International Conference on Mechanical, Industrial and Energy Engineering 2010
23-24 December, 2010, Khulna, BANGLADESH

MIE10-073

Optimization of Process Parameters in MIG Welding using Analytical Hierarchy Process

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ABSTRACT

Among the arc welding processes, metal inert gas (MIG) welding is a popular process to the present day fabrication industries. Weldment characteristics are extremely important characteristics for structural integrity. The process parameters like arc length, arc spread, current, voltage, electrode diameter and rate of energy input influence the weldment characteristics. Controlling process parameters of metal inert gas (MIG) welding is very important to obtain the desired product quality. In the present work, parametric optimization has been done in MIG through applying the analytical hierarchy process (AHP). Analytical hierarchy process (AHP) is a multiple criteria decision-making tool that has been used in almost all the applications related with decision-making. The optimization of process parameters in MIG welding from amongst a large number of different combinations of the process parameters is clearly a decision making situation and hence in the present study also the applications of AHP. This technique shows quite close estimates with the experimental results.

Keywords: MIG, Analytical Hierarchy Process, AHP, Parametric Optimization.

1. Introduction

Metal inert gas (MIG) welding utilizes an arc maintained between the work pieces and an automatically servo feed wire electrode. The arc continuously melts the wire as it is fed to the weld puddle. In this process, the consumable electrode provides the filler metal, which is feed through the electrode holder into the arc. So no additional fed is required. The weld metal is shielded from the atmosphere by a flow of an inert gas, or a gas mixture. Argon, helium, and mixtures of these gases can be used for welding steel, some O_2, CO_2 is usually added to improve the arc stability and reduce the spatter. The cheaper CO_2 can be used alone when welding steel provided that a deoxidizing wire electrode is employed, then the process is named as MAG (metal active gas) welding [1,2]. A constant voltage, direct current power source is most commonly used with MIG, but constant current systems, as well as alternating current can be used. Both the processes of MIG can be easily mechanized to give high productivity maintaining quality. However, process variables need effective control to achieve good results [1-3].

While Little [3] reported the relationship of mechanical properties of welded joint with the degree of compositions of base material, detailed investigation of the effect of the chemistry of base material on the softening of HAZ was made by Mohandas and others [4]. Hardness and microstructure were compared with the variation of the chemistry of the parent metal and the welding process to understand the influence of the alloy chemistry, and the effect of different welding processes on the weld of the same alloy [4]. In another work, Zumelzu and the others [5] observed the effect of post-weld heat-treatment and external cooling on the MIG product.

Kim and Basu [6] employed mathematical models of the MIG process to predict welding process parameters to obtain the required weld bead geometry and to study the effect of weld process parameters on the weld bead dimension.

The influence of small differences in wire characteristics on MIG-CO_2 process was evaluated by Modensi et al [7]. Data were evaluated using factorial analysis and graphical techniques to assess the effect of different wire characteristics on the welding process. Results show that differences in wire diameter produce the most important changes in the characteristics of the process.

An abductive polynomial network model of gas metal arc welding process was proposed by Simpson and others [8]. The network model is capable of learning the relationship between MIG process parameters such as wire diameter, gas flow rate, welding speed, arc current and welding voltage on the weld bead penetration. The estimated value of weld bead penetration derived from network training was compared with the measured value and was found to be quite close. Jones et al [9] found out a relation between power input to the arc in MIG, metal transfer process and base plate heating.

Optimized parameters were evolved in some other investigations led by Das S. [10-11] involving MAG welding of different steels, while another research work [12] recommends a gas mixture of argon, CO_2 and oxygen for MIG process that gives a substantial cost saving with a good control of spatter. The analytical hierarchy process (AHP) was applied to optimize the type of welding and corresponding process parameters to obtain quality but joints of aluminum alloys [13].

Considering the vital role process parameters play on the quality of weldment, in this work, a number of experiments has been conducted by varying different parameters of CO_2 gas shielded MIG process to find out an appropriate combination of the same using the Analytical Hierarchy Process (AHP)-a simple optimization tool.

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2. The basic principles of the AHP

2.1 The AHP theory

The Analytical Hierarchy Process (AHP) is a very simple and widely used decision making tool. The AHP can solve many complex multi criteria decision-making problem hierarchically [14, 15]. This was applied to solve several manufacturing and production problems.

The AHP process involves identifying a decision problem and then decomposing this into a hierarchy of smaller and simpler sub-problems, each of which could then be analyzed independently, without losing focus of the overall decision problem at hand. In the AHP, the hierarchy structure is first constructed shown in Fig.1. At the top level of the hierarchy, the goal or the objective of the decision is placed. Next the criteria, sub-criteria (if any) and decision alternatives come in the subsequent descending levels.

