Morphology and Optimisation of Impact Energy of Weldment of High Strength Low Alloy Steel

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Abstract— Morphology and optimisation of impact energy of weldment of low alloy-high strength steel were investigated in this work. The study involved the use of design of experiment via Taguchi method based on three variables, each having three levels. Minitab 16 software was used for the analysis of variance (ANOVA) and signal to noise (S/N) ratio of the impact energy. Direct current electrode positive (DCEP) was used in the electric manual metal arc (MMA) welding. The input parameters at the three levels were current (60 A, 70 A, and 80 A), metal thickness (5 mm, 7 mm, 9 mm) and root gap (2.0 mm, 2.5 mm, 3.0 mm). It was found that the input variables significantly affected the microstructure of the weldment in all the nine experiments conducted. Optimization of welding parameters was carried out to obtain the optimal input values required to give the optimal impact energy of weldment. The optimal values for the input values were 80 A for current, 9 mm thickness and 2.5 mm root gap and these were substituted in the regression equation to obtain the optimal impact energy. It was equally observed that the input variables affected the microstructure of each of the nine samples.

Keywords— ANOVA, Current, Impact Energy, Optimisation

1 Introduction

The importance of welding in production and manufacturing industries cannot be overemphasized due to its wide applications in industrial developments. Welding is an important process in engineering with probably the widest application in metal joining and production, spanning well over two millennia (Amstead and Ostwald, 1987). Engineers, scientists and researchers have always striven to come up with improved welding methods using the right parameter combinations with the aim to overcome various challenges encountered in welding processes; as a result there are numerous welding processes and methods invented and in use today. These welding methods range from braze welding, forge welding, gas, resistance, induction, arc, cold welding, and recently non-conventional or advanced welding processes like electron beam welding, laser welding, friction welding, thermit welding, flow and explosion welding (Amstead and Ostwald, 1987).

These processes differ largely in the equipment used, heat and/or pressure application, while some require other auxiliary processes to effect the weld. Welding technology can be applied virtually to every branch of manufacturing such as: ships, rail road equipment, building construction, boilers, launch vehicles, pipelines, nuclear power plants, aircrafts, automobiles, pipelines. High-strength low alloy (HSLA) steels have been widely used in the construction of buildings, pipelines and ships (Czyryca et al, 1990; Montemarano et al, 1986; Holsburg et al, 1990; Thompson, et al, 1996; Manganello, 1992). Most universal engineering materials now consist of steels and they are mainly joined by welding, especially the arc welding process because it's availability, relatively easy to operate and uses consumable electrodes (Ovat, 2012). Yongyutph et al (1992), Wen et al (2001) and Armentani et al (2007) have established some fundamental variables that affect welding process. They observed that residual stresses have strong influence on weld deformation, fatigue strength, fracture toughness and bulking strength.

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In arc welding, the length of arc is directly related to the voltage, and the amount of heat input is related to the current. As heat input is a relative measure of the energy transferred per unit length of weld. Heat is an important characteristic because, like preheat and temperature, it influences the cooling rate, which may affect the mechanical properties and metallurgical structure of the weld and the heat affected zone (HAZ) (Yoon et al, 2006). With the incorporation of automation into the arc welding process, many production companies adopted complete experimental designs and mathematical models to investigate the relevant process parameters to obtain quality weld (Ill-Soo et al, 2004).

Biswas, et al., (2009) stated that high quality can be achieved by optimizing various quality attributes or by selecting an optimal process environment that is efficient enough to fetch the desire requirements for quality. Taguchi method has been found to be a powerful tool to improve overall process quality by optimizing the welding process parameters in a way that variation is reduced to the barest minimum. Design of experiment (DOE) techniques had been used to carry out such optimization in the last two decades with a view to improving on the mechanical properties of weld materials. Among other investigators who have also worked on the optimization of welding variables using Taguchi method are Kim and Lee (2009). They used the method to suggest optimal combinations for process factors of hybrid welding methods to optimize the welding parameters of resistance spot welding process. Yoon et al., (2006) optimized the parameters of welding 7075-T6 aluminium alloy using Taguchi method. In this study, the microstructure and optimisation of impact energy of welded joint fabricated high strength low alloy steel material are investigated.

