Journal of Minerals and Materials Characterization and Engineering, 2015, 3, 298-308
Published Online July 2015 in SciRes. http://www.scirp.org/journal/jmmce
http://dx.doi.org/10.4236/jmmce.2015.34032

Optimization of Gas Metal Arc Welding Process Parameters Using Standard Deviation (SDV) and Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA)

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Received 1 June 2015; accepted 15 June 2015; published 18 June 2015

Abstract

Welding technology is very vital for the industrial development and technological advancement of any country. In this regard achieving good quality machine manufactured products cannot be over emphasized. Since welding is a very reliable method of joining metals together permanently, several methodologies have been adopted to improve the quality of weldments, such as the neural network, fuzzy logic, surface response methodology, full factorial method, and so on. In this case, the multi-objective optimization on the basis of ratio analysis (MOORA) is applied. MOORA is used to solve multi-criteria (objective) optimization problem in welding. MOORA in combination with standard deviation (SDV) was used for the optimization process. SDV was used to determine the weights that were used for normalizing the responses obtained from the mechanical test results. From applying the SDV-MOORA method, it was found that welding current of 350 A, welding voltage of 22 V, an electrode diameter of 3.2 mm and welding speed of 100 mm/s produced the weldment with the best mechanical properties. The mechanical properties compare very well with those obtained from other literature. It is, therefore, concluded that the SDV-MOORA method has successfully optimized the welding process parameters used in this study.

Keywords

SDV, MOORA, Welding Process, Bead Geometry, Mechanical Property

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How to cite this paper: Achebo, J. and Odinikuku, W.E. (2015) Optimization of Gas Metal Arc Welding Process Parameters Using Standard Deviation (SDV) and Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA). *Journal of Minerals and Materials Characterization and Engineering*, **3**, 298-308. http://dx.doi.org/10.4236/jmmce.2015.34032

1. Introduction

The failure of structural materials especially steel is of great concern globally. In Nigeria, steel pipes used for the transportation of water, oil, gas etc. are joined together by welding. Welding is designed to permanently join pieces of materials producing weldments which significantly enhance the rigidity, stability, reliability, and integrity of structural materials. If the quality of the weldment is poor, the weldment will fail either by breaking off due to its brittle nature or by corrosion. It has been proven by several researchers that the choice of welding input process parameters can alter the quality of the weldment. Therefore, optimizing these process parameters to obtain the best weld quality and multi-response properties cannot be over emphasized. The choice of the appropriate optimization tool is an ongoing research process. Researchers are using different methods to obtain the most economic input process parameters. Today, there is no known particular optimization method used for optimizing these input process parameters. Instead, several optimization methods are used and the one that has produced the most acceptable results is selected. MOORA is one of such techniques that have not been fully utilized in optimizing welding input process parameters and multi-response properties.

The international engineering and welding community is keenly interested in investing in research and development geared towards finding optimized methods for obtaining weldments of acceptable quality. Several expert methods such as artificial neural network, fuzzy logic, finite element, genetic algorithm etc. have been applied for optimizing process parameters, since it has been found that applying the most appropriate process parameters has a huge impact on the eventual quality of each weldment. It has become imperative that new methods should be explored for the purpose of obtaining better weldments to meet even more specific engineering requirements.

In this study, the Multi-Objective Optimization on the basis of Ratio Analysis (MOORA) is used to optimize the process parameters. Görener *et al.* [1] were of the opinion that the MOORA method was first used by Brauers [2]. The MOORA method is a relatively new multi-criteria decision-making method which is based on the ratio system as well as dimemsionless measurement [3] [4].

Gadakh *et al.* [5] were of the opinion that multi-objective optimization (or programming), also known as multi criteria or multi-attribute optimization, was the process of simultaneously optimizing two or more conflicting attributes (objectives) subject to certain constraints. Hwang and Yoon [6] said that multi-criteria decision-making was applied to decisions among available classified alternatives by multiple attributes. Mandal and Sarkar [7] wrote that MOORA was the process of simultaneously optimizing two or more conflicting attributes (objectives) subject to certain constraints.

