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INFLUENCE OF WELDING PARAMETERS ON MECHANICAL PROPERTIES OF HIGH STRENGTH LOW CARBON STEEL OF SUBMERGED ARC BUTT WELDS

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ABSTRACT

Hot rolled medium and high tensile structural steel plate specification to E350BR is used for boiler supporting structure. Submerged arc welding process is usually performed for heavy thickness plate built up structural fabrication, as high deposition rate of weld metal. The welding arc parameters has an influence on the chemistry of the deposited weld metal. Welding trials were conducted with different welding parameters. In this paper, the recovery of silicon and manganese content in the weld metal with respect to welding parameter were analyzed. Mechanical properties of weld metal such as Tensile and impact test were conducted at room temperature. Chemical composition and microstructure were analyzed and hardness values were measured at different locations of the weld to predict the properties of weld metal. The test results were correlated with welding parameters which yield the optimum weld chemistry which in turn enhance the strength and toughness.

KEYWORDS: Welding Parameters, Elements Transfer, Mechanical Properties.

In heavy structural steel fabrication, high strength plate material are used to enhance the weight to strength of the structure such as bridges, boiler supporting structure etc. Submerged arc welding process with Direct Current, Electrode Positive is usually employed for higher thickness structural steel fabrication in order to reduce the cycle time. Submerged arc welding process has been carried out using solid filler wire, with flux in the form of granular powder. The flux melts under the arc heat and participate in the chemical reaction [Mitra and Eager, 1984]. As soon as the reaction is over, the slag floats over the molten metal and cover the weld metal during cooling. In order to ensure the process stability, consistent mechanical properties of the weld metal should be established while fabrication. The mechanical properties are affected by dilution of base metal, flux wire combination and transfer of elements [Dallam et.al., 1985 and Burck et.al., 1990]. Welding parameters and flux-wire combinations are the critical variables in SAW process. Systematic analysis has been carried out focusing on elements transfer in molten pool during welding [Indacochea et.al., 1989, Kim et.al., 1990 and Polar et.al., 1991]. The slag protects the metal and removes the undesirable impurities during welding and metal extraction into weld metal. The flux take part in arc zone and the slag which is the result of chemical reaction. The main functions of the slag are to seal the weld, prevent oxidation, removes undesirable elements, reduce heat loss and help alloy transfer. The performance of the flux depend upon arc characteristic and chemical properties of the flux. The large thermal gradient involved during welding prevent the overall slag metal reaction. The mechanical properties of the welds are determined by welding parameters

In addition to flux, the effect of welding parameters which are responsible to weld metal chemistry was also studied [Chai and Eager, 1980]. The significant effect on weld deposit chemistry primarily depends on operating parameters [North, 1977]. The mechanical properties of the weld metal are determined by microstructure developed during welding [Joarder et.al., 1991]. The microstructure in the weld metal is affected by heat input, melting temperature, inclusion due to gas dissolution and solid-state transformation while cooling. As weld metal cools down, dissolved oxygen and deoxidizing elements in the Flux, filler wire and with welding parameters are influencing variables in SAW process. The microstructure, acicular ferrite provide good strength and toughness due to formation of fine grain size. The oxides such as boron oxide, vanadium oxide and titanium oxide in the flux enhance the formation of acicular ferrite in the weld metal [Evans, 1996]. The oxides in the flux contribute to development of oxide inclusions in the weld during slag-metal reaction and that facilitate to nucleation of acicular ferrite in weld metal [Dowling et.al., 1986]. The weld metal chemistry is based on base metal and flux-wire combination [Davis and Bailey, 1991]. In order to ensure the process stability, the consistent mechanical properties of weld should be established while fabrication. Strength and toughness are the critical properties of the weld metal, when dynamic loading is envisaged. The objective of this experiment is to study the effect of welding parameters on chemical composition, microstructure, strength and toughness of the weld metal

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applied on E350 BR steel using medium manganese filler wire by submerged arc welding process.