2 Materials and Method

2.1 Materials

High strength low alloy (HSLA) material of 125 mm length and 75 mm width was used for experimental study. Chemical analysis conducted on the material using optical emission spectrometer (OES) at Engineering Materials Development Institute, Akure shows the following elemental compositions: C (0.88%), Si (1.04%), Mn (1.49%), P (0.23%), Ni (0.95%), Cr (0.92%), Mo (1.17%), Ti (0.16%), S (0.19%), Al (0.33%), Co (0.51%), W (2.13%), V (0.38%), Sn (0.12%) and Fe (89.3%). An electrode (E6013 type) with 350 mm length by 3.25 mm diameter was used during the welding process. The polished surface of samples for morphology studies were etched using nital etchant solution of nitric acid and ethanol in the ratio of 2 ml to 98 ml respectively.

2.2 Methods

The material of the same production batch and chemical composition was used in this experiment. Thicknesses of 5 mm, 7 mm and 9 mm were selected and cut into plates of lengths 125 mm and width 75 mm. For each samples, six pieces of the coupon were cleaned, single v-grooved and welded using the 3.2 mm diameter by 350 mm long, rutile electrodes. They were then numbered for easy identification. The samples were carefully welded and guided by the Taguchi method in combining the variables levels for the nine runs as adopted from the Minitab 16 software. The welding input parameters and their levels are presented in Table 1. For a three-factor-three-level experiment, Taguchi had specified L9 (33) orthogonal array for experimentation as shown in Table 2.

Table 1: Welding process input parameters

Input parameter	L1	L2	L3
Current(amps) -A	60	70	80
Material thickness (mm)-B	5	7	9
Root gap (mm)- C	2	2.5	3

Table 2: Experimentation layout using an L9 orthogonal array.

Experimental run	A	B	C
1	60	5	2
2	60	7	2.5
3	60	9	3
4	70	5	2.5
5	70	7	3
6	70	9	2
7	80	5	3
8	80	7	2
9	80	9	2.5

2.3 Evaluation of Microstructure

Preparation of samples for microstructural examinations involved cutting of the samples to suitable sizes followed with grinding on a rotary wheel using emery papers of various grit sizes. Polishing was done with a diamond compound gel to give a mirror-like appearance to the material for a better surface finish. This was followed with etching which involves coating of the metal with etchant that helps to reveal the microstructure of the section of the metal. Etchant used was a nital solution which contains a solution of 2 ml of nitric acid and 98 ml of ethanol. The microscopic examination was carried out using the computer assisted optical microscope, with particular attention given to the weld areas and the heat affected zone and the images were captured at X200 magnification.

2.4 Impact Energy Test

The impact test which is a test of material to shock resistance or impact load was carried out using test samples notched at 28 mm to one edge and at the centre of the weld, after being ground to have a near flat surface. Test samples were held in the clamp chucks incorporated in anvils at the base, with the notch side facing the striker direction. The pendulum was then moved to the rest position and kept in that position with a locking mechanism, in order to freely hit the test sample at a hit spot of about 22 mm above the notch. The impact energy reached before material failure as indicated on the scale was recorded. The notches are 2 mm for the 5 mm thick plates and 3 mm for the 7 mm and 9 mm plates. All the notches were obtained at an angle of 450 as shown in Figure 1.

