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Effect of Process Parameters on the Shielded Metal Arc Welding of HY100 High Strength Low Alloy Steel

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ABSTRACT: This study investigated the effect of process parameters on the mechanical and microstructure properties of welded HY100 HSLA steel using shielded metal arc welding. The study revealed the influence of heat on a welded joint at constant voltage of 30 volts. It was observed that heat input of 1.22 kJ/mm produced high ultimate tensile strength of 300 MPa when E7018 electrode was used. When the heat input was 2.12 kJ/mm, the lowest ultimate tensile strength (UTS) of 265 MPa was observed, which show that high UTS is achieved at a lower heat input. In the case of yield strength of the welded joint, lower heat input of 1.22 kJ/mm produced the highest yield strength of 316 MPa using E7018 electrode. The lowest yield strength of 133 kJ/mm was achieved at heat input of 0.88kJ/mm using E6013 electrode. While higher hardness of 236.3 BHN was achieved at heat input of 1.22 kJ/mm using E6013 electrode thereby indicating that E6013 electrode induces better hardness at welded joint. The microstructure study revealed that the variations in the microstructure of the various welded zones occurred as a result of different heat inputs.

KEYWORDS: Mechanical test, microstructure, indentation, heat input, arc voltage, fusion

I. Introduction

Welding is an efficient and economical method for joining of metals. It is a fabrication process that joins materials, usually metals or thermoplastics by causing coalescence. This is often done by melting the work pieces and adding a filler material to form a pool of molten material (the weld pool) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the welded [1]. In all welding types, the work pieces are melted along a mutual edge or surface, so that the molten metal and often the filler metal are allowed to form a common pool or puddle [2]. Welding is one of the most common fabrication techniques which are extensively used to obtain good quality weld joints for various structural components. Welding has made significant impact on the large number of industries by raising their operational efficiency, productivity and service life of the plant and relevant equipment [3]. In arc welding, the length of arc is directly related to the voltage, and the amount of heat input is related to the current. Heat input is a relative measure of the energy transferred per unit length of weld. It 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) [4]. Welding technology can be applied virtually to every branch of manufacturing viz: 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 [5-9]. The principal advantages of these materials are not only their good combination of strength and toughness, but also their good weldability. In this study, the effect of process parameters such as

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welding current, welding speed and type of electrodes on the mechanical and microstructure of shielded metal welding of HY100 high strength low alloy steels were investigated.

II. RELATED WORK

Most universal engineering materials now consist of steels and they are mainly joined by welding, especially the arc welding process because it is availability, relatively easy to operate and uses consumable electrodes [10]. Yongyutph et al, [11]; Wen et al,[12] and Armentani et al, [13] have equally established that residual stresses have strong influence on weld deformation, fatigue strength, fracture toughness and bulking strength

III. MATERIALS

In this study, 5 mm thick HY100 high-strength low-alloy (HSLA) steel was used as workpiece material and two different types of electrodes (E6013 and E7013). High-strength low-alloy steel (HSLA) is a type of alloy steel that provides better mechanical properties and greater resistance to corrosion than carbon steel . HSLA steels vary from other steels in that they are not made to meet a specific chemical composition but rather to specific mechanical properties. They have carbon content between 0.05 and 0.25% to retain formability and weldability. Other alloying elements includes manganese and small quantities of copper, nickel, niobium, nitrogen, vanadium, chromium, molybdenum, titanium, calcium, rare earth elements, or zirconium. Copper, titanium, vanadium and niobium are added for strengthening purposes. Because of the higher strength and toughness of HSLA steels, it usually requires between 25 to 30% power to form, as compared to carbon steels. Copper, silicon, nickel, chromium, and phosphorus are added to increase corrosion resistance. Two types of welding electrodes were used for the welding during the experiment .One was general purpose electrode E6013 and the other low hydrogen E7018. Tables 1, 2 and 3 show the composition of HY100 HSLA steel, E6013 electrode and E7013 electrode respectively. The technical specifications for the two electrodes are 3.2 mm of diameter and 350 mm of length.

