OPTIMIZATION OF GMAW WELDING PARAMETERS FOR MICRO-ALLOYED A572 GR.50 STEEL

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ABSTRACT

Gas metal arc welding (GMAW) is a simple process due to which it is mostly automated, and hence once welding parameters are established, it is possible to produce long and repeatable welds. Mechanical/material properties around heat affected zone (HAZ) are greatly influenced by the welding parameters. In the present study, emphasis was to observe the weld bead variations, morphology and weld microstructure with respect to different current and travel speed combinations under the same heat input. The results revealed that combination of parameters had significant effect on microstructural feature of welded structure and hence weld strength. Through Taguchi approach optimum parameters were established for the welding and the performance corresponding to this were observed in terms of microstructure, hardness and strength.

KEYWORDS: GMAW, Shielding Gas Mixture (82%Ar+18CO₂), Microstructure & Tensile Strength

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1. INTRODUCTION

High-strength low-alloy (HSLA) steels, or micro alloyed steels, are designed to provide better mechanical properties and/or greater resistance to atmospheric corrosion. Specific mechanical properties/chemical properties can be achieved by micro alloying[1] ASTM A572 gr 50 HSLA is a columbium-vanadium steel grade having wide applications in offshore structures, shipbuilding, bridges, oil/gas vessels, agricultural and construction machines etc[2]. Depending upon the applications and requirements, welding process can provide desired attachment between two surfaces, although the weld strength does get affected by the direction of rolling of the base metal and other metallurgical properties. Welding process can easily accommodate a base plate thickness of 0.5 to 15mm[3]. For fabrication of large and complex structures the weld joint strength is also affected by direction of rolling and metallurgical properties[4]. Gas metal arc welding provides the benefit of long, uniform and defect free joints through parametric control and automation. In GMAW, arc generated between consumable electrode and work-piece provides sufficient heat energy for change in properties of weld bead(WB) as well as of un-melted base metal i.e. HAZ. Heating cycles in welding leads to variation in weld joint strength, thus it becomes essential to analyze the effect of microstructural changes on strength of the welded joint. For a favorable microstructural feature and optimum joint strength, emphasis is given to the welding process parameters in order to achieve the optimum width of HAZ. Although, it is reported that[5, 6] cold cracks that are often observed in HAZ of HSLA steels are related to microalloying elements and thermal cycle experienced by the material during welding. Low level of carbon equivalent (CE) for A572 gr 50 steels are more weldable and lesser susceptible to cold cracking[2]. The susceptibility for cracking can be reduced by low cooling rate, while at high cooling rates, the structures like martensite are the prerequisite for creating the cold cracks leading to lower strengths. Although ferrite and perlite are not sensitive to

cold cracks, HAZ would have superior toughness if structures like martensite and lower bainite are present while quenched structures like martensite is the prerequisite for engendering cold cracks[7]. The welding parameters greatly affect the heat input during welding and hence the microstructural feature and consequently the hardness and strength. Microstructural features are affected by heat input first and then by cooling rate. Higher heat input leads to generation of coarser grain structure[8]. Moreover, welding speed and shielding gas regulation influence the cooling rate. Higher welding speed may result in under fill or humping bead due less heat input, considered as geometrical weld defect which affect the quality of production[9, 10]. However, cracks and ripple cavities are formed at low speeds (due to high heat input) while center line cavities and cracked versions arise due to high speeds. Also, lower welding speeds lead to increase in percentage of intergranular ferrite(IGF). Shielding gas composition and its flow characteristic significantly affect weld and HAZ area. As weld bead surface, heat extraction, and ultimately the mechanical properties are affected by gas flow rate and maximum gas coverage and protection of bead is ensured by sufficient shielding[11, 12]. Among frequently chosen blends of shielding gases (like Ar+He, Ar+CO₂, Ar+ CO₂ +He+ O₂ etc.), blend of CO₂ with Ar being an economical choice (than He) is generally chosen which leads to better arc stability, higher penetration, low spatter and better weld quality[13]. Studies from various studies reported so far, it can be observed that emphasis has been on the weld metal configuration and properties due to weld cycle. Blending of Argon and CO₂ can be further investigated for sound weld and gas flow rate effect on bead shape. HAZ in HSLA steels having a soft zone can be deleterious for the welded joint and is of great concern[14]. Methods like PWHT can be fruitful in the austenite region to eliminate soft HAZ zone in HSLA but cannot be used for larger structures. External cooling methods, like copper backing and argon purging can be a useful tool[15]. The size and number of defects like cracks, center cavities, cracked center cavities, ripple cavities, undercut and humps increased markedly with the welding current. Studies suggests that all welding parameters must be considered to estimate weld geometry with certainty[16]. The effect of parameters like Current (I), weld speed(s) and gas flow rate(f) has been chosen for investigation in the present study. Current and weld speed dictate not only the overall heat imparted in the weld metal and HAZ but, also, predicts the shape, size and metallography of WB and HAZ and finally the strength.