EXPERIMENTAL PROCEDURE

Test Plate Preparation

High strength low carbon steel plate to specification IS 2062 E350 BR in as rolled condition was identified for experiment with specimen size of 150 x 250 mm and thickness of 28 mm. The test plate ends were prepared for single V groove butt weld profile. The prepared butt joint was welded by submerged arc welding machine with solid wire electrode of AWS, SFA5.17-EM12K specification and solid wire Ø4.0 mm was used with agglomerated basic flux. The chemical composition of the base metal, flux and filler wire are given in table 1, 2 and 3 respectively. The chemical composition of wire play a key role in SAW process Chemical composition is restricted to limitation as specified such as Carbon, manganese, silicon, Sulphur, phosphorous and copper. The copper is limited to 0.5 percent that includes the copper coating over the filler wire. If the other elements are present in the filler wire and total should not be exceeded 0.50 percent excluding iron.

Table 1: Chemical composition of base metal

Elements	C	Mn	P	S	Si	Al	Nb	V	Ti
Wt %	0.170	1.260	0.027	0.010	0.265	0.020	0.030	0.033	0.024

Table 2: Chemical composition of the flux

Material	Elements (wt %)			
	SiO_2+TiO_2	CaO+ MgO	Al_2O_3+MnO	CaF_2
Agglomerated Fluoride basic flux(BI=1.6)	15	30	30	20

Table 3: Chemical composition of the filler wire

Elements (wt %)	C	Mn	Si	S	P	Cu
EM12K, wire Ø 4 mm	0.108	0.986	0.210	0.014	0.012	0.17

The welding parameters were selected such that the heat input of 1.97, 2.02 and 2.2 kJ/mm. The heat input were calculated using equation (1) form the selected welding parameter and parameters were represented in table 4. The weld joint was radio-graphically tested and the soundness of the butt joint ensured.

Table 4: Welding parameters

Ref. No	Welding current, I	Welding voltage, V	Welding speed V, mm/minute	Stick out length, mm	Heat input kJ/mm
1	350	30	320	26	1.97
2	450	30	400	28	2.025
3	550	30	450	28	2.2

Test specimens were prepared from welded specimens for tensile, impact, hardness test, chemical analysis and microstructural examination. Tensile (10x12.5 mm) test specimens were prepared in the welded specimen at different locations across the section thickness and tensile test were conducted on prepared samples. The Charpy impact test specimens were also ground and etched with 10% nital to locate accurate placement of V notches. Test samples were prepared with size 10x10x55 mm with 45 degree V notch of 2 mm depth and with root radius 0.25 mm. Impact test conducted on prepared samples in order to examine the toughness of the weld metal.

Microstructure examinations (Method ASTM E407-11E1& ASM HAND BOOK VOL 7) were conducted on polished surfaces of welded region. The surface was prepared by mechanical polishing with different grades of emery sheets and etched by aqua regia (Royal water) 1:3(Nitric: hydrochloric acid) a yellow orange liquid. The microstructure at different locations of weld metal were captured through optical microscope.

The surface was macro etched to identify location of weld metal. Hardness values were measured at various locations across the weld metal and indentation made by ball Ø2 mm with using load 100 kgf by hardness testing machine, Rockwell hardness with B scale. Chemical analysis were conducted on prepared samples at different locations of weld metal and content of oxygen in the weld metal were analyzed from prepared samples.

RESULTS AND DISCUSSION

Welding Parameters

Welding current determines the rate at which the electrode is melted, base metal fusion and dilution. Increasing the welding current, enhance the amount of filler metal, flux use, penetration and weld reinforcement. When other parameters remain constant, high current will lead to narrow bead with excess penetration which may result in melt 'run-out'. Higher current enhance the fluidity of molten metal and slag, which may tends to run-out of the joint. Additional reinforcement will enhance the weld shrinkage and can cause distortion. On the contrary, low current will result in unstable arc and can cause weld defect.

Welding voltage which governs the length of the arc column, in turn controls the width of the weld. High voltage increases the dilution of base metal and the flux consumption due to wider weld bead. Therefore arc voltage is a key parameter in controlling chemical composition. Welding speed is inversely proportional to heat input, which usually control the bead width and penetration. When all other parameters remain constant, increase in welding speed produces narrower weld bead and increased cooling rate may result in hard micro structure. Low welding speed results in a large molten metal which leads to increased flux consumption and produces weld defect. The effective heat input can be determined on process parameter such as voltage, current and welding head travel speed. For seam welding, the heat input (q_w) is determined by heat input per unit length (kJ-mm^{-1}).

$$q_w = \frac{V \times I \times 0.06}{v} \quad (1)$$

Where V is welding voltage, I is welding current with welding speed, v (mm-minute^{-1}) and process efficiency is neglected.