Table 1: Chemical composition of HY100 HSLA steel

Elements	C	Mn	Si	Cr	Ni	Mo
Wt (%)	0.20	0.10 -0.40	0.15- 0.35	1.00- 1.80	2.25- 3.50	0.20- 0.66

Table 2: Chemical composition of E6013 electrode

Elements	C	Si	Mn	P	S
Wt(%)	≤ 0.12	≤ 0.35	0.3-0.6	≤ 0.04	≤0.035

Table 3: Chemical composition of E7018 electrode

Elements	C	Mn	Si	P	S	Mo
Wt(%)	0.07	1.05	0.55	0.016	0.010	0.15

IV. METHODOLOGY

A). Welding process

The transformer type general purpose welding machine, Origo^{TM} Arc 300 was used for the welding of the HY100 HSLA plates in this experiment. Welding process usually requires current as high as 80A and it can even be as high as 12,000A in spot welding. Low current as low as 5A can also be used in welding of two razor blades together with gas tungsten arc welding. A welding

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power supply can be as simple as a car battery and as sophisticated as a modern machine based on silicon controlled rectifier technology with additional logic to assist in the welding process. In this experiment, two plates were machined to dimension of 200 mm x 75 mm x 5 mm for each set of welding process. They were filed, brushed and thoroughly cleaned. The edge preparation suitable for this weld is V- Butt type. The V groove angle of 60^0 and root face of 2 mm was obtained when two pairs of plates were joined together. The edges were cut using grinding machine. Eight pairs of plates were made ready for the study. They were then divided into two groups each to be welded with a different type of electrode and each group with same welding conditions. The root run was firstly done on each of the plates to prepare the groove for the bead to be laid. Laying of the bead was done after the slag was removed from the root bead. The varied welding parameters were electrode type, current and welding speed, while arc voltage was held constant. The primary variable in determining the heat input is the welding current. An increase in amperage means higher deposition rates, deeper penetration and more mixture. The machine setting determines the basic amperage for SMAW. However change in arc length further change amperage. Arc current is reduced by longer arc length. Arc voltage is also directly related to arc length. As the arc length increases, the arc voltage increases. Arc voltage has a direct effect on the heat input computation. It also controls the width of the weld bead [14]. Steady control of arc current and voltage depends on the welder's skill. Welding Speed is defined as the rate of travel of the electrode along the seam or the rate of travel of the work under the electrode along the seam.

$$\text{Weld travel Speed} = \frac{\text{electrode travel}}{\text{arc time}} \text{ mm/min} \qquad 1$$

Heat input is a relative measure of the energy transferred per unit length of weld. Heat input is typically calculated as the ratio of the power (i.e. voltage x current) to the velocity of the heat source (i.e. the arc) as follows:

$$\text{Heat input rate or arc energy, (Q)} = \frac{V \times I \times 60}{v} \text{ J/ mm} \qquad 2$$

where V= arc voltage in volts, I = welding current in ampere, v = speed of welding in mm/min

Table 4: Welding Parameters

S/N	Electrode used	Voltage (V)	Current (A)	Time (s)	Speed (mm/min)	Heat input (kJ/mm)
1	E6013	30	90	113	106	1.530
2	E6013	30	90	65	185	0.880
3	E6013	30	125	113	106	2.120
4	E6013	30	125	65	185	1.220
5	E7018	30	90	113	106	1.530
6	E7018	30	90	65	185	0.880
7	E7018	30	125	113	106	2.120
8	E7018	30	125	65	185	1.220

In addition to this experimental procedure above, visual inspection which involved non- destructive examination (NDE) techniques to check the quality of welds was equally employed. NDE is capable of increasing the quality of fabrication and reducing the generation of weld defects [14] and it is cheap and simple to carry out. There are three stages of visual inspection, (i) pre-welding, (ii) during welding (iii) post welding inspection. The pre-welding inspection aimed at ensuring that the workpiece is of the right quality, size and that is free from any defects. During the welding inspection, the process was checked to ensure that the procedure complies with the AWS specification. The post-weld inspection was carried out to ensure that the specimen was free from weld cracks, porosity, slag appearance and inclusions, bead size and shape, penetration etc.