Stanujkic *et al.* [8] were of the opinion that multiple-criteria decision-making (MCDM) could be generally described as the process of selecting one from a set of available alternatives, or ranking alternatives, based on a set of criteria, which usually had a different significance. The multi-objective optimization by ratio analysis (MOORA) which was a part of MCDM was first introduced by Brauers and Zavadskas [9].

Some researchers have used MOORA for solving product or system optimization problems. Chakraborty [10] applied the MOORA method for decision-making in a manufacturing environment. Karande and Chakraborty [11] applied the MOORA method for the selection of materials. Chaturvedi and Sharma [12] optimized CNC wire cut EDM for OHNS steel using MOORA methodology. Görener *et al.* [1] applied the MOORA method for selecting where a bank should be located. Gadakh *et al.* [5] optimized welding process parameters using the MOORA method.

Brauers and Zavadskas [13] expanded the scope of MOORA to be known as MULTI-MOORA. Ozcelik *et al.* [14] in their paper wrote that Brauers and Zavadskas [13] developed the equation for the full multiplicative form of MOORA known as MULTI-MOORA method. Farzamnia and Babolghani [15] applied the group decision making process for material supplier selection in a supply chain using MULTI-MOORA technique under fuzzy environment.

In this study, the SDV-MOORA method was used to optimize the welding process parameters used for gas metal arc welding of mild steel plates. SDV was the standard deviation method used for determining the weight attached to each mechanical property. The results obtained from the optimized process parameters would be compared with those obtained using other optimization methods.

2. Materials and Methods

2.1. Materials

Five large weld deposits were made for each application of the sixteen process parameters on 4 mm mild steel plates. Each of these weld deposits are sectioned into three parts. One part was used to determine the Bead geometry (see **Figure 1**), the other part was used to conduct the Charpy V-Notch (CVN) Impact test. The CVN specimen is shown in **Figure 2**, while the remaining part was machined into the tensile specimen (see **Figure 3**) for conducting the tensile test.

Five tensile specimens are prepared using a CNC Lathe machine. Tensile tests are carried out in 100 kN computer controlled Universal Testing Machine as used by Prasad *et al.* [16]. The specimens were loaded at a rate of 1.8 kN/min as per ASTM specifications, so that these tensile specimens can undergo the deformation process. From the stress strain curve obtained, the ultimate tensile strength (UTS) of the weld joints is evaluated and the average of the five test results was recorded.

2.2. Method

The method adopted by El-Santawy and Ahmed [18] was used in this study. The methodology is expressed as contained herein under:

2.2.1. Weight Allocation via Standard Deviation

Standard deviation is applied to this study for unbiased allocation of weights. The importance of weights in solving Multi-Criteria Decision Making (MCDM) problems cannot be over emphasized. To determine the standard deviation, the range standardization was done using Equation (1) to transform different scales and units among various criteria into common measurable units in order to compute their weights.

$$X'_{ij} = \frac{X_{ij} - \min\limits_{1<j<n} X_{ij}}{\max\limits_{1<j<n} X_{ij} - \min\limits_{1<j<n} X_{ij}} \tag{1}$$

where $\max X_{ij}$, $\min X_{ij}$ are the maximum and minimum values of the criterion (j) respectively. The Standard deviation (SDV) is calculated for every criterion using Equation (2)

$$SDV_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(X_{ij} - \overline{X'_j}\right)^2} \tag{2}$$

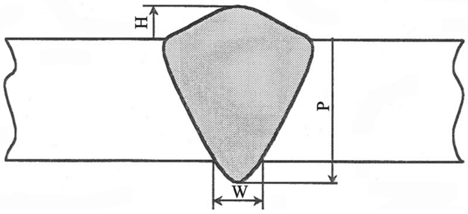

Figure 1. Bead geometry [17].