Optimizing the result and choosing the best possible way to get superior properties are key point in the present investigation. HSLA steels designed for better metallurgical and mechanical strength becomes more sensitive to heat input and the welding parameters due to which acceptable range becomes very narrow. Increase in current promotes percentage of IGF consequently toughness decreases with wider CGHAZ generated during slowly cooled weld joints[17]. Shielding gas also influences the total heat retained in the welded area as it protects oxidation and removes the heat and ultimately affects the metallurgy of the weld joint. Optimum process parameters control the size and metallurgical properties of WB and HAZ.

2. MATERIALS AND METHODS

AISI A572 gr 50 hot rolled plates with dimension 200 mm × 50 mm × 5mm were machined on milling machine to get the 60°V groove joint configurations, as shown in Figure 1(a). IS6419(AWS A5.18:ER70S-6) Consumable electrode with diameter 1.2 mm has been used for experimentation. As it is known to provide minimum spatter and stable arc during MIG/GMAW under optimum welding conditions[18]. It is an acceptable interpretation that, slightly over alloyed filler metal with equal or slightly higher tensile strength with respect to base metal should be used[19]. The chemical composition of base metal and filler material has been tabulated in Table 1. The work pieces to be welded were cleaned with ethanol and then butt-welded by automatic GMAW machine (ESAB RC-AUTO-K400). The set-up used for the welding has been shown in figure 1(b).

Table 1: Chemical Composition wt%

Grade	C	Si	Mn	Mo	Cr	P	S	Ni	V	Cd	Co	Fe
A572 gr. 50	0.08	0.4	0.35	0.02	0.02	0.02	0.01	0.015	0.001	0.001	0.002	Balance
Filler wire ER70S-6	0.19	0.98	1.61	--	--	0.025	0.025	--	---	---	---

Figure 1: A) Schematic Diagram of Welded Joint Configuration, B) Actual Diagram of Welding Setup Used.

GMAW welding torch mounted on a variable speed (up to 10mm/sec) MAXIMIG 251 trolley was used for experimentation. Fabricated workpieces were tacked with root gap of 1.2mm and rigidly mounted on Cu backing plate using fixture for fabrication. A 10° torch angle and work piece to contact tube distance of 15mm was set for fabrication. Shielding gas composition of 82%Ar- 18%CO₂ in Direct Current Electrode Positive mode has been used for experimentation. As gas mix is known to provide stable arc with deeper penetration at lower current values because CO₂ has lower ionization potential ultimately/consequently it increases the total heat imparted to the work piece. With increase in CO₂ there has been decrease in UTS from 2 to 4% and least effect on YS[20].