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B) Tensile Test

The specimen for tensile test was prepared by cutting a section of the plate and machining it to the standard dimension. The specimens were tested for tensile strength using the maekawa testing machine (Model: $AS^2$50ACT). The edges of the specimens were fitted to the jaws of the testing machine by means of chuck. They were then subjected to increasing tensile stresses until fracture. The tensile loads as well as the elongation of previously marked gauge lengths in the specimen were measured with the help of load dial of the machine and extensometer respectively. Hooke's law was applied to evaluate elastic range as shown in equations 3 to 5. While the plastic range behaviour of the metal can be expressed using equations 6 and 7.

$$Stress = \frac{load}{original\,area}\left(N/mm^2\right) \qquad 3$$

$$Strain = \frac{Extension}{original\,guagelength} \qquad 4$$

$$Slope\ (Young's\ \text{modulus} = \frac{stress}{strain}(N/mm^2) \qquad 5$$

$$Yield\ \ stress = \frac{load\ at\ upper\ yield\ \ po\text{int}}{original\ area}(N/mm^2) \qquad 6$$

$$Ultimate\ tensile\ strength\,(UTS) = \frac{\max imum\,load}{original\,area}(N/mm^2) \qquad 7$$

Equation (7) is the most important parameter as it is the one used in design in conjunction with a safety factor, and is always quoted when comparing metals and describing their mechanical properties .

C). Hardness Test

Specimens for hardness test were cut from the plates. Polishing of the surface was required for Brinell hardness test because the presence of grease, oxide scales or debris will significantly affect the hardness values obtained. Although scratches or surface roughness have very small effects on the hardness values measure, they were reduced to ensure accurate result. The steel ball (indenter) was pressed on the surfaces of the specimens for about 30 seconds to provide impressions. The impressions were not distorted and not too deep so as to avoid too much of plastic deformation which might lead to errors of the hardness values. The hardness measurements were taken on 2 mm intervals along the sample thickness starting from the bead centre of the welded metal towards the parent metal. The diameters of the impression were measured using a low magnification microscope thrice and the average value calculated. Brinell hardness value for each of the specimens was then calculated. The typical test uses a 10 mm diameter steel ball as an indenter with a 29 kN force. For softer materials, a smaller force is required; for harder materials, a tungsten carbide ball is substituted for the steel ball. The indentation is measured and hardness calculated as:

$$\text{BNH} = \frac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)} \qquad (8)$$

where P = applied force (N), D = diameter of indenter (mm) and d = diameter of indentation (mm)

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BHN is designated by the most commonly used test standards (ASTM E10-12 and ISO 6506–1:2005) as HBW (H from hardness, B from Brinell and W from the material of the indenter e.g tungsten carbide). In former standards HB or HBS were used to refer to measurements made with steel indenters. HBW is calculated in both standards using the SI units as

$$BHN = 0.102\frac{2F}{\pi D\left(D-\sqrt{D^2-d^2}\right)} \quad (9)$$

where F = applied force (N), D = diameter of indenter (mm), d = diameter of indentation (mm)

D) Microstructure Test

Optical microscope was used for analyzing metallographic specimens. The microscopes magnification range between 50 and 1000, but higher magnifications are possible with specialized oil immersion lenses. The welded samples were sectioned at the fusion zones to make the specimens. Grinding was carried out using emery papers progressively to obtain finer grade. Polishing was carried out carefully to produce mirror like and ridges free surface. The samples were etched with 2% Nital (2% HNO_3 in 98% ethyl alcohol) solution and then dried. The prepared samples were observed using the metallurgical trinocular microscope (Model MM039BOOM) at the magnification of 400X. The microstructures of the fusion zone, heat affected zone and the adjacent base metal for each of the specimens were revealed.

V RESULTS AND DISCUSSIONS

A). Inspections

Pre welding inspection of the material was conducted and observation were made as shown in Table 5 and the result for post welding inspection is equally shown in Table 6

Table 5: Quality of material inspection

S / N	Inspection	Observation
1	Quality	Good
2	Type	The same type of material
3	Size	The same size of material
4	Cleanliness	Good
5	Freedom from defects	Yes

Table 6: Results for after welding inspection

S/N	Inspection	Results / comments
1	Appearance of slag	The colour of slag for E6013 was grey while that of E7018 was brown
2	HAZ and base metal appearance	Not too different from pre weld condition
3	Porosity	The joints are free from porosity
4	Slag inclusion	The joints are free from slag inclusions
5	Weld cracks	No weld cracks
6	Bead size	Bead sizes increases as the current increases
7	Bead shape	
8	Deposition of the electrodes	Deposition increases as the speed decreases
9	Penetration	Penetration is better for a lower speed

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B) Tensile Strength

The ultimate tensile and yield strength properties of the specimens were displayed in Table 7 and 8 and the variation of tensile properties with the process parameters are shown in Figures 1 and 2 for the variation of ultimate tensile and yield stress with heat input rate.