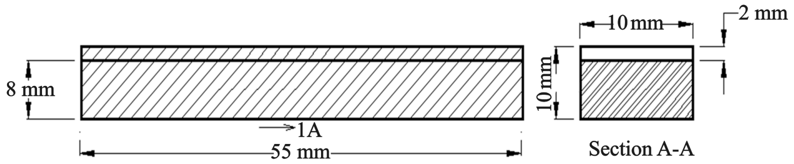

Figure 2. Schematic diagram of charpy V notch impact test specimen.

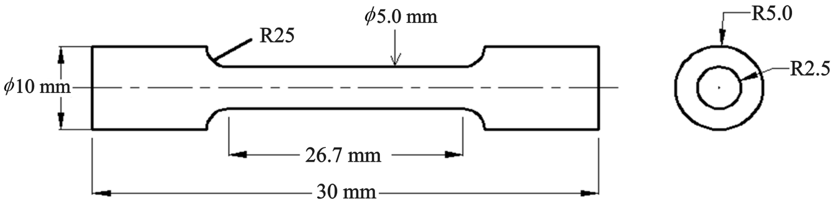

Figure 3. Schematic diagram of tensile specimen.

where $\overline{X'_j}$ is the mean of the values of the j^{th} criterion after normalization and $j = 1, 2, \cdots, n$. After calculating for SDV for all criteria, the next step is to determine the weights, W_j of all the criteria considered.

$$W_j = \frac{SDV_J}{\sum_{j=1}^{n} SDV_J} \tag{3}$$

where $j = 1, 2, \cdots, n$.

2.2.2. Application of MOORA

The Multi-Objective Optimization on the basis of Ratio Analysis (MOORA) method starts with a decision matrix as expressed by Equation (4)

$$D = \begin{array}{c|ccccc|} & C_1 & C_2 & C_3 & \cdots & C_n \\ A_1 & X_{11} & X_{12} & X_{13} & \cdots & X_{1n} \\ A_2 & X_{21} & X_{22} & X_{23} & \cdots & X_{2n} \\ A_3 & X_{31} & X_{32} & X_{33} & \cdots & X_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ A_n & X_{m1} & X_{m2} & X_{m3} & \cdots & X_{mn} \end{array} \tag{4}$$

The procedure for using MOORA for ranking alternatives is described here under;

Step 1: Compute the normalized decision matrix by vector method as defined by Equation (5)

$$X'_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \tag{5}$$

where $i = 1, \cdots, m$; $j = 1, \cdots, n$

Step 2: Calculate the composite score as expressed in Equation (6)

$$Z_i = \sum_{j=1}^{b} X'_{ij} - \sum_{j=b+1}^{n} X'_{ij}; \text{ where } i = 1, \cdots, m \tag{6}$$

where $\sum_{j=1}^{b} X'_{ij}$ and $\sum_{j=b+1}^{n} X'_{ij}$ are the benefit and non benefit (cost) criteria, respectively. If there are some attributes more important than the others, the composite score becomes as expressed in Equation (7)

$$Z_i = \sum_{j=1}^{b} W_j X'_{ij} - \sum_{j=b+1}^{n} W_j X'_{ij}, i = 1, \cdots, m \tag{7}$$

where W_j is the weight of j^{th} criterion

Step 3: Rank the alternatives in descending order.

Figure 4 shows the sequence of operations that was performed in the framework of multicriteria decision support system

3. Results and Discussion

3.1. Results

The matrix design used to prepare the layout for the welding procedure is presented in **Table 1**.

Table 2 shows the welding process parameters and their levels

Table 3 shows the decision matrix used for categorizing the weld mechanical properties and bead geometry

Where UTS is the Ultimate Tensile Strength, CVN is the Charpy V-Notch Impact Energy, BP is the Bead Penetration, BH is the Bead Height and BW is the Bead Width.

3.1.1. Weight Allocation

In this study, the weight allocation for each of the output parameters, that is, the weld mechanical properties and the bead geometry were determined. In determining the weight, the range of standardized decision matrix is determined using Equation (1). **Table 4** shows the summary of the range of standardized decision matrix.

