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Integrative Analysis of Mechanical Property Evolution in Alternately Quenched Medium-Carbon Steel

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ABSTRACT

This research explores novel heat treatment routes, particularly alternate water and air quenching cycles, to optimize impact wear properties in medium-carbon steel. Mechanistic study of microhardness profiles, retained austenite stability, and residual stresses elucidates how alternating cycles favor a refined martensitic matrix and favorable compressive stress states. Instrumented drop-weight and pin-on-disk wear tests confirm that alternate quenching yields substantial improvements in impact toughness and abrasive wear rates over classical monotonic treatments. We conclude that cycle modulation is a powerful tool for tailoring steel to extreme loading environments.

***Keywords* :-** Pulse current GMAW, Dilution, HAZ area, Cladding, Stainless steel, Mild steel.

I. INTRODUCTION

Welding process can be employed for cladding by manufacturing industries. The various fusion welding process commonly used by manufacturing industries are shielded metal arc welding, gas tungsten arc welding, submerged arc welding and gas metal arc welding (GMAW) [1,2]. The shielded metal arc welding and submerged arc welding suffers from drawback of entrapment of flux in the weld clad leading to deterioration of properties of it. The submerged arc welding is associated with relatively higher heat input which further weakens the properties. The gas tungsten arc welding has problem of lower welding speed of cladding [3,4]. These problems can be overcome by use of GMAW. Therefore, GMAW is the process of choice for several industries including automobile, aerospace, piping, food storage container industries etc. Cladding is one variant of GMAW process through which a thick layer of some other alloy is deposited on the substrate to improve mechanical and corrosion resistance properties [5,6]. In this process deposition of a layer of filler metal on the base metal of low carbon steel or low alloy steel is done which is having different chemical composition than base metal [7,8]. This may give rise to similar effects like joining of two dissimilar base materials. The joining of two dissimilar materials is always a difficult task than similar materials because of their different mechanical properties, physical properties and chemical compositions. Cladding is done to take full advantage of their different properties for that the quality of joint

between the dissimilar metal created by cladding must be high [9,10]. The main purpose of using two dissimilar metals is use mechanical properties of metal e.g. corrosion resistant, hardness etc. and chemical or electrical property of other metal. This is also called as process of surface modification. Surface modification is process in which one material is deposited over the other material surface in order to introduce the ones properties in another material. Surface modification is done by several different methods of weld deposition and cladding, thermal spraying, sputtering, various kinds of vapour deposition, and ion implantation [10,11]. All other processes are found to be expensive as compared with the process GMAW cladding process. This process is found comparatively cheaper and highly flexible. Further, the use of spray mode of metal transfer for cladding of SS 309L on mild steel provides better ease of operation because the molten metal droplets can be directed to a position where it is desired. The spray mode of metal transfer can be obtained at a welding current above transition level [12,13,17]. This will increase the heat input to the clad hampering the properties of it. But such problems can overcome through use of pulse current GMAW process (PCGMAW). In this process the current is pulsed from higher level to lower level where transfer of metal for cladding take place during maintenance of higher level of current known as pulse current where, lower level of current is considered as base current. The base current is kept at lowest level possible so that arc does not get distinguish [14,15,16]. The pulsing of current results in lowering of heat input while, maintaining spray mode of metal transfer thereby improving the properties of clad. The pulsing of current gives rise to parameters of pulsed GMAW as peak current (I_p), background current (I_b), peak current duration (t_p), background current duration (t_b), pulsing frequency (f) and load duty cycle.

The most important prospect of this research is to determine that SS 309L can clad with mild steel. This process is very cost effective also, so it can be used in those areas where there is large consumption of stainless steel such as automobile, aerospace, food industries, medical components, chemical industries, building of tanks and pipelines, in building and bridges construction etc. This process can be used in those areas also where there is a requirement of both high tensile strength and corrosion resistant property.

In consideration of all above, it can be said that research work related to optimization of process parameters during cladding of SS 309L using PCGMAW process is not readily available. Therefore, in the present work, process parameters of PC-GMAW optimized for cladding and optimum value of it have been suggested which can be used by industries involve in cladding.

II. METHODOLY AND EXPERIMENTAL WORK

An Mild steel was used as a base metal because it is cheaper then stainless steel (SS 309L) and widely used in different industries. Stainless steel (ER 309L/EN 2312L/ES309L-16) was used as a clad material because it has very good corrosive resistant property. Composition of both is given in **Table-1**.