SAW Flux

Flux is an important consumable for achieving good quality of weld. The composition of flux includes oxides of Mn, Si, Ti, Al, Ca, Mg and other components. The flux is characterized by Basicity Index (BI) and responsible for oxygen transfer to the weld metal. Basicity of the flux is defined as the mass ratio of 'basic' to 'acid' oxides in the slag phase. Basicity more than one is called chemically basic, ratio near unity is called chemically neutral and those less than one is chemically acidic. The basicity or acidity of a flux is related to component of ingredients. Chemically, basic flux are high in MgO or CaO and [Tuliani, et al., 1969] defined as

$$BI = \frac{CaO + MgO + BaO + Na_2O + K_2O + CaF_2 + LIO_2 + 0.5(MnO + FeO)}{SiO_2 + 0.5(Al_2O_3 + TiO_2 + ZrO_2)} \quad (2)$$

Basicity flux has lower weld metal oxygen content being manufactured by agglomeration technique, which contribute better mechanical properties due to less density of inclusions and gases. Basic flux has less density and viscosity which contribute lower current carrying capacity rate and penetration as compared to acidic flux. This flux is hygroscopic and therefore, less tolerant to rust and scaling. It has close control on weld chemistry and deposit. These flux are rich in CaO, MgO, CaF_2, Na_2, K_2O and MnO.

The oxygen content in weld metal is of fundamental importance to nucleation of acicular ferrite. Oxygen content decrease with increasing flux basicity up to 1.25 and remain constant approximate 250 PPM. The reduction in oxygen level in weld metal produces clean weld with regard to oxide inclusions and consequently improves strength and toughness of the weld metal.

Heat Input on Element Transfer

The final microstructure of steel welds and their properties are highly influenced by the weld metal chemistry. The average chemical composition of the weld metals and base metal (BM) obtained using the Optical Emission Spectroscopy (OES) are presented in Table 5.

Table 5: Chemical composition of weld (ASTM E415)

Ref.	Elements (wt%)											
	C	Si	Mn	P	S	Cr	Ni	V	Al	Cu	Ti	Nb
BM	0.188	0.259	1.253	0.023	0.0053	0.0146	0.004	0.032	0.029	0.0062	0.024	0.028
Weld1	0.062	0.789	0.627	0.022	0.010	0.0743	0.026	0.013	0.018	0.033	0.029	0.009
HAZ 1	0.176	0.310	1.182	0.021	0.007	0.022	0.006	0.029	0.028	0.009	0.024	0.025
Weld2	0.052	0.798	0.629	0.019	0.009	0.067	0.024	0.010	0.024	0.034	0.033	0.007
HAZ 2	0.185	0.258	1.253	0.022	0.006	0.015	0.004	0.032	0.029	0.006	0.025	0.029
Weld3	0.053	0.807	0.633	0.020	0.009	0.068	0.024	0.011	0.022	0.034	0.030	0.007
HAZ3	0.179	0.283	1.206	0.023	0.006	0.017	0.005	0.030	0.028	0.007	0.024	0.028

The changes in the weld metal elemental compositions were due to the dilution effect of the base metals by the filler electrode. The extent of dilution of the base metal depend on the amount of electrode material melted, which is depended on heat input. The weld metal elemental compositions that were mostly affected by varying heat input were those of carbon, aluminum, oxygen, nitrogen, manganese and silicon. Those of chromium, nickel, molybdenum, titanium, Sulphur and manganese were minimal.

Since carbon is present in the base metal and the filler rod at different levels, any change in carbon content of the weld metal is ascribed to dilution caused by the electrode. As the welding current increased, electrode melting increased which, in turn, increased dilution but reduced the carbon content. With increasing current the carbon content in the weld metals decreased. The reduction in carbon content will reduce the carbides formed in the welds. The silicon content of the base metal of E350BR steel was 0.265 wt.% and in weld metal was increased to 0.807 wt.% (from table 5). The source of additional silicon into the weld metal was from the flux. The source of the silicon pick-up was from the flux, it meant that increased heat input resulted in increased flux consumption which increased the silicon content of the weld metal.