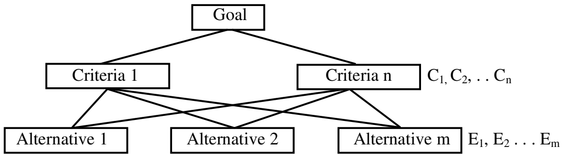

Fig.1 Typical hierarchy structure of the AHP

Weights are then assigned to criteria, according to their relative importance. Alternatives are then evaluated based on their relative importance of the alternatives of each criterion in the hierarchy, by pair-wise comparisons, using Saaty's scale shown in Table 1 of absolute numbers which is used to assign numerical values to both quantitative and qualitative judgements. To assign weighs, it is only necessary to perform $n - 1$ comparisons as in. The number of judgements, J, that have to be made in a full pair-wise comparison can be determined by [16].

The results of these comparisons are recorded in a matrix, the consistency matrix shown in Eq.(1), which should be both transitive Eq.(2) and reciprocal Eq.(3). In comparison matrix A, the elements a_{ij} compare alternatives *i* and *j* of a decision problem [17].

$$A = \begin{vmatrix} 1 & .. & a_{ij} & .. & a_{1n} \\ .. & 1 & .. & .. & .. \\ 1/a_{ij} & .. & 1 & .. & .. \\ .. & .. & .. & 1 & .. \\ 1/a_{1n} & .. & .. & .. & 1 \end{vmatrix} \tag{1}$$

$a_{ij} = a_{ik}.a_{kj}$ where i, j, and k are alternatives in the matrix; for j>k>i (2)

$$a_{ij} = {}^{1}\!/_{a_{ik}} \tag{3}$$

This comparison matrix is then checked for consistency, and can only be considered consistent if, and only if the matrix satisfies both Eq.(2) and Eq.(3). Numerical weights are assigned to each element of the comparison matrix, based on their relative importance, where the total sum of weights of all alternatives in a criterion must equal a 1 or 100%. This could be done using one of several methods, two of the most common of which are the Eigenvector Method (EM) and the Geometric Mean [16, 17]. Priorities are then derived for each alternative. These are then ranked in order of relative preference, where the best / optimal alternative is the selected.

$$A.\omega = \lambda_{max}\omega \tag{4}$$

where A is the comparison matrix; ω is the eigenvector; λ_{max} is the maximum Eigen value of matrix A.

Table 1 Saaty's fundamental 9 point scale for comparative judgements

Intensity of importance	*Definition*	*Explanation*
1	Equal importance	Two factors contributes equally to the objective
3	Moderate importance	Experience and judgement slightly favor one over the other
5	Strong importance	Experience and judgement strongly favor one over the other
7	Very strong importance	Experience and judgement very strongly favor one over the other. Its importance is demonstrated in practice.
9	Extreme importance	The evidence favoring one over the other is of the highest possible validity.
2,4,6,8	For compromise between above values	Sometimes one need to interpolate compromise judgement numerically

Table 2 Random Index (RI) values [17]

N	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Priorities are estimated using Eq.(4) by finding the principal eigenvector, ω, of the matrix. Normalizing ω makes it the vector of priorities of elements of one level with respect to the upper level [18].

In order to maintain consistency when deriving priorities from pair-wise comparisons, the number of elements in a decision problem should be ≤ 9. AHP allows for inconsistency in decision-making, and at the same time provides a measure of this inconsistency in each set of judgements, which is deemed unacceptable if it is $\geq$ 0.10. Consistency is measured by the consistency ratio Eq.(5). CI is further defined as Eq.(6). The average consistencies of RI from random matrices are given in Table 2, derived from Saaty's book, in which the upper row is the order of the random matrix, and the lower is the corresponding index of consistency for random judgements.

$$CR = \frac{CI}{RI} \qquad (5)$$

where CI is the consistency index; RI is the ratio index.

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (6)$$

where λ_{max} as above; n is the dimension.

2.2 The AHP calculation

There are several methods for calculating the eigenvector (local weights). Multiplying together the entries in each row of the matrix and then taking the nth root of that product gives a very good approximation to the correct answer. The nth roots are summed and that sum is used to normalize the eigenvector elements to add to 1.00.