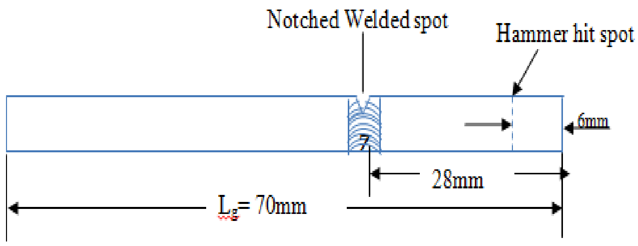

Fig. 1: Welded notched specimen for Izod impact test

3 Results and Discussion

3.1 Microstructure of the Weldment

Figure 2 shows the microstructure of the base material (BM), while Figures 3 to 11 show the miscrostructure of the weldment for the samples obtained from the nine experiments. Figure 3 has layers of white ferrite with dark patches of fairly dark pearlite in the fusion zone (FZ), than the heat affected zone (HAZ). It is an indication of a fairly stronger weldment than the HAZ. In Figure 4, a dark pearlite is more pronounced in the heat affected zone (HAZ) than the weld/fusion zone. This implies a weaker weld joint than the BM and HAZ. Figure 5 revealed that both HAZ and FZ have the presence of ferrite and pearlite, which implies they are mildly hard; but with finer grains in the FZ. This means a slightly stronger weld joint. Figure 6 revealed higher proportion of cementite in fine pearlite grains. Thus, the implication is that the weld zones were harder than Figures 3, 4 and 5.