Table 7. Ultimate tensile strength

S/N	1	2	3	4
UTS (MPa) with E6013	285	270	265	290
UTS (MPa) with E7018	290	280	270	300
Heat (KJ/mm) input	1.53	0.88	2.12	1.22

Table 8: Yield strength

S/N	1	2	3	4
Yield Strength (MPa) with E6013	250.0	133.3	266.7	200
Yield Strength (MPa) with E7018	199.3	256.7	183.3	316.7
Heat (KJ/mm) input	1.53	0.88	2.12	1.22

Figure 1 shows the joint with the highest ultimate tensile strength of 300MPa welded with E7018 at heat input value of 1.22 kJ/mm. The least UTS value of 265MPa using E6013 was recorded for the heat input of 2.12 kJ/mm. The values of ultimate tensile strength with heat input subjected to the process parameters are also shown in the figure.

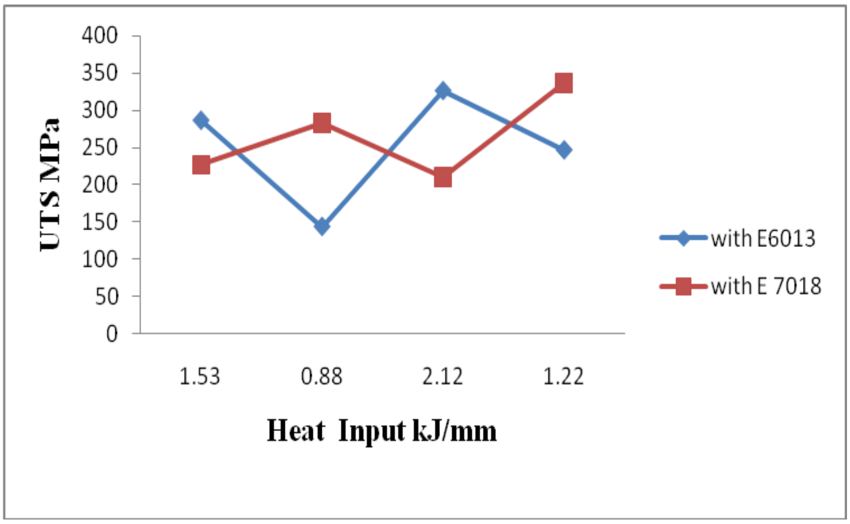

Figure 1: Variation of ultimate tensile strength with Heat input

From the above results of ultimate tensile test, it can be deduced that the ultimate tensile strength is higher at lower heat input. At higher speed, the heat input is lowered which resulted into a better improvement of ultimate tensile properties of the material. It also shows that welding with the E7018 electrode gave higher ultimate tensile.