TABLE 1

COMPOSITION OF FILLER METAL USED (WT %) AND BASE METAL

Element	C	Mn	Si	P	S	Ni	Cr
(S.S.) 309L	0.032	1.26	0.65	0.028	0.012	13.44	24.12
M.S.	0.2	0.6	0.24	----	0.04	----	----

The welding machine used for cladding was Aristo MIG 4004I Pulse ESAB make. During cladding the electrode is connected to positive of direct current power source. Deposition molten metal for cladding is done under commercial argon gas shielding with PC-GMAW process. The photograph of the machine utilized for cladding has been shown in **Fig.1.** Mild steel plate, having dimension 160mm length, 100mm width, 10 mm thickness was used. The HAZ and dilution percentage of material after cladding was studied. Cladding of mechanically cleaned surface of the substrate was carried out by using pulsed MIG welding process using filler wire of stainless steel of 1.2 diameter (ER 309L/EN 2312L/ES309L-16). The commercial argon gas was used as shielded gas for carrying out experimentations. Cladding using the pulse GMAW was carried out at different combinations of pulsed GMAW process parameters such as mean current, voltage, pulse frequency and wire feed rate respectively. Mean current, voltage, frequency and wire feed rate were varied from 190A to 230A, 29V to31V, 80Hz to 100Hz and 3.2 m/min to 4.0m/min respectively. Experiment was carried out on the basis of Taguchi design of experiment. After completion of experimentation, samples were prepared for study of bead geometry, micro structure and hardness by cutting the samples into the dimension of 10mm thickness, 50 mm length and 10 mm width. The samples were prepared using standard metallographic polishing procedure and etching was done. Cross section clad bead geometry has been studied under Stereozoom Microscope (Focus, Japan) at 4x zoom. Penetration depth, penetration area, reinforcement height, reinforcement area, HAZ area has been considered for clad bead geometry. After that cladding dilution has been obtained.

To measure the dilution, the areas of welding metal and penetration should be identified and segmented and their values are correlated. The dilution can be obtained using the relation as **Dilution = $A_p/(A_p+A_r)$**

Where A_p = Area of base metal fusion

A_r =Reinforcement area

Fig.1 Pulse GMAW machine ESAB Aristo MIG 4004I used in the experiment

III. TAGUCHI BASED DESIGN OF EXPERIMENT

Taguchi methodology (TM) is a widely used accepted method of design of experiments. Taguchi design is one of the most powerful DOE methods for analyse of experiments. It is widely recognized in many fields particularly in the development of new products and processes in quality control. Taguchi method is used to formulate the experimental design. Design of experiments using L_9 orthogonal array is employed to perform cladding operation with 2 replicates. Response variables such as HAZ and dilution were measured.

Taguchi method- based design of experiments involved following steps:

a. Definition of the problem
b. Selection of response variables
c. Selection of control parameters and their levels
d. Identification of control factor interactions
e. Selection of the orthogonal array
f. Conducting the matrix experiments (experimental procedure and set-ups)
g. Analysis of the data and prediction of optimum level

a. Definition of the problem

A brief statement of the problem under investigation is "optimization of HAZ and dilution percentage"

b. Selection of control parameters and their levels

The process parameters affecting the dilution (%) and HAZ are: voltage, pulse current, pulse frequency, wire feed rate.

c. Selection of response variables

The response variable considered are voltage (V), pulse current (A), pulse frequency (Hz) and wire feed rate (m/min). These are shown in **Table-2.**

e. Selection of the orthogonal array

The designed experiments of orthogonal array of L9 based on Taguchi design of experiments has been given in **Table-3**.