2.1 Optimization by Taguchi Analysis

In this study, concept of Design of Experiment (DOE) has been used through Minitab 17 software to optimize the welding parameters for A572 gr. 50 steel. Taguchi's robust design approach was used to generate the L9 orthogonal matrix. 3 factors and 3 level has been chosen on the basis of preliminary results of GMAW welding as shown in table 2 and table 3. Total 9 experiments were conducted based on input parameters and corresponding levels to find the influence of welding variables of current (I), gas flow rate(f) and welding speed(s) on tensile strength, hardness and microstructures.

Taguchi's method has been proved to be a popular tool for gaining the benefits of quality and cost effectiveness by reduced experimentation cost for researchers[14]. Various steps involved in Taguchi method are Process parameters identification, defining the levels, selection of experimental matrix, evaluation of signal to noise ratio, analysis of variance (ANOVA), determination of optimal level for factors followed by confirmation of optimal process parameter[21]. Workpieces were also analyzed for quality of weld in terms of weld bead appearance as performance measure.

Table 2: L9 Array, Welding Variables for Experimentation

Factors	Level 1	Level 2	Level 3
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Current (I) in Amp	100	135	170
Gas flow rate (f) in L/min	10	14	18
Welding Speed (S) in mm/sec	1.25	2.50	3.75

Table 3: L9 Matrix Results for HI, YS and UTS

Sample No.	Current (Amp)	Gas Flow Rate (L/min)	Welding Speed (mm/sec)	Heat Input (kJ/mm)	Yield Strength (MPa)	UTS (MPa)
S1	100	10	1.25	1.1424	330	390
S2	100	14	2.5	0.5376	329	389
S3	100	18	3.75	0.3584	321	405
S4	135	10	2.5	0.77112	334	395
S5	135	14	3.75	0.57456	328	385
S6	135	18	1.25	1.54224	320	390
S7	170	10	3.75	0.68544	313	399
S8	170	14	1.25	1.82784	320	435
S9	170	18	2.5	0.91392	325	410

2.2 Evaluation of Signal to Noise(S/N) Ratio

YS, UTS and heat input were chosen as response variables to evaluate the effect of various parameters. Therefor “higher the better” for YS and UTS were selected for analysis. Also lower the better criteria was selected for Heat input.

After experimentation with Minitab17 using Taguchi method UTS S/N ratio has been tabulated in table 4. Further to find out the effects and contribution of Yield Strength(YS) Versus Current, Gas Flow Rate, and Weld Speed for criteria of

Table 4: Taguchi Analysis for UTS S/N Ratio

Level	Welding Current	Gas flow rate	Welding speed
1	51.92	51.92	52.14
2	51.82	52.09	52.00
3	52.35	52.08	51.96
Delta	0.53	0.17	0.18
Rank	1	3	2

“Larger the better” and its response for means has been tabulated in table 5. For effect and contribution of UTS Verses Current, gas flow rate, weld speed once again “Larger the better” criteria has been used and its response for means has been tabulated in table 6. Through the analysis it was deduced that current is the most influential parameter followed by weld speed and gas flow rate. Main effects plot for data means has been an indicative for finding the optimum parameter.

Table 5: Taguchi Analysis: Yield Strength Versus Current, Gas Flow Rate and Weld Speed

Response for Signal to Noise Ratios “Larger is Better”				Response for Means		
Level	Welding Current	Gas Flow Rate	Welding Speed	Welding Current	Gas Flow Rate	Welding Speed
1	50.32	50.25	50.37	328.0	325.7	330.3
2	50.11	50.36	50.40	320.3	330.0	331.3
3	50.57	50.38	50.23	338.0	330.7	324.7
Delta	0.46	0.13	0.17	17.7	5.0	6.0
Rank	1	3	2	1	3	2

Table 6: Taguchi Analysis: UTS Versus Current, Gas Flow Rate, Weld Speed

Response for Signal to Noise Ratios “Larger is Better”				Response for Means		
Level	Welding Current	Gas Flow Rate	Welding Speed	Welding Current	Gas Flow Rate	Welding Speed
1	51.92	51.92	52.14	394.7	394.7	405.0
2	51.82	52.09	52.00	390.0	403.0	398.0
3	52.35	52.08	51.96	414.7	401.7	396.3
Delta	0.53	0.17	0.18	24.7	8.3	8.7
Rank	1	3	2	1	3	2