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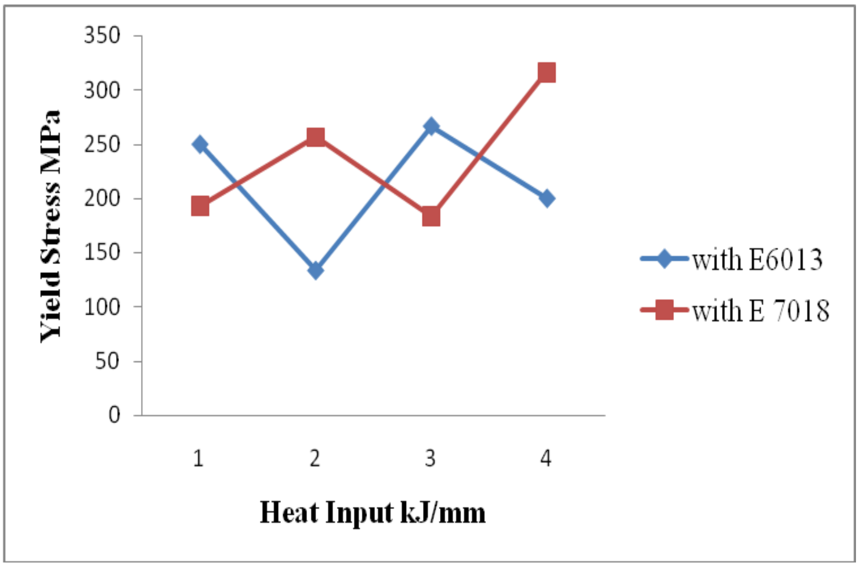
Figure 2 show the best joint in terms of yield strength of 316.7MPa with heat input of 1.22 kJ/mm when E7018 was used. It followed by welded joint that has yield strength of 266.7MPa welded with E6013 at the heat input of 2.12 kJ/mm. The best joint in terms of ductility has the percentage elongation of 10.1. It was welded with E6013 at the heat input of 1.22 kJ/mm followed by the joint having the percentage elongation of 9.6, welded with E6013 at 0.88 kJ/mm.



. Figure 2: Variation of yield strength with heat input

From the above results of yield strength, it can be deduced that the yield strength is higher at lower heat input. At higher speed, the heat input is lowered which resulted into a better improvement of yield strength properties of the material. It also shows that welding with the E7018 electrode gave higher yield strength.

C). Hardness

The hardness was affected by the heat input as shown in Table 9 and Figure 3. The highest hardness value of 236.3 HBN was recorded for the heat input of 1.22 kJ/mm when it was welded with E6013 electrode. The lowest hardness value of 103.7 HBN was recorded for the heat input of 2.12 kJ/mm for E6013 electrode.

Table 9: Result for Hardness Test

S/N	1	2	3	4
Hardness Value(with E6013)	150.4	150,4	130.7	236.3
Hardness Value(with E7018)	103.7	105.4	123.8	103.7
Heat (KJ/mm) input	1.53	0.88	2.12	1.22

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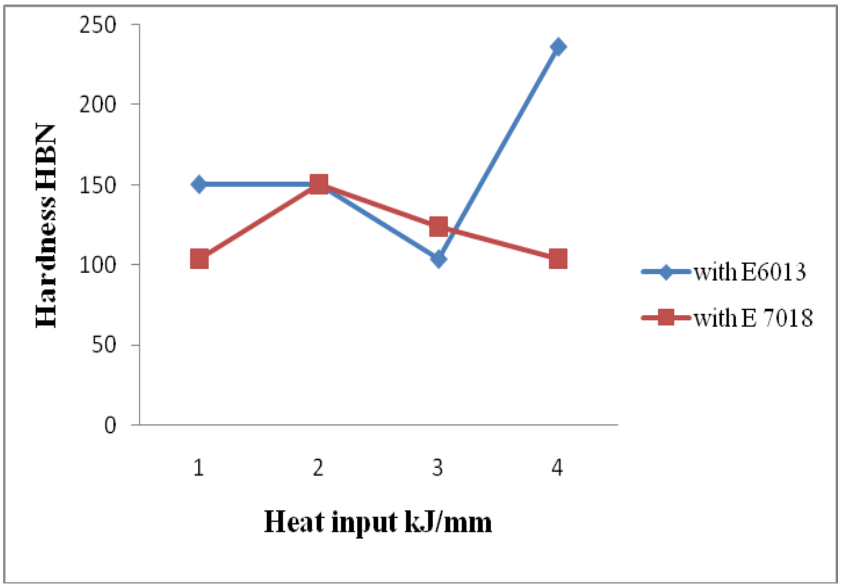

Figure 3: Variation of Hardness Values with Heat input

D) Microstructure

Plate 1 – 8 revealed the variations in the microstructure of the various welded zones as a result of different heat inputs. These determine the grain sizes and compositions of the phases present. As it can be seen, the final microstructures of the welded zones are different from one another and these determine the mechanical properties of the final welded joints. The finest grain size has the highest tensile strength alongside with good hardness value. The results for the metallographic examinations of the various specimens are showed in Plate 1 – 9.