Microstructural Analysis

The microstructure of the E350BR base metal consists primarily of equi-axed polygonal ferrite grains and pearlite aligned with the rolling direction and shown in fig.1.

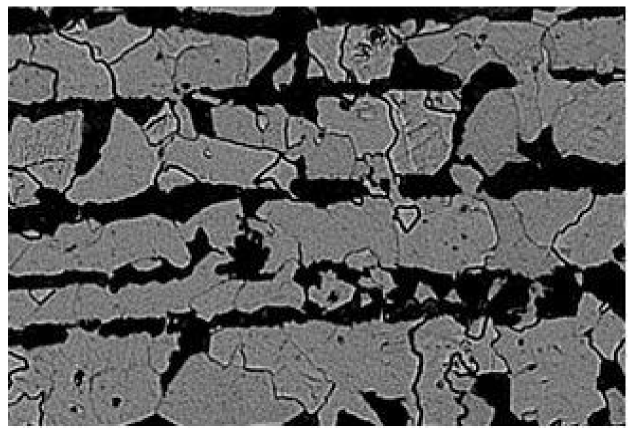

Figure 1: Base metal microstructure@100X

From the investigation, HAZ size is decreased with increasing welding speed, but increases with increasing welding current. When heat input is increased by increasing welding current, for a given welding speed, electrode melting increases and so does the volume of the molten pool. This increases the amount of heat input results in an increase in the HAZ. The micro structure for weld 1 at HAZ (fig.1.a) consists, mix of coarse and fine grains of ferrite and pearlite with some bainite. The HAZ microstructure for weld 2,(fig.1.b) shows zone of mixed fine and coarse grains of ferrite and some bainite structure and for weld 3(fig.1.c), HAZ shows mix of coarse and fine grains of ferrite and pearlite with some bainite.