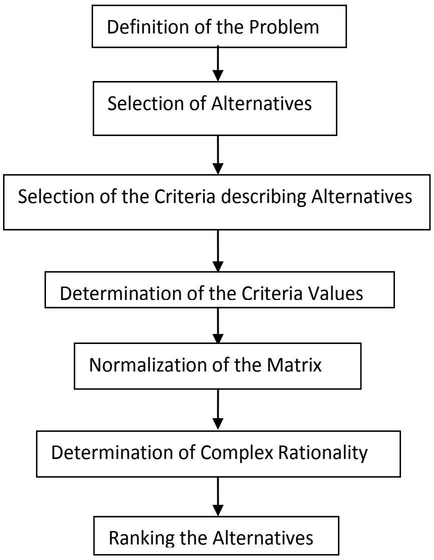

Figure 4. Sequence of operations performed in the framework of multi-criteria decision support system [19].

Table 1. Matrix design.

	A	B	C	D
0	1	2	3	4
+	+	-	-	-
+	+	+	-	-
+	+	+	+	-
+	+	+	+	+
+	-	+	+	+
+	+	-	+	+
+	-	+	-	+
+	+	-	+	-
+	+	+	-	+
+	-	+	+	-
+	-	-	+	+
+	+	-	-	+
+	-	+	-	-
+	-	-	+	-
+	-	-	-	+
+	-	-	-	-

Table 2. Process parameters and their levels.

Process Parameters	Unit	Levels	
		Low	High
Current	A	280	350
Voltage	V	22	38
Electrode diameter	mm	1.6	3.2
Welding speed	mm/s	100	135

Table 3. Decision matrix.

Sample Number	Maximum			Minimum	
	UTS (MPa)	CVN (J)	BP (mm)	BH (mm)	BW (mm)
1	420	110	2.04	2.25	10.82
2	500	100	1.12	2.85	5.14
3	380	80	2.58	3.10	7.22
4	320	90	1.03	2.51	11.42
5	410	60	1.45	3.72	5.35
6	220	100	1.05	2.05	8.83
7	280	55	2.01	2.15	10.72
8	510	115	3.50	3.88	4.50
9	480	85	3.78	2.85	6.85
10	320	60	2.15	2.15	11.20
11	250	95	1.90	2.98	12.40
12	310	83	2.42	2.06	9.80
13	520	100	3.82	2.97	4.18
14	430	70	2.25	3.08	8.32
15	270	60	1.65	2.15	10.74
16	290	80	1.88	2.70	12.88

Table 4. Summary of range of standardized decision matrix.

Sample No.	UTS, MPa	CVN, J	BP, mm	BH, mm	BW, mm
1	0.67	0.92	0.36	0.11	0.76
2	0.93	0.75	0.03	0.44	0.11
3	0.53	0.42	0.56	0.57	0.35
4	0.33	0.58	0	0.25	0.83
5	0.63	0.08	0.15	0.91	0.13
6	0	0.75	0.01	0	0.53
7	0.20	0	0.35	0.06	0.75
8	0.97	1	0.89	1	0.04
9	0.87	0.50	0.99	0.44	0.31
10	0.33	0.08	0.40	0.06	0.81
11	0.10	0.67	0.31	0.51	0.95
12	0.30	0.47	0.50	0.01	0.65
13	1	0.78	1	0.50	0
14	0.70	0.25	0.44	0.56	0.48
15	0.17	0.08	0.22	0.06	0.75
16	0.23	0.42	0.31	0.37	1

The next step is to determine the standard deviation and weights using Equation (2) and Equation (3) as shown in **Table 5**.

3.1.2. Application of MOORA

In applying the MOORA method, the first step was to square each value in **Table 1**, X_{ij}^2, this lead to the creation of **Table 6**.

Applying $X'_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}}$ for each column in **Table 3** and **Table 6**, **Table 7** was created therefrom.

Table 5. Weights assigned to criteria.

Property	SDV_j	W_j
UTS	0.57607	0.20578
CVN	0.55074	0.19674
BP	0.55655	0.19881
BH	0.53803	0.19220
BW	0.57800	0.20647

Table 6. The square value of X_{ij}.