Plate 1 is the microstructure of received HY100 HSLA steel. The bright region indicates ferrite crystals with boundaries. The dark areas indicate the alloy carbide content in the steel. The ferrite iron is also known as α-iron with BCC structure. The carbon content in the alloy carbide is about 0.2%. The structure of the alloy carbide is of very fine dispersion in the pure ferrite matrix. The ferrite iron is responsible for ductility, good tensile strength and impact strength of this metal. The distortion of the pearlitic phase to produce alloy carbide by the alloying elements (Ni, Mo, Mn & Nb) eliminates toughness reducing the effect of a pearlitic volume fraction but still maintains and increases the material strength by refining grain size.

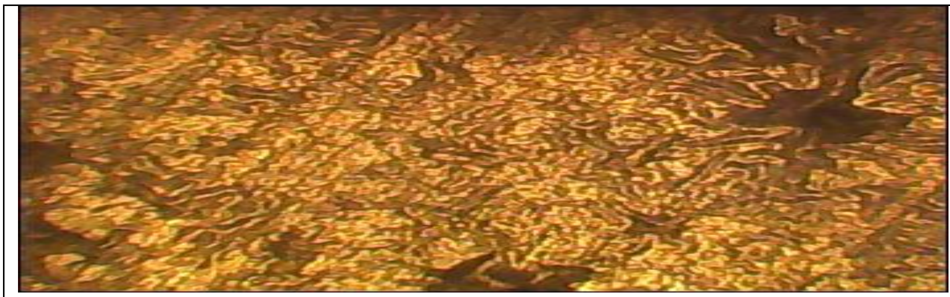

Plate 1: Micrograph of received specimen (X 400)

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Plate 2. Micrograph of specimen subjected to heat input of 1.53kJ/mm using E6013 (X 400)


Plate 3. Micrograph of specimen subjected to heat input of 1.53kJ/mm using E7018 (X 400)

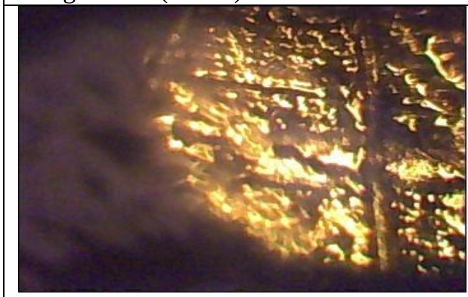
Plate 4. Micrograph of specimen subjected to heat input of 0.88kJ/mm using E6013 (X 400)


Plate 5. Micrograph of specimen subjected to heat input of 0.88kJ/mm using E7018 (X 400)


Plate 6. Micrograph of specimen subjected to heat input of 2.12kJ/mm using E6013 (X 400)


Plate 7. Micrograph of specimen subjected to heat input of 2.12kJ/mm using E7018 (X 400)

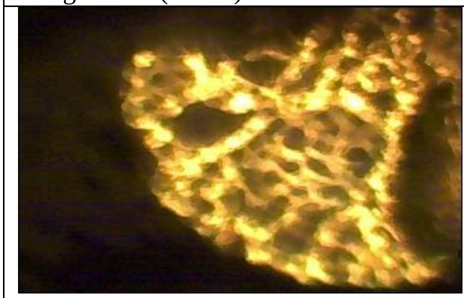
Plate 8. Micrograph of specimen subjected to heat input of 1.22kJ/mm


Plate 9. Micrograph of specimen subjected to heat input of 1.22kJ/mm

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using E6013 (X 400)	using E7018 (X 400)

Plate 2 micrograph shows a fusion zone of a material welded under the conditions of 90A current, 106 mm/min speed resulting in a heat input value of 1.53 kJ/mm and using E6013 electrode. This micrograph revealed deposition of alloy carbide in ferrite matrix along grain boundaries. The diffusion is non-uniform. Clusters of alloy carbide/ pearlite are seen at points close to the edge. Presence of small amount of ledeburite is noticed in this microstructure. Very scanty blow holes are also seen. The structure enhances good ultimate tensile strength and hardness properties.

Plate 3 shows the micrograph for the material welded at current of 90A, speed of 106 mm/min resulting with heat input value of 1.53kJ/mm and using E7018 electrode. The micrograph shows the fine grains of well diffused alloy carbide in the ferrite matrix. The low heat input which is responsible for higher cooling rates ensures very limited grain growth in the microstructure. The fine structure accounts for good tensile strength and hardness. Higher percentage (like 60%) of ferrite in the microstructure still makes the steel ductile. Very scanty blowholes are present. This shows that the joint is almost defect- free.