Fig. 2: Microstructure of base material

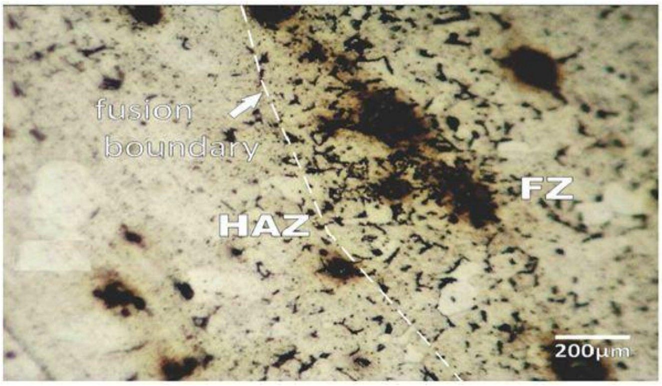

Fig. 3: Microstructure of weldment from experimental run 1

Fig.4: Microstructure of weldment from experimental run 2

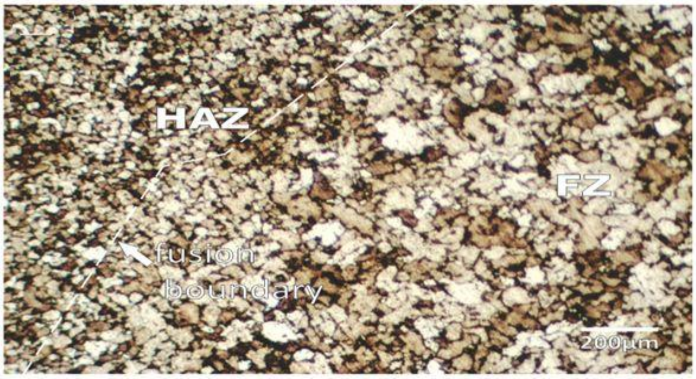

Fig.5: Microstructure of weldment from experimental run 3

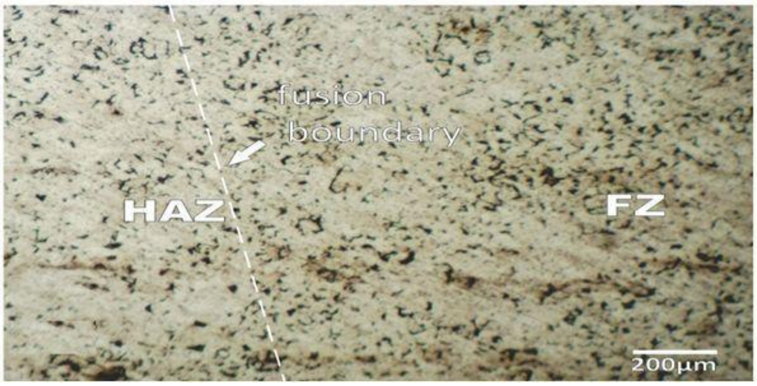

Fig. 6: Microstructure of weldment from experimental run 4

It can be seen that Figure 7 is similar to Figure 6, however, there were slightly more cementites in the pearlite region of the FZ. In Figure 8, there are more pronounced ferrites in the HAZ region indicate a moderately stronger region than FZ. Figure 9 has a moderately stronger fusion zone also than the HAZ. It contains microstructural feature of pearlite. In Figure 10, finer grains of dark pearlite can be seen in the fusion zone compared with more granular light ferrite in the heat affected zone, which suggests a weaker HAZ than the weld joint. In Figure 10, similar microstructure with the base material was observed. In Figure 11, an inter- granular fine to coarse grains of ferrite with pearlite is observed in the FZ. This implies moderate hardness in the weld/fusion zone. It could be deduced from the photo-micrographs that the varied input parameter combinations have significant effects on the metallurgical grains and structural formations of the welded material and hence its mechanical properties.

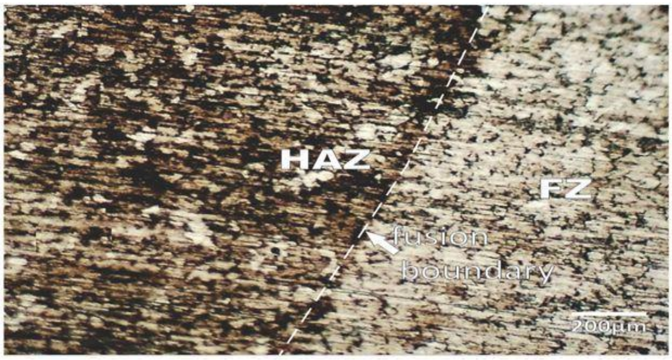

Fig.7: Microstructure of weldment from experimental run 5

Fig.8: Microstructure of weldment from experimental run 6

Fig.9: Microstructure of weldment from experimental run 7

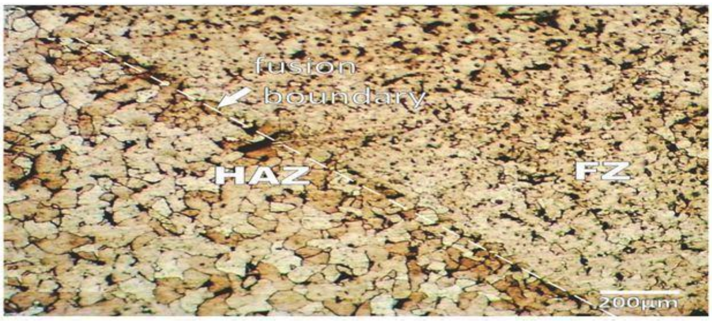

Fig.10: Microstructure of weldment from experimental run 8

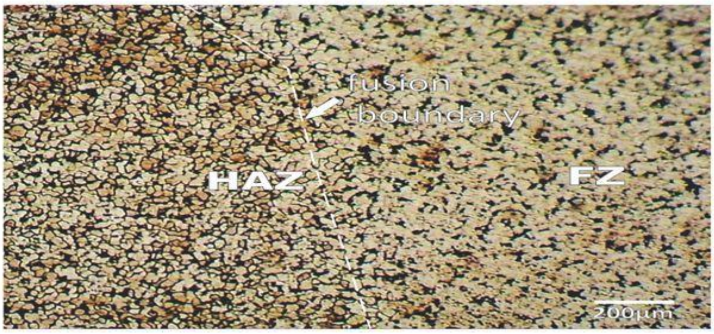

Fig.11: Microstructure of weldment from experimental run 9

3.2 Analysis of Variance and Signal-to-Noise Ratio of Impact Energy

Table 3 show the results obtained for impact energy and its signal-to-noise ratio. The impact energy values were used to analyse the contribution of each input factor on the impact energy, while the signal-to-noise ratio values were used to determine the optimum value of each factor.

Table 3: Impact energy values and S/N ratio

Exp. Run	Impact Energy (J)	S/N ratio for Impact Energy
1	32.54	30.25
2	79.99	38.06
3	89.48	39.04
4	103.04	40.26
5	59.66	35.51
6	143.72	43.15
7	65.08	36.27
8	162	44.19
9	151.85	43.63

Analysis of variance (ANOVA) being a standard statistical tool was used to determine the significant effects of the factors on the impact energy obtained in this experiment.. This analysis was conducted for α = 0.05 significance level, at the 95% confidence level. The relative importance for each factor is given in the order of their percentage contribution as shown in Table 4.