Sample No.	UTS, MPa	CVN, J	BP, mm	BH, mm	BW, mm
1	176,400	12,100	4.1616	5.0625	117.0724
2	250,000	10,000	1.2544	8.1225	26.4196
3	144,400	6400	6.6564	9.6100	52.1284
4	102,400	8100	1.0609	6.3001	130.4164
5	168,100	3600	2.1025	13.8384	28.6225
6	48,400	10,000	1.1025	4.2025	77.9689
7	78,400	3025	4.0401	4.6225	114.9184
8	260,100	13,225	12.2500	15.0544	20.2500
9	230,400	7225	14.2884	8.1225	46.9225
10	102,400	3600	4.6225	4.6225	125.4400
11	62,500	9025	3.6100	8.8804	153.7600
12	96,100	6889	5.8564	4.2436	96.0400
13	270,400	10,404	14.5924	8.8209	17.4724
14	184,900	4900	5.0625	9.4864	69.2224
15	72,900	3600	2.7225	4.6225	115.3476
16	84,100	6400	3.5344	7.3984	165.8944
$\sum_{i=1}^{m} X_{ij}^2$	2,331,900	118,493	86.9175	123.0101	1357.8959
$\sqrt{\sum_{i=1}^{m} X_{ij}^2}$	1527.0560	344.2281	9.3230	11.0910	36.8496

Table 7. Normalized weld properties.

Sample No.	UTS, MPa	CVN, J	BP, mm	BH, mm	BW, mm
1	0.2750	0.3196	0.2188	0.2029	0.2936
2	0.3274	0.2905	0.1201	0.2570	0.1395
3	0.2488	0.2324	0.2767	0.2795	0.1959
4	0.2096	0.2615	0.1105	0.2263	0.3099
5	0.2685	0.1743	0.1555	0.3354	0.1452
6	0.1441	0.2905	0.1126	0.1848	0.2396
7	0.1834	0.1598	0.2156	0.1939	0.2909
8	0.3340	0.3341	0.3754	0.3498	0.1221
9	0.3143	0.2469	0.4054	0.2570	0.1859
10	0.2096	0.1743	0.2306	0.1939	0.3039
11	0.1637	0.2760	0.2038	0.2687	0.3365
12	0.2030	0.2411	0.2596	0.1857	0.2660
13	0.3405	0.2963	0.4097	0.2678	0.1134
14	0.2816	0.2034	0.2413	0.2777	0.2258
15	0.1768	0.1743	0.1770	0.1939	0.2915
16	0.1899	0.2324	0.2017	0.2452	0.3495
Weight, w_j	0.20578	0.19674	0.19881	0.19220	0.20647

The next step is to multiply each parameter value in **Table 7**, with their corresponding weights. This action leads to the creation of **Table 8**.

This last step is to sum the parameters comprising of the higher the better (maximum) and the smaller the better (minimum) respectively. **Table 9** is created and ranked therefrom.

3.2. Discussion of Results

3.2.1. Categorization of Test Results

This study investigates the utilization of standard deviation and multi-objective optimization on the basis of ratio analysis (MOORA) tools in the selection of appropriate gas metal arc welding process parameters.

Table 8. Clustered weld properties and bead geometry according to criteria.

Sample No.	Maximum			Minimum	
	UTS, MPa	CVN, J	BP, mm	BH, mm	BW, mm
1	0.0566	0.0629	0.0435	0.0390	0.0606
2	0.0674	0.0572	0.0239	0.0494	0.0288
3	0.0512	0.0457	0.0550	0.0537	0.0404
4	0.0431	0.0514	0.0220	0.0435	0.0640
5	0.0553	0.0343	0.0309	0.0645	0.0300
6	0.0297	0.0572	0.0224	0.0355	0.0495
7	0.0377	0.0314	0.0429	0.0373	0.0601
8	0.0687	0.0657	0.0746	0.0672	0.0252
9	0.0647	0.0486	0.0806	0.0494	0.0384
10	0.0431	0.0343	0.0459	0.0373	0.0627
11	0.0337	0.0543	0.0405	0.0516	0.0695
12	0.0418	0.0474	0.0516	0.0357	0.0549
13	0.0701	0.0583	0.0815	0.0515	0.0234
14	0.0580	0.0400	0.0480	0.0534	0.0466
15	0.0364	0.0343	0.0352	0.0373	0.0602
16	0.0391	0.0457	0.0401	0.0471	0.0722

Table 9. Ranking step.