The next stage is to calculate $\lambda_{\max}$ so as to lead to the Consistency Index and the Consistency Ratio. We first multiply on the right the matrix of judgements by the eigenvector, obtaining a new vector. This vector is, of course, the product A.ω and the AHP theory says that A.ω= $\lambda_{\max}$ ω so we can now get four estimates of $\lambda_{\max}$ by the simple expedient of dividing each component of vector by the corresponding eigenvector element. The mean of these values is our estimate for $\lambda_{\max}$. If any of the estimates for λ_{max} turns out to be less than n, there has been an error in the calculation, which is a useful sanity check. The Consistency Index for a matrix is calculated from $CI = \frac{\lambda_{max} - n}{n-1}$.

The final step is to calculate the Consistency Ratio for this set of judgements using the CI for the corresponding value from large samples of matrices of purely random judgments using the Table 2.

The calculation of the eigenvector from the pair-wise comparisons is of relative importance. The first eigenvector has given the relative importance attached to criteria, such as heat affected zone, bead height and bead width, but different alternatives combination contribute to differing extents to the satisfaction of those criteria. Thus, subsequent matrices can be developed to show how alternative parametric combinations satisfy the objectives or goal. (The matrices from this lower level in the hierarchy will each have their own eigenvectors and CRs.) The final step is to use standard matrix calculations to produce an overall vector giving the answer we seek, namely the relative merits of the alternatives vis-à-vis the goal or objectives.

3. Details of experiments

In this study, welding of rectangular low carbon steel (0.25% carbon) bars has been done in a MIG set up. To have continuous straight welding with desired speed, a motor driven torch holder has been designed to use.

Although there are several parameters affecting the weldment in MIG, few important parameters are selected for present study, such as welding current, welding voltage and welding speed. Depending upon the trial tests, range of parameters chosen are-

1) Welding current-120, 220, 236, 260, 276, 300, 316, 332, 248 and 362 ampere
2) Welding voltage- 80 volts
3) Welding speed-300 and 420.

Similar work-pieces are joined with CO_2 shield in double-butt joint fashion under natural air cooling, Keeping a root gap of 1.5mm. No preheating is employed. The joint is kept horizontal position with the torch angled at 75^o. Welding is done using1.2mm diameter low carbon steel electrode.

The weld joints are first inspected visually. Next, Hardness test is performed to find out Brinell Hardness Number (HBN), following filler metal deposition rate is calculated for different alternatives. Depth of penetration, bead height, bead width and heat affected zone is measured by taking a cross-section of the bars. These results are utilized to construct the analytical hierarchy process model to find out the appropriate process parameters of MIG welding for the work-piece material considered in the present experimental work.

4. AHP: For optimizing the MIG condition

In this section, the technique to optimize the condition for MIG is discussed. Ten alternative conditions are considered for optimization and their experimental observations are shown in Table 3.

On the basis of six criteria shown in Table 4, the AHP is constructed. The pair-wise comparison matrix for criteria for this problem of selection of optimum parametric condition, S is given in Table 5. This table shows the preferences for selection of criteria compared with other criteria to judge quality weld. For each criteria (C), preferences of the alternatives (E) are tabulated in Table 6 through Table 11. Combining the pair-wise comparison matrices for criteria and alternatives, global matrix is formed as shown in Table 12.

Table 3 Alternative conditions and experimental observations

Alternative No.	*Speed (mm/min)*	*Voltage (volt)*	*Current (amp)*	*MDR (gm/sec)*	*DOP (mm)*	*BH (mm)*	*BW (mm)*	*HAZ (mm)*	*BHN*
E_1	300	80	120	0.336	0.56	4.37	5.74	0.72	477
E_2	300	80	220	0.635	1.11	2.99	6.75	1.10	415
E_3	300	80	236	0.625	0.32	3.16	6.94	1.44	285
E_4	300	80	260	0.521	0.85	2.41	7.54	1.76	321
E_5	300	80	276	0.364	1.44	2.50	8.69	1.16	285
E_6	420	80	300	0.230	1.87	2.29	9.93	1.02	302
E_7	420	80	316	0.521	1.49	2.50	10.53	1.67	321
E_8	420	80	332	0.869	1.86	2.05	10.76	1.35	229
E_9	420	80	348	1.020	1.19	2.53	11.59	1.21	285
E_{10}	420	80	362	0.357	1.57	1.70	8.22	1.13	363

Table 4 Condition selection criteria

Criteria No.	*Criteria*
C_1	Filler Metal Deposition Rate
C_2	Depth of Penetration (DOP)
C_3	Bead Height (BW)
C_4	Bead Width (BH)
C_5	Heat Affected Zone (HAZ)
C_6	Brinell Hardness Number (BHN)