2.3 Analysis of Variance (ANOVA) For S/N Ratios

After analyzing through ANOVA (table 7) it was observed that various parameters contributed in response variables. Current contributed the most (53%) followed by welding speed (6.6%) and gas flow rate (6.25%). Optimum process parameter analyzed through main effect plot as shown in figure 2(a) was 170Amp current, 14L/min gas flow rate and 1.25mm/sec welding speed i.e. sample no. S8. Effects can also be seen through the surface plots drawn in figure 2(b) and 2(c). The Taguchi's results can be verified through the microstructural changes and hardness patterns which would be discussed later.

Table 7: Analysis of Variance for UTS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Age Contribution
Current	2	1030.2	1030.2	515.1	1.60	0.385	53.61
Gas flow rate	2	120.2	120.2	60.1	0.19	0.843	6.25
Welding speed	2	126.9	126.9	63.4	0.20	0.835	6.60
Error	2	644.2	644.2	322.1			33.55
Total	8	1921.6					

S = 17.9475 R-Sq = 66.47% R-Sq(adj) = 0.00%

Figure 2: a) Main Effects Plot for Data Means, Surface Plot of UTS Versus b) Current and Weld Speed c) Current and Gas Flow Rate.

Samples for microstructure characterization, tensile and hardness tests were prepared according to ASTM standard. For microstructure, samples were metallographically polished i.e. grinding (SiC emery papers upto 2500 grit size), mechanical polishing followed by chemical etching with 2% Nital (HNO_3) solution for 20 s. Optical microscopy was conducted by Leitz Metallux-3) at different magnification (100X and 500X). For Vickers micro hardness test the indentations were taken at 2.5 mm below the top surface along transverse section at an interval of 0.5 mm at a load of 100 g and 10 sec dwell time. Dog-bone shaped specimens were prepared for tensile test according to ASTM E8M-04 Standard using CNC

machine followed by grinding upto 800 grit size emery paper to remove the irregularities occurred during welding [22]. Tensile test was conducted on a computer controlled Instron (4206) under ambient condition at a cross head speed of 1 mm/min. The fractured surfaces were observed under SEM for fractography.

3. RESULTS AND DISCUSSIONS

3.1 Heat Input Analysis

Heat input in welding plays an important role in formation of different phases/microstructure in WB, FZ and HAZ. It has been calculated using following equation and tabulated in table 3 [23]:

$$\text{Heat Input (Kj/mm)} = 0.84 \frac{\text{Voltage (V)} \times \text{Current (Amps)}}{1000 \times \text{Travel speed (mm/s)}}$$

Calculated HI values for Samples S1 to S9 prepared under different conditions has been tabulated in table 3, which varied from a maximum of 1.74 kJ/mm (in sample no. S8) to a minimum of 0.34 kJ/mm (in sample no. S3). It can be observed that current is the most influencing parameter with 53.6% contribution (from Taguchi analysis). It governs the total heat imparted in the welding as it is directly proportional to HI and increased electrode melting rate for higher heat input [17]. The HI has large effect on the soft zone width in HAZ as well as control the maximum temperature attained causing variable hardness in the WB and HAZ. It is evident from the hardness graph that, there lies a soft zone governed by cooling rate in WB and HAZ [24]. It is evident from the tensile test and hardness test results tabulated in table 3 and 11. Samples S2, S3, S5 and S7 with low heat input (up to 0.65 kJ/mm) and medium gas flow rate of 12 l/min or responds to higher cooling rate which leads to the formation of harder phases and increases strength and the microhardness of the HAZ and WB. Also, for sample no S1, S4, S6, S9 and S8 with high welding heat input (max. 1.74 kJ/mm) due to constitutional super cooling, there is sufficient time for grain growth in coarse grain heat affected zone (CGHAZ) which also caused the disappearance of martensite gradually with the formation of bainitic structure. Increment in width of HAZ can be easily observed for high HI from micrograph of HAZ as it forces slow cooling and microstructural change for larger area in HAZ. The wider HAZ width is undesirable as it increases the non-uniform structured area, in welded joints and hence the critical failure zone. For various weld parameters/heat inputs HSLA steel base metal experienced different thermal cycles, and different microstructures were formed in HAZ [16]. When the welding heat input was around 0.5 kJ/s, the cooling time was low and thus fast cooling rate easily produced brittle and hard phases in HAZ.

