6
I	Welding current 3	A	140	160

J	Welding voltage 3	V	17	21
K	Travel speed 3	mm/s	3	5
L	Weaving width 3	mm	4	6

Table 2: L-16 Orthogonal Array (OA)

Exp. No.	**Factor Level**											
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2
4	1	1	1	2	2	2	2	2	2	2	2	1
5	1	2	2	1	1	2	2	1	1	2	2	1
6	1	2	2	1	1	2	2	2	2	1	1	2
7	1	2	2	2	2	1	1	1	1	2	2	2
8	1	2	2	2	2	1	1	2	2	1	1	1
9	2	1	2	1	2	1	2	1	2	1	2	1
10	2	1	2	1	2	1	2	2	1	2	1	2
11	2	1	2	2	1	2	1	1	2	1	2	2
12	2	1	2	2	1	2	1	2	1	2	1	1
13	2	2	1	1	2	2	1	1	2	2	1	1
14	2	2	1	1	2	2	1	2	1	1	2	2
15	2	2	1	2	1	1	2	1	2	2	1	2
16	2	2	1	2	1	1	2	2	1	1	2	1

For calculating TNQL and MSNR multiple quality characteristic distortion and undercut has been calculated using Equation 3. Two unequal weights were assumed for calculating TNQL. The assumed weight for distortion is w_1=0.2 and undercut is w_2=0.8. Table 3 shows the value of OA, QL, NQL, TNQL and MSNR for 9 mm plate.

Table 3: OA, QL, NQL, TNQL and MSNR for 9 mm plate

Exp. No.	**Response**		**Quality Loss (QL)**		**Normalize QL**		**TNQL**	**MSNR (dB)**
	DTN	**UC**	**DTN**	**UC**	**DTN**	**UC**		
1	4.627	1	21.405	1	0.065	0.050	0.115	9.391
2	5.318	1	28.277	1	0.086	0.050	0.136	8.666
3	4.711	2	22.190	4	0.067	0.200	0.267	5.728
4	5.619	1	31.569	1	0.096	0.050	0.146	8.358
5	4.725	4	22.322	16	0.068	0.800	0.868	0.616
6	4.611	2	21.258	4	0.065	0.200	0.265	5.774

7	5.305	4	28.139	16	0.086	0.800	0.886	0.528
8	4.727	1	22.341	1	0.068	0.050	0.118	9.285
9	4.893	1	23.938	1	0.073	0.050	0.123	9.109
10	4.595	1	21.110	1	0.064	0.050	0.114	9.425
11	8.104	2	65.668	4	0.200	0.200	0.400	3.984
12	8.112	2	65.798	4	0.200	0.200	0.400	3.979
13	4.713	1	22.209	1	0.068	0.050	0.118	9.299
14	5.305	4	28.139	16	0.086	0.800	0.886	0.528
15	5.463	1	29.840	1	0.091	0.050	0.1407	8.517
16	4.813	3	23.161	9	0.070	0.450	0.5204	2.837

Table 4: Multiple S/N Response (Average Factor at Different Levels)

Symbol	**Factors**	**Level 1**	**Level 2**	**Optimum Parameters**
A	Welding current 1	0.6043*	0.596	130
B	Welding voltage 1	0.7330*	0.4673	18
C	Travel speed 1	0.6665*	0.5337	5
D	Weaving width 1	0.6601*	0.5402	2
E	Welding current 2	0.547	0.6532*	160
F	Welding voltage 2	0.7220*	0.4783	17
G	Travel speed 2	0.5707	0.6295*	5
H	Weaving width 2	0.5896	0.6106*	6
I	Welding current 3	0.4129	0.7874*	160
J	Welding voltage 3	0.5829	0.6173*	21
K	Travel speed 3	0.7675*	0.4328	3
L	Weaving width 3	0.6609*	0.5394	4

* Optimum level for Distortion and Undercut

From the two (2) levels of welding the optimum parameters from each weld pass. The optimum factors for response optimizer are welding current 1 (130 A), welding voltage 1 (18 V), travel speed 1 (5 mm/s), width of weaving 1 (2 mm), welding current 2 (160 A), welding voltage 2 (17 V), travel speed 2 (5 mm/s), width of weaving 2 (6 mm), welding current 3 (160 A), welding voltage 3 (21 A), travel speed 3 (3 mm/s) and width of weaving 3 (4 mm/s).