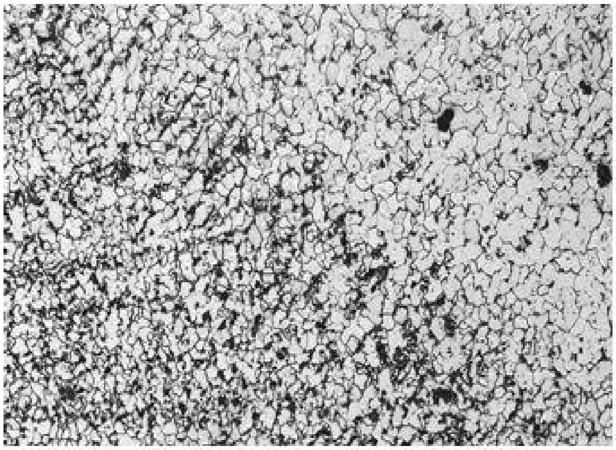

Figure 1a: Weld 1-HAZ@200X

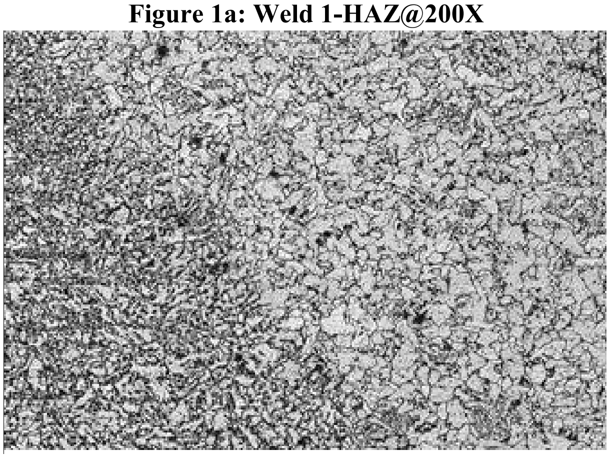

Figure 1b: Weld 2-HAZ@200X

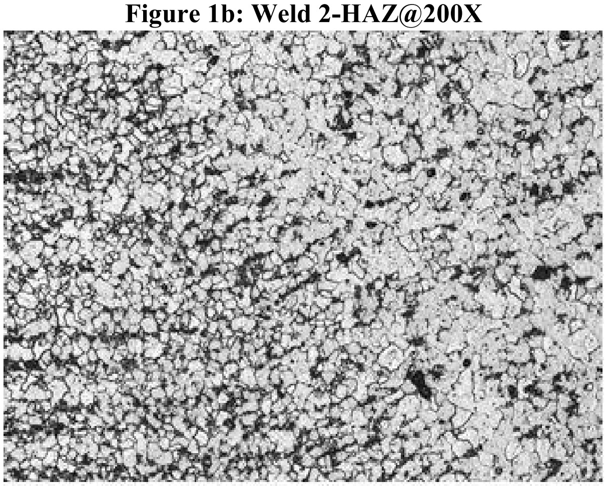

Figure 1c: Weld3- HAZ@200X

The microstructure in the weld metal not only effect of cooling rate but also diffusion of alloying elements. The austenite grain growth occurs after solidifications during cooling in the temperature range approx.1200 °C. In multi-pass welding, the layer are getting annealed on subsequent layer deposited one over and above previous layer deposited. High heat input and low cooling rate favor grain growth. From fig.1.d, shows columnar grains of ferrite and carbides, typical of weld microstructure with some inter refined zones for heat input 1.9kJ/mm and fig.1.e, Weld shows mixed zone of ferrite and bainite with some widmanstatten plates of ferrite for heat input 2.02kJ/mm. Fig 1.f, weld shows mixed microstructure of ferrite and bainite for heat input 2.25 kJ/mm.

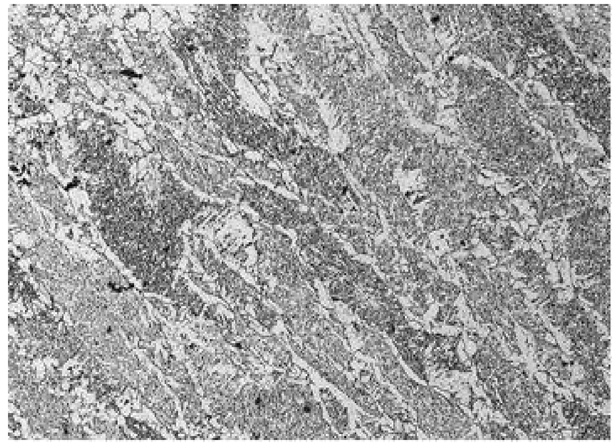

Figure 1d: Weld1-Weld metal@200X

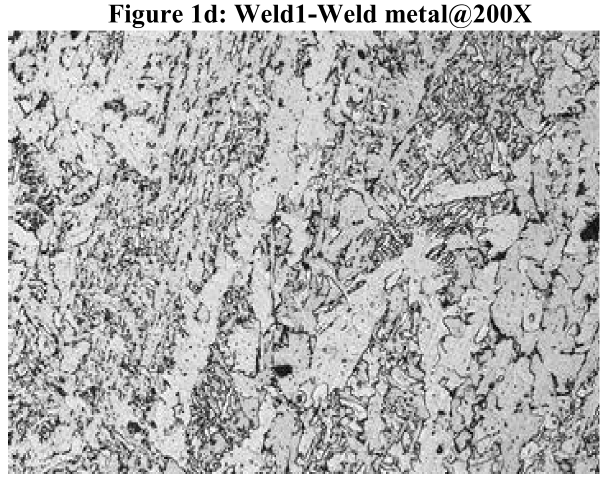

Figure 1e: Weld2- Weld metal@200X

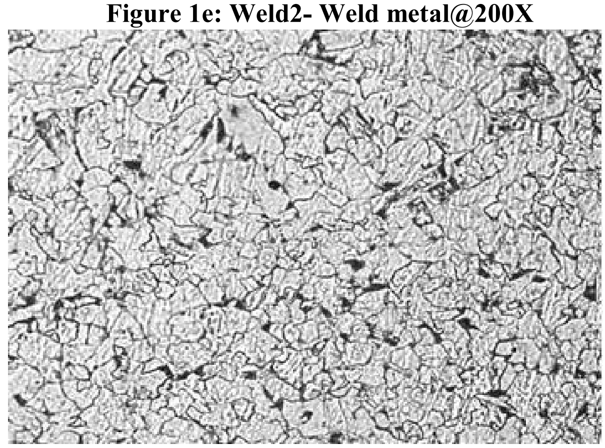

Figure 1f: Weld 3- Weld metal@200X

Notch Toughness

The toughness of steel is influenced by rapid cooling below 300 °C and mainly affected by presence of impurities in steel and welds, which segregate prior to austenite grain boundary during cooling. Manganese and silicon are elements which affects notch toughness. The notch toughness was investigated in order to ensure the impact strength of the weld metal at room temperature.