3.2 Macrostructure Analysis

Each nital etched sample revealed a distinctly visible HAZ along arc surrounding weldment. Welding parameters for sample no S1, S3, S8 and S9 produced a perfect bead shape and good penetration with depth to width ratio not exceeding 2:1 which will avoid solidification cracking [25]. Top and side view of welded joint with different welding parameters are tabulated in table 8. These samples depict perfect elliptical bead top with respect to other parameters. Bead width varied from 5.41 mm (for S2) to 8.76 mm (for S4) at the top. Sample S2 has the highest reinforcement followed by S8 and S9 which further lowered to the base plate level in S5 plate for 3.75 mm speed and medium gas flow rate. No undercuts or other defects were found on any sample within the weld parameters selected, but sample S5 and S7 has beads almost collinear with welded plate.

Table 8: Macrostructure, Bead width, Fusion Area and Bead Appearance

Sample No	S1	S2	S3	S4	S5	S6	S7	S8	S9
Cross Sectional View
Bead top View
Bead Width (mm)	8.76	7.28	6.99	8.55	7.56	5.41	6.67	8.12	7.78
Bead Appearance	Good	Good	Very Good	OK	Not Good	Not Good	Good	Very Good	Very Good

High heat input gave wider bead at lower speeds. Appearance of bead shown fully protected bead with luxurious appearance without any spatter spots or defects on either side of weld also providing benefit of no further finishing requirement for the weld. At various heat inputs excellent welds can be performed by selecting proper combinations as conditions for S3, S7, S8 and S9 which has good tensile strength as revealed from tensile test results.

3.3 Microstructural Analysis

The effect of different parameters on microstructural variation was studied through optical micrographs as shown in figure 3 at resolution 500X. Ferrite and a small amount perlite can be observed from the micrograph. According to the Taguchi analysis the optimum parameters were for sample no. S8. BM, WB and HAZ microstructures has been shown in figure 4. S8 depicting the microstructural features containing ferrite, pearlite, and acicular ferrite with narrow CGHAZ with respect to other parameters.

Figure 3: Base Metal A572 gr. 50. **Figure 4: Optical Micrograph of S2, S3, S7 and S8 with a) Weld Bead, b) CGHAZ, c) FGHAZ, d) Base Material.**

The effect of different heat inputs with different preheat temperatures (PT) on microstructure in CGHAZ has been

studied, and the optical microstructures are shown in Gas flow rate has significant effect on the cooling rate in WM and HAZ region. A lower shielding gas flow rate for sample 3 would result in a fast weld metal cooling rate which favours the production of a finer microstructure. As from micrograph of different samples from sample no 4, 5 and 6 with increasing gas flow rate. Similarly from micrograph of different samples for increasing heat input from S3 (5.02kJ/cm), S7(6.34kJ/cm), S6(16.06kJ/cm) and S8 (16.47kJ/cm) the average prior-austenite grain size in CGHAZ increases gradually. The microstructures consist of martensite (dark spots), a number of M-A constituents, and some grain boundary ferrite (GBF) distributed along the prior-austenite grain boundaries and bainitic structure in WM. With increase in heat input the grain size in CGHAZ has increased due to constitutional super cooling effect as well as martensite has disappeared from CGHAZ at higher heat inputs as for sample no.S7and S8.