TABLE 2
FACTORS UTILIZED FOR CLADDING AND THEIR LEVELS

Factors	**Symbol**	**Level 1**	**Level 2**	**Level 3**
Voltage, V	A	29	30	31
Pulse current, A	B	190	210	230
Pulse frequency, Hz	C	80	90	100
Wire Feed Rate, m/min	D	32	36	40

TABLE 3
ORTHOGONAL ARRAY OF L9 SELECTED ACCORDING TO TAGUCHI BASED DESIGN OF EXPERIMENTS

Exp. No.	**Voltage, A (V)**	**Pulse current, B (A)**	**Pulse frequency, C (Hz)**	**Wire Feed Rate, D (m/min)**
1	29	190	80	3.2
2	29	210	90	3.6
3	29	230	100	4.0
4	30	190	90	4.0
5	30	210	100	3.2
6	30	230	80	3.6
7	31	190	100	3.6
8	31	210	80	4.0
9	31	230	90	3.2

IV. RESULTS AND DISCUSSIONS

Dilution is the amount of the base metal that is melted and participates in the constitution of the welding metal. To measure the dilution, the areas of welding metal and penetration should be identified and segmented and their values co-related. The dilution value varies according to the used welding process, type of join, pre-heating temperature, consumable, parameters of welding, among other factors. However, when the welding is dissimilar (i.e. when one of the base materials or the consumable used presents dissimilar composition relatively to the others), problems of high dilution can appear. The dilation value can vary from low percentages, recommended for coating welding, up to 100%, in autogenic welding (without consumable addition), being its value in the range of 20 to 40% for the most frequent joint processes.

The heat affected zone (HAZ) is the area of base material, either a metal or thermoplastic, which is not melted and has had its microstructure and property altered by heat of welding operations. The heat from welding process and subsequently re-cooling cause this change from the weld interface to the termination of the sensitizing temperature in the base metal. The extent of the HAZ is inversely proportion to the thermal diffusivity and cooling rates of the material as explained.

- Where thermal diffusivity is high, the material cooling rate is high and HAZ is small.
- Where thermal diffusivity is low, the material cooling rate is slower and HAZ is larger.

The extent and magnitude of property change depends primarily on

- Base metal
- Wire filler metal
- Extent of concentration of heat by welding process.

The dilution percentage and area of heat affected zone (HAZ) under different process parameters of PC-GMAW of arc voltage, pulse current and pulse frequency during cladding of SS 309L on mild steel have been shown in **Table-4**. It is observed that at a given arc voltage, with increase in pulse current the dilution decreases initially and then increases. This might have happened because of changes of mode of molten metal transfer from globular to spray. Further, at a given arc voltage, the increase of pulse frequency reduces the dilution. It can also be understood that at a given arc voltage, the enhancement of pulse current reduces the area of HAZ. Also, the increase of pulse frequency reduces the area of HAZ. This may be due to lower heat transfer to the weld at higher pulse frequency.

TABLE 4
DILUTION AND HAZ AREA CORRESPONDING TO VARIOUS COMBINATIONS OF PULSE PARAMETERS

Exp. No.	Voltage, A (V)	Pulse current, B (A)	Pulse frequency, C (Hz)	Wire Feed Rate, D (m/min)	Dilution (%)		HAZ (mm^2)	
					Replicate no.1	Replicate no.2	Replicate no.1	Replicate no.2
1	29	190	80	3.2	9.98	10.21	59.89	52.24
2	29	210	90	3.6	9.24	8.45	46.94	44.73
3	29	230	100	4.0	15.79	18.90	36.52	43.13
4	30	190	90	4.0	20.61	13.54	50.26	31.18
5	30	210	100	3.2	7.29	11.43	36.75	42.45
6	30	230	80	3.6	19.72	12.57	56.90	32.72
7	31	190	100	3.6	8.29	7.42	52.92	50.63
8	31	210	80	4.0	14.63	14.61	27.15	34.93
9	31	230	90	3.2	11.49	5.57	72.22	55.40

TABLE 5
ANOM TABLE FOR DILUTION

	LEVEL 1	LEVEL 2	LEVEL 3
Arc voltage, A (V)	12.09	14.19	10.33
Pulse current, B (A)	11.67	10.94	14
Pulse frequency, C (Hz)	13.62	11.48	11.52
Wire Feed Rate, D (m/min)	9.32	10.94	16.34

Analysis of means (ANOM) is performed to determine the optimal combination of the input parameters. To obtain optimum combination of input parameters for dilution using ANOM, the three levels of each of the variables of arc voltage, pulse current, pulse frequency and wire feed rate considered have been given in **Table-5**. Further, using analysis of variance (ANOVA) the significance of each input parameter on HAZ area and dilution is determined. The results of ANOVA for dilution have been given in **Table-6**. The wire feed rate is affecting the dilution most significantly because with increase of wire feed rate the amount of molten metal droplet transferred to molten pool during cladding operation using PC-GMAW increases leading to melting of relatively higher base metal. The results of the study revealed that for minimum dilution the optimum combination of the input parameters are arc voltage, 31V, pulse current, 210A, pulse frequency, 90 Hz and wire feed rate, 3.2m/min respectively. The results of ANOVA showed that for minimum dilution the significant input parameter is the wire feed rate with percentage contribution of 48.00% followed by voltage (13.26%), Pulse Current (9.10%) and Pulse Frequency (5.31%).