Mn and Si contents in the flux are to be controlled to get a clean weld metal, because these elements segregate and create uneven microstructure distribution in the weld metal. Silicon increases strength and hardness but to a lesser extent than manganese. For best welding condition, silicon content should not exceed 0.10%. However, amounts up to 0.30% are not as serious. Manganese increases hardenability and tensile strength, but to a lesser extent than carbon. Manganese also tends to increase the rate of carbon penetration during carburizing and acts as a mild deoxidizing agent. Hence carbon is restricted to within 0.05% in weld metal. Impact energy observed at different heat input such as 1.9, 2.025 and 2.25 kJ/mm were presented in the figure 2, 3 and 4 respectively. From the fig, the notch toughness is increasing in trend with increased heat input. This is due to element transfer to weld metal. However the toughness is decreases when heat input greater than 7 kJ/mm as investigated by many workers.

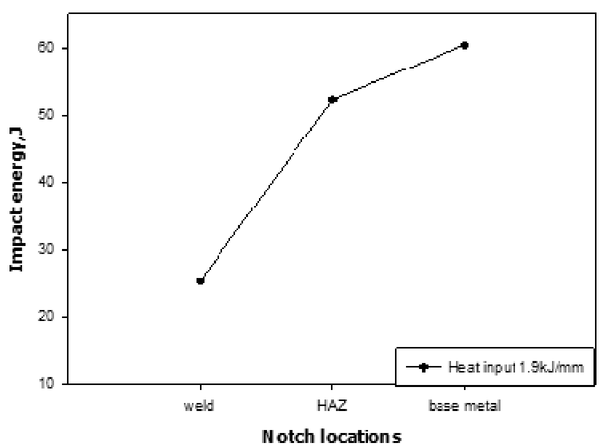

Figure 2: Notch toughness, heat input at 1.9kJ/mm

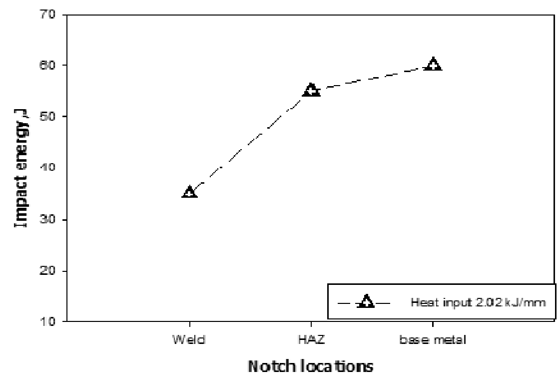

Figure 3: Notch Toughness, heat input at 2.02 kJ/mm

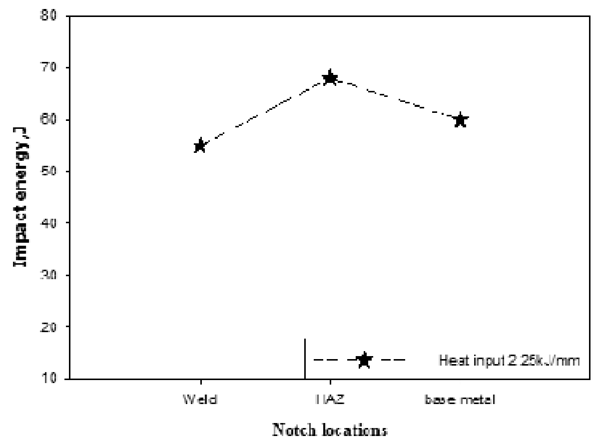

Figure 4: Notch toughness, heat input at 2.25 kJ/mm

Hardness and Strength Analysis

The hardness testing is usual approach to determine the properties of various zones of weld metal. Considering the heat input, the temperature gradient across the weld as well as base metal responsible for different types of microstructure set in. Considering the weld and base metal, hardness distribution in different zone is shown in fig.5. The maximum hardness value are found to be order of 80 to 85 HRB in weld metal and 75 to 80 HRB in base metal. The variation in properties in the weld metal and HAZ can be attributed to several factors particularly phase composition on cooling rate. Heat input 1.9 kJ/mm resulted in maximum hardness values in weld metal. The increasing hardness with heat input1.9 kJ /mm is associated with the presence of hard structure. In multi-pass welding, intermediate weld layers are heated when weld metal is laid one over the other and subsequently layers are annealed. The hardness across the weld zone revels that there is no appreciable variations, since the intermediate layers are relieved from strain due to heating of previous welding pass and layer.