The essential final steps is to verify the MTM suggested optimum parameters by conducting the Experiment and measure the distortion and undercut as the response confirmation. Table 5 shows the experimental verification result.

Table 5: Result of Verification Experiment for MTM optimized parameters

Number of Run	Distortion	Undercut
1st	4.553	1
2nd	4.501	1
Average	4.527	1

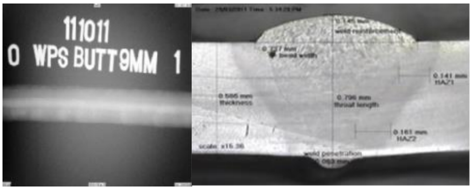

Figure 2: Digital X-ray and Macrograph

Figure 2 shows the X-ray and Macrograph that were carried out for the sample of experimental 9 mm butt joint workpiece. Table 6 shows optimized welding parameters for 9 mm low carbon steel for each pass. The result shows that optimized parameters were Current 130-165 A, Voltage 18-21 V and Traveling speed 3-5 mm/s. These welding parameters were obtained from analysis by mean MINITAB and further verified by experimental procedure.

Table 6: Optimized Welding Parameters for 9 mm Low Carbon Steel

Weld Pass	Current (A)	Voltage (V)	Travel Speed (mm/s)	Weaving width (mm)
Root	130	18	5	2
Hot	160	17	5	6
Capping	160	21	3	4

Tensile Test on Welded Specimen

Based on the optimised welding parameters in Table 6, two (2) sets of welding parameters are selected for fatigue analysis experiment. The parameters used are set A and B with 2 specimens for each parameter. Table 7 shows the welding parameters used for this experiments. Specimen 3 and 4 was labelled under parameters of set A and Specimen 1 and 2 was under parameters set B. Fractured specimen are shown in Figure 4 and 5.

Table 7: Welding Parameters for Set A and Set B.

Welding Parameter	**Root pass**		**Hot pass**		**Capping**	
	A	**B**	**A**	**B**	**A**	**B**
Current (A)	120-160	90-170	120-170	100-170	120-180	100-180
Voltage (V)	18	18	20	18	21	18
Wire speed (m/min)	3.8	3.9	4.0	3.9	4.2	3.9
Weld speed (mm/s)	6		4		2	

Tensile test was carried out on selected four specimens of the welding process. Figure 3 shows the Stress-Strain curve obtain from the tensile stress for each specimen for set A and B.

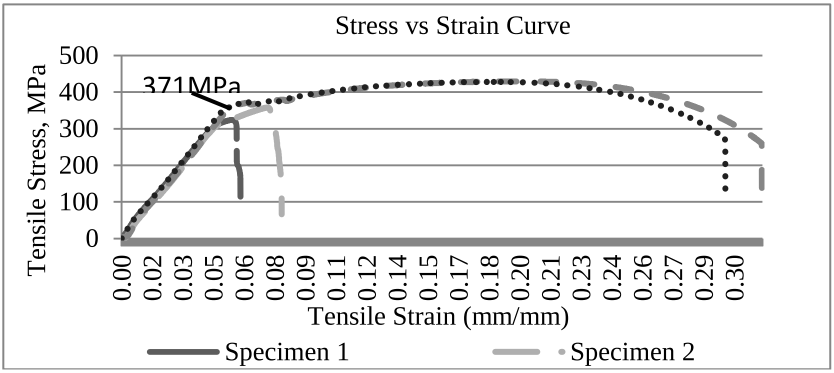

Figure 3: Stress-Strain Graph of Specimen 1, 2, 3 and 4.