Sample No.	$\sum \text{max}$	$\sum \text{min}$	$\sum \text{max} - \sum \text{min}$	Rank	
1	0.1630	0.0996	0.0634	5	
2	0.1485	0.0782	0.0703	4	
3	0.1519	0.0941	0.0578	6	
4	0.1165	0.1075	0.0090	13	
5	0.1205	0.0945	0.0260	9	
6	0.1093	0.0850	0.0243	10	
7	0.1120	0.0974	0.0146	12	
8	0.2090	0.0924	0.1166	2	
9	0.1939	0.0878	0.1061	3	
10	0.1233	0.1000	0.0233	11	
11	0.1285	0.1211	0.0074	15	
12	0.1408	0.0906	0.0502	7	
13	0.2099	0.0749	0.1350	1	Best
14	0.1460	0.1000	0.0460	8	
15	0.1059	0.0975	0.0084	14	
16	0.1249	0.1193	0.0056	16	

In the first instance, a layout matrix design is established as contained in **Table 1**. **Table 2** contains the process parameters, which comprises of the current, voltage, electrode diameter, and welding speed. The process parameters are either in low level (−) or high level (+). The low and high levels of the process parameters in **Table 2** are placed in their various locations in **Table 1**, where current, voltage, electrode diameter and welding speed are denoted, as A, B, C and C respectively in **Table 1**.

From **Table 1**, it can be seen that there is a sixteen process parameter layout design. Each process parameter welding operation was used to make five weldments. The UTS, and CVN of the weldments were determined by conducting the tensile test, as well as, the charpy V-Notch impact test. The height, width, and penetration of the bead geometry of these weldments were measured and determined. **Table 3** classified these properties according to their quality values, which shows that the larger the UTS, CVN, and BP the better the quality of the weldment. Whereas, the smaller the BH and BW the better the quality of the weldment.

This is because, UTS defines the strength of the weldment. Therefore, the greater the strength of the weldment, the more the weldment possesses the capacity to carry loads. This quality actually extends the service life of the weldment. The CVN measures the energy required to absorb impact loads. The higher the CVN value, the greater the chances of the weldments to absorb any applied impact load. This on the one hand tends to increase the service life of the weldment. The weld bead penetration is an important factor considered in assessing the quality of weldments. The higher the weld penetration, the lower the weld undercuts, and the higher the weld joint reinforcements. This however increases the strength and quality of the weldment.

Table 4 shows the sixteen standard deviations, determined for each of the mechanical properties, whereas, **Table 5** shows the overall standard deviations and the corresponding weights assigned to each mechanical property. **Tables 6-9** show the MOORA application process for determining the optimum welding process parameters.

3.2.2. Result Analysis

The UTS considered in this study is within the range of 220 MPa and 520 MPa. Appling MOORA the selected process parameters thereof produced a weldment with a UTS of 520 MPa. The CVN considered in this study is in the range of 55 J and 115 J. By Appling the MOORA a CVN of 100 J was obtained. This indicates that when the CVN value is above the threshold value of 100 J. This may negatively affect on the long term the service life of the weldment.

The BP considered in this study is within the range of 1.03 mm and 3.8 mm. By applying the MOORA technique, BP was found to be 3.83 mm. This indicates that the more the gaps between the weld joints are covered by the molten weld metal, the better, because the strength is increased, porosity is reduced to the barest minimum or eliminated, and the weld joints are held together to an acceptable level. This study shows that the joint gap of weldment 13 was fully covered by the molten weld metal.