Table 5 Pair-wise comparison matrix for criteria

S	C_1	C_2	C_3	C_4	C_5	C_6	*Local weight*
C_1	1	1/3	1/5	1/7	1/2	1/4	0.0396
C_2	3	1	1/8	1/6	1/3	1/4	0.0507
C_3	5	8	1	1/2	1/3	1/5	0.1278
C_4	7	6	2	1	1/7	1/6	0.1366
C_5	2	3	3	7	1	1/4	0.2163
C_6	4	4	5	6	4	1	0.4291
	$\lambda_{max} = 6.6188$			CR = 0.0998			

Table 6 Pair-wise comparison matrix for filler metal deposition rate

MDR	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	*Local Weight*
E_1	1	¼	1	¼	1/6	1/7	1/7	1/7	1/7	½	0.019
E_2	4	1	4	1	1/3	1/3	1/5	1/5	1/5	3	0.052
E_3	1	¼	1	¼	1/6	1/6	1/7	1/7	1/7	½	0.020
E_4	4	1	4	1	1/3	1/3	1/5	1/5	1/5	3	0.052
E_5	6	3	6	3	1	1	½	½	½	6	0.123
E_6	6	3	6	3	1	1	½	½	½	6	0.123
E_7	7	5	7	5	2	2	1	1	1	5	0.195
E_8	7	5	7	5	2	2	1	1	1	5	0.195
E_9	7	5	7	5	2	2	1	1	1	5	0.195
E_{10}	2	1/3	2	1/3	1/6	1/6	1/5	1/5	1/5	1	0.028
		$\lambda_{max} = 10.3585$				CR = 0.0267					

Table 7 Pair-wise comparison matrix for depth of penetration

DOP	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	*Local Weight*
E_1	1	½	½	1/3	1/5	¼	¼	½	1/3	¼	0.032
E_2	2	1	1	1/5	1/6	1/6	1/3	1	1/7	½	0.038
E_3	2	1	1	1/5	1/6	1/6	1/3	1	1/7	½	0.038
E_4	3	5	5	1	1	1	1/3	1/7	½	1/3	0.083
E_5	5	6	6	1	1	1	1/3	1/7	½	1/3	0.091
E_6	4	6	6	1	1	1	1/3	1/7	½	1/3	0.089
E_7	4	3	3	3	3	3	1	¼	1/5	1/3	0.116
E_8	2	1	1	7	7	7	4	1	6	4	0.266
E_9	3	7	7	2	2	2	5	1/6	1	½	0.163
E_{10}	4	2	2	3	3	3	3	¼	2	1	0.167
		$\lambda_{max} = 10.5961$				CR = 0.0445					

Table 8 Pair-wise comparison matrix for bead height

BH	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	*Local Weight*
E_1	1	2	1/3	1/5	1/3	1/7	1/3	1/3	¼	½	0.036
E_2	½	1	4	3	1/5	¼	1	1	1	1	0.081
E_3	3	¼	1	5	2	1/6	1/8	1/8	1/6	1/5	0.044
E_4	5	1/3	1/5	1	1/3	1/3	1/3	½	1	½	0.051
E_5	3	5	½	3	1	1	1	¼	1/7	1/6	0.075
E_6	7	4	6	3	1	1	1	3	2	¼	0.177
E_7	3	1	8	3	1	1	1	1	1	1	0.140
E_8	3	1	8	2	4	1/3	1	1	1	1	0.138
E_9	4	1	6	1	7	½	1	1	1	1	0.142
E_{10}	2	1	5	2	6	4	1	1	1	1	0.115

λ_{max} = 10.5709 CR = 0.0426

Table 9 Pair-wise comparison matrix for bead width

BW	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	*Local Weight*
E_1	1	1	1	1/3	½	1/6	1/6	1/5	¼	1/3	0.034
E_2	1	1	1	¼	1/3	1/3	¼	1/7	1	¼	0.038
E_3	1	1	1	2	½	1/3	1/6	8	¼	3	0.079
E_4	3	4	½	1	3	1/5	¼	2	4	1/5	0.091
E_5	2	3	2	1/3	1	1/3	1/7	1/6	1/3	2	0.059
E_6	6	3	3	5	3	1	1/5	1/5	3	½	0.129
E_7	6	4	6	4	7	5	1	1	½	1/8	0.179
E_8	5	7	8	½	6	5	1	1	1	1/8	0.164
E_9	4	1	¼	¼	3	1/3	2	1	1	7	0.099
E_{10}	3	4	3	5	½	2	8	8	1/7	1	0.184