Specimen from set B shows that fracture occurs at load below 350 MPa while specimens from set A fracture at 371 MPa. Both specimens from set A have Ultimate Tensile Strength (UTS) of 427 MPa. Figure 4 show the fracture line for set A and B. Specimen of set A shows fracture line outside the weld line and set B shows fracture at the weld line.

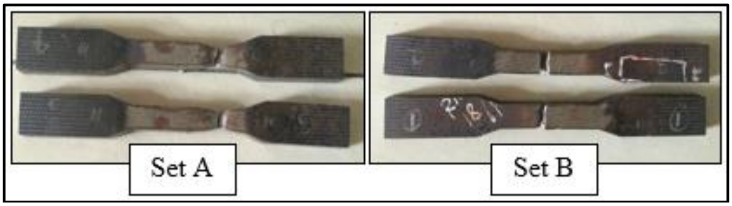

Figure 4: Fracture line from the Tensile Test

Fatigue Life Assessment

Three sets of specimens were set for fatigue testing. The sets are set A, B and Base. The set A and B are the specimen with welding parameters shown before (Table 7). For the set Base which the specimen was taken from the same base metal without any welding process. The Figure 4 shows the result fracture line attain from Fatigue Life experiment for Set A, B and Base.

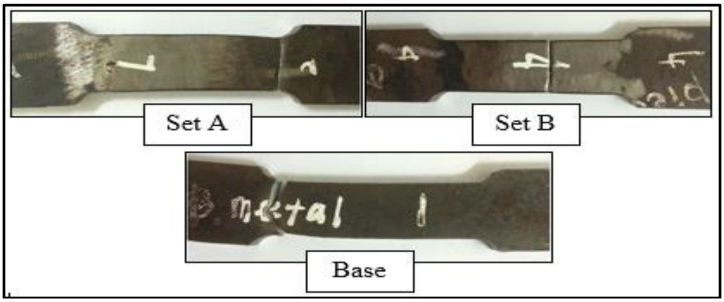

Figure 5: Fatigue Life Fracture on Set A, B and Base specimen.

Table 8 shows the fatigue life failure cycle for 9 mm low carbon steel. The specimen from set A, the fracture occurs at the base metal away from the weld line at a cycle of 27080. For set B, the fracture occurs close to weld line at a lower cycle of 3856. For final specimen, Base, the specimen fracture at the neck of the specimen which is almost similar to set A, however the cycle was higher at 56990.

Table 8: Fatigue Life Failure Cycle

Specimen	**No of Cycles**
Set A	27080
Set B	3856
Base Metal	56990

From the Fatigue Life Experiments it shows that set A fatigue failure was significantly high compare to set B. Hence it can conclude that welding parameters from set A can be used for improving the fatigue life of this 9 mm low carbon steel.

Conclusion

From this study, it can be concluded that by applying MTM with orthogonal array samples created from Taguchi design, robotic welding for 9 mm low carbon steel optimum parameters can be analysed. The results were further analysed by fatigue assessment. From the calculated result shown in Table 6, welding parameters chosen for set A which shows in Table 7, was selected as the optimum parameters for 9 mm Low Carbon Steel plate. Table 9 shows the optimized welding parameters and the Fatigue Analysis result for set A. For future work, this parameter will be used to evaluate the fatigue life assessment of low carbon steel at different stress level.

Table 9: Set A Welding Parameters and Fatigue Analysis Results.

Welding Parameter	**Root pass**	**Hot pass**	**Capping**
Current (A)	120-160	120-170	120-180
Voltage (V)	18	20	21
Wire speed (m/min)	3.8	4.0	4.2
Weld speed (mm/s)	6	4	2
Fatigue Test (Cycles)	27080		

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