On the other hand, the second category shows that the smaller the bead height and bead width the better the quality of the weldment. This corresponds with actual welding practice. The smaller the BH and BW are, the better the quality of the weldment will be. The range of BH considered in this study is 2.05 mm and 3.88 mm. By applying the MOORA method, the BH obtained was 2.97 mm. This indicates that BH of 2.05 mm was too small to be considered and a BH below 2.97 mm may not have enough weld metal to sustain the strength possessed by the weldment when loads are applied. Therefore, for this study, BH with a value of 2.97 mm is considered the threshold value when using the optimum process parameters. The BW considered in this study is within the range of 4.18 mm and 12.88 mm. By applying the MOORA method, BW of 4.18 mm was obtained. This indicates that BW values above 4.18 mm may contain too much weld metal. Too much weld metal adds to the weight of the weldment and this may not be good for the overall structure of the material.

For this study, weldment 13, is found to possess the best mechanical property. From **Table 1** and **Table 2**, the process parameters for weldment 13 correspond to a welding current of 350 A, a welding voltage of 22V, an electrode diameter of 3.2 mm and welding speed of 100 mm/s. The mechanical properties produced by the weldment made by these process parameters are UTS of 520 MPa, CVN of 100 J, BP of 3.8 mm, BH of 2.97 mm and BW of 4.18 mm.

The results from this study were compared with similar work found in literature. Such as Gunaraj and Murugan [20] who predicted and optimized the weld bead volume for submerged arc process and obtained bead penetration of between the range of 3.04 mm and 3.80 mm, and bead width was in the range of 7.9 mm and 9.1 mm. From this study, the BP matches that obtained by Gunaraj and Murugan [20] and also the BW obtained in

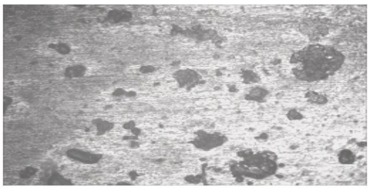

Figure 5. Microstructure of weldment from optimized process parameters.

this study is better than the one determined by Gunaraj and Murugan [20].

Figure 5 shows the microstructure of the optimized weldment. From the microstructural view it can be seen that the black and white colours are heterogeneously prominent. The white grains are ferrite, while the black ones are the pearlite. However, pearlite contains ferrite and cementite. Cementite is considered to be very hard and dense. From **Figure 5**, it can be seen that obviously pearlite is more in proportion than ferrite. As a result of this, the strength, that is the UTS of the optimized weldment is expected to be high and the weldment ductile as the ferrite is considerably high. Since it is observed that the optimized process parameters gave a good level of weld metal penetration, the fusion between the parent material and the weld metal would also be high with very good machinability because of its ductility. This analysis reveals that the optimized weldment is of very good quality.

4. Conclusions

Mild steel plates were joined by applying specific process parameters to carry out the welding operation. The weld metals were machined into various test specimens. Mechanical properties, UTS, and CVN were determined using the test specimens. The mechanical properties were found within the category. The larger the test result was, the better the quality of the weldment would be, whereas the individual weldment was bisected and BP, BH and BW were measured.

BP falls into the larger the test result, the better the quality of the weldment whereas, BH and BW fall into the smaller the test results, the better the quality of the weldment or bead geometry. The MOORA technique was applied to optimally select the welding process parameters that produced the weldment with the best properties. However, standard deviation was used to determine the weights allocated to each value of the mechanical property utilized in the course of running the MOORA process.

This study summarily covers the application of MOORA method in the selection of optimized welding process parameters for welding mild steel plates using the gas metal arc welding techniques. This multi-objective optimization tool utilizes a ranking method for the process parameters selection process.

From the results obtained, it can be found that the selected optimized process parameters are within the range of optimized process parameters obtained in literature. It is hereby concluded that MOORA method has successfully optimized the process parameters considered in this study and that these optimized process parameters are compared well with those obtained by other investigators who apply other known optimization models. The microstructure of the weldment produced by the optimized process parameters was also investigated to confirm the quality of the weldment. The analysis of the microstructure reveals that the weldment produced by the optimized process parameters is of excellent weld quality.

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