Plate 4 shows micrograph of a welded joint at the current of 90A, speed of 185 mm/min resulting in a heat input value of 0.88 kJ/mm and using E6013 electrode. The precipitate of alloy carbide is seen to be both diffused and dendrite in nature. The concentration is mostly along the grain boundaries and the edge of the zone and more blow holes are seen.

Plate 5 shows the micrograph of a joint welded with current of 90A and a speed of 185 mm/min resulting in a heat input value of 0.88 kJ/mm and using E7018 electrode. The heat input is moderately low. This accounts for faster cooling rate with little grain growth. The structure has a very fine grain, while the proportions of ferrite and the solute compositions are almost the same. The mechanical properties of this joint were more enhanced.

Plate 6 shows the micrograph of welded joint at high current of 125A and speed of 106 mm/min resulting in a heat input value of 2.12 kJ/mm with E6013 electrode. The structure was predominantly fine grains of alloy carbide in the ferrite matrix. But a section was seen where scanty equi-axed alloy carbide was uniformly diffused in the ferrite matrix. Though the heat input is high, the finer grains were as a result of low speed which accounted for deeper penetration. The mechanical properties were good but comparatively lower than that obtained for low heat inputs.

Plate 7 shows the micrograph of a welded joint subjected to the conditions of 125A, speed of 106 mm/min resulting in a heat input value of 2.12 kJ/mm and with E7018 electrode. The alloy carbide has equi-axed structure uniformly scattered in the ferrite matrix. The grain growth was comparatively higher, thus a coarse structure was enhanced. The patches of alloy carbide are larger and are also formed at the edge of the fusion zone. This structure accounts for lower mechanical properties.

Plate 8 shows micrograph of welded joint at a current of 125A, 185mm/min speed using E6013 electrode. The heat input is 1.22KJ/mm. The micrograph reveals well diffused equi-axed compound of cementite and alloy carbide in the ferrite matrix. Also depositions of the cementite/ alloy carbide precipitate were seen. The clusters formed along the edge were uniform. The combine precipitation strength and transformation strength in the acicular ferrite matrix at the base metal was not too distorted as the heat input was not too high. The structure shows that the joint has good mechanical properties.

Plate 9 micrograph shows the recrystallization of alloy carbide and small amount of cementite during heating. The joint was subjected to the current of 125A and speed of 185 mm/min resulting in heat input value of 1.22 kJ/mm with E7018 electrode. The structure was finer but not well diffused in the ferrite matrix.

VI CONCLUSIONS

The effect of input parameters on the mechanical and microstructure properties of welded HY100 HSLA steel revealed that samples welded at lower heat input have the best mechanical properties in terms of ultimate tensile strength and hardness values.

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It equally showed that at higher heat input, mechanical properties tend to decrease despite the welding induces strength and hardness. It was also noted that current played a major role in determining the heat input. Moreover, welding speed affects the heat input more than the welding current. Furthermore, welding electrode affects, to a large extent, the mechanical properties of the welded joint. With the same heat input, variation in mechanical properties resulted due to change in welding electrode. The following conclusions can be made as the effect of welding conditions on shielded metal arc welding of HY100 high strength low alloy steel.

1. The welding current has the highest influence on the heat input, which in turn affects the welded metal microstructure. Very low current induces welded defects (in the form of undercutting and lack of penetration) while excessive current caused high heat input which resulted in blow holes, excessive penetration and electrode damage. when the welding current was excessively high, it decreased the UTS and hardness values due to resulting higher heat input. Moderate current is advisable for arc welding depending on the requirement.
2. The welding speed is inversely proportional to the heat input, it has effect on the welded joints in relation to the other process parameters, with good welding current, selection of suitable welding speed ensure fine grain size in the final microstructure.
3. Even with the same heat input, there are still variations in the microstructure as a result of different electrodes used, this occurs as a result of impurities in the form of hydrogen inclusions due to electrode type. Low hydrogen content electrode produces less defective weld than those with high hydrogen contents.

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