λ_{max} = 10.9443 CR = 0.0704

Table 10 Pair-wise comparison matrix for heat affected zone

HAZ	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	*Local Weight*
E_1	1	1/3	1/3	½	½	4	3	1	1/5	1/3	0.063
E_2	3	1	1	¼	¼	½	1/3	½	¼	1/6	0.044
E_3	3	1	1	1/5	1/7	1/3	4	2	1/8	1	0.065
E_4	2	4	5	1	3	½	½	1/7	¼	6	0.111
E_5	2	4	7	1/3	1	¼	¼	2	1/3	¼	0.091
E_6	¼	2	3	2	4	1	1/3	½	1	1/5	0.078
E_7	1/3	3	¼	2	4	3	1	1/3	1/7	4	0.093
E_8	1	2	½	7	½	2	3	1	3	½	0.130
E_9	5	4	8	4	3	1	7	1/3	1	1/8	0.173
E_{10}	3	6	1	1/6	4	5	¼	2	8	1	0.159

λ_{max} = 10.9231 CR = 0.0688

Table 11 Pair-wise comparison matrix for Brinell hardness number

BHN	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	*Local Weight*
E_1	1	1	1	¼	1/5	1/3	1/7	1/6	1/6	1/3	0.024
E_2	1	1	1	¼	1/5	1/3	1/7	1/6	1/6	1/3	0.024
E_3	1	1	1	¼	1/5	1/3	1/7	1/6	1/6	1/3	0.024
E_4	4	4	4	1	½	2	¼	1/3	1/3	2	0.081
E_5	5	5	5	2	1	3	1/3	½	½	3	0.120
E_6	3	3	3	½	1/3	1	1/5	¼	¼	1	0.053
E_7	7	7	7	4	3	5	1	2	2	5	0.259
E_8	6	6	6	3	2	4	½	1	1	4	0.180
E_9	6	6	6	3	2	4	½	1	1	4	0.180
E_{10}	3	3	3	½	1/3	1	1/5	¼	¼	1	0.053

λ_{max} = 10.2754 CR = 0.0205

Table 12 Local and global weights for alternatives and local weights for criteria

Alt No.	*Local weights*						*Global weights*
	MDR	DOP	BH	BW	HAZ	BHN	
	0.0396	0.0507	0.1278	0.1366	0.2163	0.4291	
E_1	0.019	0.032	0.036	0.034	0.063	0.024	0.0355
E_2	0.052	0.038	0.081	0.038	0.044	0.024	0.0393
E_3	0.020	0.038	0.044	0.079	0.065	0.024	0.0435
E_4	0.052	0.083	0.051	0.091	0.111	0.081	0.0840
E_5	0.123	0.091	0.075	0.059	0.091	0.120	0.0983
E_6	0.123	0.089	0.177	0.129	0.078	0.053	0.0892
E_7	0.195	0.116	0.140	0.179	0.093	0.259	0.1872
E_8	0.195	0.266	0.138	0.164	0.130	0.180	0.1666
E_9	0.195	0.163	0.142	0.099	0.173	0.180	0.1623
E_{10}	0.028	0.167	0.115	0.184	0.159	0.053	0.1065

5. Results and Discussion

Assessment of weld quality has first been made through visual observation of depth of penetration, height and width of weld bead and heat affected zone. From the experimental results of low carbon specimens, it is clearly seen that at 80 volts, 316 amp current and 420 mm/min speed good weld is resulted. For the low travel speed of welding torch with medium weld voltage and all the current combinations good penetration and thick and uniform metal deposition are observed. On the other hand, at the higher speed of welding torch the penetration and metal deposition are not uniform, spatter of the filler metal is observed. It also observed from the experiment, penetration decreases with high voltage, current and speed condition. At the combination of voltage 80 volts, current 316 ampere and speed 420 mm/min is favorable condition for welding because at this combination the global weight of the alternative is maximum. Other high global weights are obtained for E_8, E_9 and E_{10}. Finally, applying the concept of analytical hierarchy process, we are able to optimize the parameters of metal inert gas welding and solve this practical problem to take a complex decision about this problem which is more effective for welding.

6. Conclusion

Following conclusions may be drawn from the work reported;

1) From the AHP analysis it is found that for low carbon steel at 80 volt, 316 amp, and 420 mm/min speed, the result is satisfactory as the global weight of E_7 is the maximum. This is in conformity with the results observed from the experiments.
2) One can use this process to find out proper sets of parameters to have a good welding joint by MIG or any other processes having large number of parameters.
3) Since the imperfect definition of factors may cause either difficulty in comparison or omission of information, AHP structure identification and element selection of each hierarchy can hence have a direct effect on the results.
4) Like other systems analysis methods, AHP still has its limits for application. but nevertheless, the research shows that in dealing with the decision-making problems of a multi-hierarchy system, AHP provides a powerful tool through synthesizing various options and finally gives both qualitative and quantitative analyses, and the process itself is in fact a process of understanding the complex system.

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