HSLA steels derive strength by the formation, presence and dispersion of fine carbide particles in the microstructure. Presence of carbon provides solid solution strengthening while concurrently enabling in a noticeable increase in hardenability arising from the formation, presence and dispersion of alloy carbide particles in the microstructure. Lesser martensite was found in the CGHAZ possibly due to high HI and low carbon content of the parent steel. The WM zone microstructure ferrite, acicular ferrite (AF), polygonal ferrite (BF) and Widmanstatten ferrite and upper and lower bainite (WSPF)[26]. Similar structures have been found in AISI 1010 steel welds.

3.4 Microhardness Analysis

The hardness of base material was observed to be 150VHN. The hardness values of different zones of weld joints of sample S8 with parameters 170Amp(I), 18 l/min(f) and 2.5 mm/sec(s) speed is depicted in figure 5(a). Micro hardness for various other samples showed a variation in hardness from base to center of weld bead and has been tabulated in table 9. A sudden dip in hardness just after the fusion line in the CGHAZ was also observed which we speculate due to larger grain size. It was found that hardness of all zones of weld joints of weld pool and HAZ enhances with the increase of weld speed and current due to faster solidification of weld pool at higher speed and relatively faster cooling rate at higher welding speed because of lower temperature gradient.

Table 9: Hardness Distribution in Different Zones of Welded Specimen

Sample No	BM (Substrate)	S1	S2	S3	S4	S5	S6	S7	S8	S9
Weld metal	152	268	265	265	278	275	274	277	265	272
CGHAZ		215	270	278	199	203	180	200	245	202
FGHAZ		250	268	290	263	256	249	265	255	254

Figure 5: a) Hardness Distribution for S8, b) Tensile Test Results According to L9 Matrix, c) SEM Fractograph of S8.

3.5 Tensile Test Analysis

Generally, the weld metal is kept comparatively stronger, and the joint properties are controlled by weld metal chemical composition and microstructure. In uniaxial tensile tests, all specimens fractured away from weld bead i.e. either in base metal or HAZ. Various results of tensile test has been tabulated in figure 5(b). Yield strength (YS) and ultimate tensile strength (UTS) of base plate were observed to be 318MPa and 390MPa respectively (point 0). Maximum strength was observed for sample S8 with parameters of 170amp current, 18l/min gas flow rate and 2.5mm/sec weld speed and is in agreement with the results obtained from Taguchi analysis. With increase in current there has been decrease in yield strength and has similar effect with increase in heat input due to decrease in cooling rate. Gas flow rate influenced the grain size in WB and HAZ causing grain size at low gas flow rate and higher UTS and YS. Scanning electron micrograph of fractograph of specimen S8 is shown in figure5(c). It can be observed that it resembles the typical ductile mode fracture with dimples and plastic flow (white lines). Nb, Ti, V, etc. being a strong carbide/nitride forming elements, contributing to strength by precipitation hardening as they have limited solubility in ferrite and austenite[27]. It may be the reason that the yield strengths of most of the welds increased compared to the parent metal. The percentage elongation of yield point is attributed to the interaction of solute atoms and moving dislocations[28].

4. CONCLUSIONS

The following conclusions may be derived from the experimental investigations:

- From the present investigation, significant variations in bead morphology and weld microstructure can be seen which occur under identical heat input but with different current and travel speed combinations.
- Optimum parameters for higher strength, low heat input and uniformity in grain size in HAZ was achieved with sample no S8. So 170Amp of current, weld speed of 1.25 mm/sec and gas flow rate of 14l/min is recommended for welding the specimens.
- With increase in current from 100Amp to 170Amp there is increase in hardness of HAZ and decrease in ultimate tensile strength was observed and hence with weld at center of the specimen the work piece gets fractured from the HAZ.
- Welding heat input (welding current and speed) affects microstructure of weld metal. As heat input increases, the width of HAZ area also increases and decreases due to increased melting rate. Significant grain coarsening was found in the HAZ of all the joints.

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