Table 4: ANOVA of Impact energy

Factor	DOF	SS	MS	F	P
Current (I) Amp	2	5273	2636.5	2.56	32.26
Thickness (mm) {T}	2	5684	2842	2.76	34.78
Root gap (mm) {RG}	2	3328	1664	1.62	20.36
Error	2	2058.99	1029.5		12.60
Total	8	16343.99	2043.0		100

While signal- to- noise (S/N) ratio was used to determine the optimum level of each factor. In the analysis of signal-to- noise ratio for impact energy, optimized level was obtained using the larger-the better S/N ratio quality characteristics as represented by equation (1) and presented in Table 3.

$$S/N = -10\log\frac{1}{n}\left(\sum_{i-1}^{n}\frac{1}{{y_i}^2}\right) \qquad (1)$$

where y = given factor level combination responses, n = number of factor level combination responses.
The values of input variables plotted against the values of S/N ratio as shown in Figure 12, indicates the optimal values of the three input variables. The optimal values of the combination of level 3 (current of 80 A), level 3 (thickness of 9 mm) and level 2 (root gap of 2.5 mm) gave the optimum value of impact energy when substituted into regression equation.

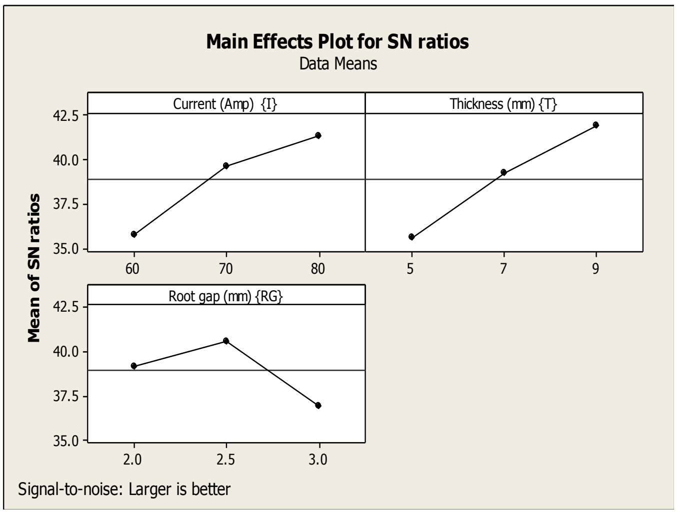

Fig.12: Main Effect Plots for Impact Energy

3.3 Optimisation for Impact Energy

The regression equation for the impact energy was generated using the Minitab 16 software as shown in equation (2).

$$\text{Impact Energy} = -112 + 2.95I + 15.4T - 41.3RG \quad (2)$$

where I is current, T is thickness and RG is root gap

The values of I, T and RG obtained from the main effect plot are the optimal values for the input variables. Substituting these optimal values of these input variables in equation (2) gave the optimum value of the impact energy. In order to validate the optimum value, these optimised values of input variables were used as input values to conduct another welding experiment and then subjected the weldment to impact energy test. The optimal input variables were substituted in the regression equation to give a theoretical value of 159.35 J, while the validation test gave 159.08 J. The percentage error of 0.17% was obtained and this can be considered acceptable.

4 Conclusion

The impact energy on high strength low alloy steel weldment was studied and the following conclusion can be drawn. The three varied input parameters; current, material thickness and root gap with the appropriate level of combination have pronounced effect on the response characteristics on the output product of the process. It was observed that the varied input parameter combinations have significant effects on the metallurgical grains and structural formations of the welded material. Analysis of variance showed that thickness with (34.78%) has significant contribution to impact energy and closely followed by current (32.26%). Regression equation was generated using the Minitab 16 software to determine theoretical value by substituting the optimal values obtained from the main effect plot. The percentage error in the theoretical value and validated value of impact energy was 0.17%, which is within acceptable level.

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