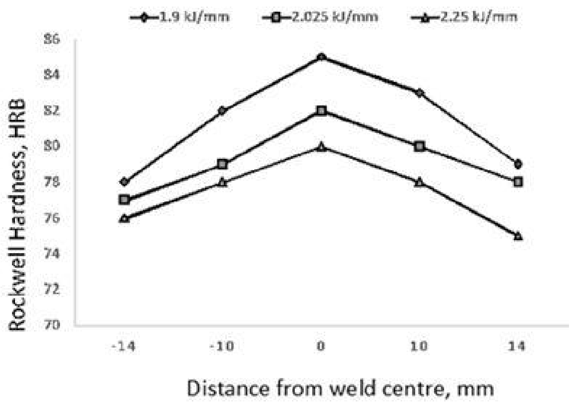

Figure 5: Hardness Values

Tensile strength is one of the key factor, while selection of filler metal and flux. The process parameters have to be established to get the required strength and toughness. The manganese, silicon and other alloying elements are transferred from filler and flux during welding. The increase in silicon during slag-metal reaction, increases the tensile strength of weld metal [Ichire et.al., 1991]. The tensile strength is considered as key factor for test of welded specimen. Yield strength is taken into account, when the base metal is considered for tension test. The tensile strength of the weld is estimated for different heat input and shown in fig.6.

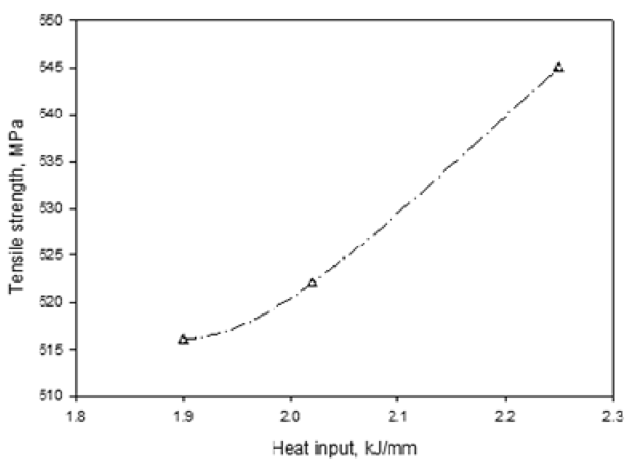

Figure 6: Strength vs Heat input

INFERENCE

The mechanical properties of the weld is based on wire-flux combination and heat input parameters. It is good agreement with prediction of mechanical properties based on welding parameters [Kanjilal et.al., 2006]. Slag-metal reaction enhance the elements transfer from flux and wire. Manganese is with optimum level 0.627 to 0.633%, but silicon transfer is ranging from 0.789 to 0.807%. The increase in silicon enhances the tensile properties but reduce the yield strength. The impact strength is in increasing trend with increase in heat input. However the, heat input is restricted to maximum of 7 kJ/mm to get an optimum properties. The microstructure at the center of the weld zone is completely different from the heat affected zone. At low heat input, microstructure at HAZ is represented by fine grained ferrite and pearlite. The weld metal microstructure shows columnar grains of ferrite and carbides. At higher heat input, microstructure at weld metal is mixed grains of ferrite and bainite. Therefore, the hardness values are comparatively high in welds at low heat input (1.9 kJ/mm). Hardness values in weld metal and base metal are comparatively equal with base metal at high heat input (2.25kJ/mm). These is due to microstructure developed during high heat input and process annealing of layers.

CONCLUSION

1. The optimum weld metal properties are considered based on strength and toughness of the welds, In SAW process, flux-filler wire combination and welding parameters decides the properties of weld metal.

2. Based on investigation, the heat input 2.25 kJ/mm is the optimum parameter for SAW process for E350BR to get desired mechanical properties,

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