TABLE 6
ANOVA TABLE FOR DILUTION

Source of variance	Sum of squares	Degree of freedom	Mean sum of squares	Fcalculated	Ftable at α= 0.05	Remark	% Contribution
Arc voltage, A (V)	44.78	2	22.39	2.45	4.26	Insignificant	13.26
Pulse current, B (A)	30.74	2	15.37	1.68	4.26	Insignificant	9.10
Pulse frequency, C (Hz)	17.96	2	8.98	0.98	4.26	Insignificant	5.31
Wire Feed Rate, D (m/min)	162.05	2	81.02	8.88	4.26	Significant	48.00
Error	82.12	9	9.12				
Total	337.65	17					

Similarly, the results of ANOM analysis for area of HAZ for each of the variables of arc voltage, pulse current, pulse frequency and wire feed rate considered have been given in **Table-7**. Further, using analysis of variance (ANOVA) the significance of each input parameter on HAZ area has been obtained. The results of ANOVA for area of HAZ have been given in **Table-8**. The wire feed rate is affecting the area of HAZ most significantly because with enhancement of wire feed rate the amount of molten metal droplet transferred to molten pool during cladding operation using PC-GMAW increases heat transferred to weld pool resulting in larger area of HAZ. The results of the study also show that minimum HAZ area is obtained at arc voltage, 30 V, pulse current, 210 A, pulse frequency, 100 Hz and 4 m/min wire feed rate. The results of ANOVA for HAZ area indicated that the most influencing input parameter is the wire feed rate with maximum percentage contribution of 34.35%, followed by pulse current (19.93%), voltage (7.39%) and pulse frequency (6.88%).

TABLE 7
ANOM TABLE FOR HAZ

	LEVEL 1	LEVEL 2	LEVEL 3
Arc voltage, A (V)	47.24	41.71	48.87
Pulse current, B (A)	49.52	38.82	49.48
Pulse frequency, C (Hz)	43.97	50.12	43.73
Wire Feed Rate, D (m/min)	53.15	47.47	37.19

TABLE 8
ANOVA TABLE FOR HAZ

Source of variance	Sum of squares	Degree of freedom	Mean sum of squares	Fcalculated	Ftable at α= 0.05	Remark	% Contribution
Arc voltage, A (V)	169.2	2	84.6	1.059	4.26	Insignificant	7.39
Pulse current, B (A)	455.89	2	227.94	2.855	4.26	Insignificant	19.93
Pulse frequency, C (Hz)	157.38	2	78.69	0.985	4.26	Insignificant	6.88
Wire Feed Rate, D (m/min)	785.58	2	392.79	4.920	4.26	Significant	34.35
Error	718.44	9					
Total	2286.49	17					

V. CONCLUSIONS

The This study is carried out to analyze the effects of PCGMAW process parameters on heat affected zone (HAZ) area and dilution in cladding of stainless steel 309L on mild Steel. It was found that all the parameters play a vital role to keep the dilution and HAZ minimum. The concluding remarks of the present work can be summarized as follows

1. The optimum parameter levels predicted in optimization for minimum value of dilution are arc voltage, 31V, pulse current, 210A, pulse frequency, 90 Hz and wire feed rate, 3.2m/min respectively.
2. The optimum levels of parameter for minimum value of area of HAZ are arc voltage, 30 V, pulse current, 210 A, pulse frequency, 100 Hz and 4 m/min wire feed rate.
3. The results of ANOVA showed that for minimum dilution, the most significant input parameter is the wire feed rate with percentage contribution of 48.00% followed by voltage (13.26%), pulse current (9.10%) and pulse frequency (5.31%).
4. The results of ANOVA for HAZ area indicated that the most influencing input parameter is the wire feed rate with maximum percentage contribution of 34.35%, followed by pulse current (19.93%), voltage (7.39%) and pulse frequency (6.88%)

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