Nigerian Journal of Technology (NIJOTECH)
Vol. 31, No. 2, July, 2012, pp. 213–218.

ISSN 1115-8443

EFFECTS OF HEAT INPUT ON THE CHEMICAL COMPOSITION AND HARDNESS OF MILD STEEL WELD

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Abstract

This study examines the thermochemical reactions which alter weld metal chemistry by applying the arc heat considering the convective, radiation and arc heat losses. From numerical analysis, it was found that the radiation heat loss was dominant in the welding process which confirms the claims made by other investigators. From a Spectrometric analysis carried out on all the welded metal specimens after the welding process, it was found that certain alloying elements were lost and others gained. However, multivariate regression analysis revealed that the quantity of Ni present in the base metal, wire, and weldment are higher than the optimum quantity of 1.68 percent by weight. The values for Mn available in the base metal, wire, and weldment are less than the optimum quantity of 1.21 percent by weight. However, the other alloying elements present in weldment fall within the expected optimum values. Most of the significant elements responsible for weldment hardenability such as C, Mo, and Cr were drastically reduced in quantity during the prolonged welding process. In this study the relationship between thermal effect and weld metal chemistry has been adequately treated.

Keywords: alloying element, brinell hardness number (BHN), chemical composition, heat input, thermochemical reaction, weldmetal

1. Introduction

The application of arc heat to melt electrodes which form droplets that eventually produce a weld is a significant area of interest to many researchers. The application of heat stirs up a chemical reaction within the weld pool and causes the molten metal to circulate in a process known as mixing. As the arc heat increases, the mixing becomes turbulent [1-3]. In this turbulent condition, alloying elements are lost and gained because the weld pool becomes unstable at this stage. At the center of the turbulent weld pool, the distribution of heat is uniform, whereas, at the boundaries of the weld pool and the workpieces meant to be welded together, which is the cooler region, a differential heat distribution predominates. This unstable distribution of heat creates a favourable condition for the absorption of oxygen which if absorbed in significant quantities can distort the ductility of the weld metal. This claim is supported by the reports made by Steinberg et al [4,5], that iron particles oxidize in the air in the solid phase. Lau et al. [6] observed that oxygen enters the metal due to plasma-metal reactions in the arc column. This claim was supported by Eagar [7] and Chai and Eagar [8].

Heat is the dominant factor responsible for thermochemical reactions that occur in weld pools, and upon cooling the weld metal chemistry is altered. This statement is supported by Sun and Wu [9] when they reported that welding heat input is the key factor influencing liquid flow, heat and mass transfer, and the thermal cycle in the pool. Eagar [10] reported that thermo-chemical analysis can be a powerful tool in determining which chemical steps control the joining process. The author emphasized that in fusion welding, thermo-chemical analysis has been used to aid in the development of self shielded steel welding electrodes. It has also been used in the reliable prediction of fume formation during arc welding, and applied further in understanding evaporation-limited weld pool temperatures in arc, laser and electron beam processing, as well as in the development of welding fluxes for both steel and titanium alloys. The author further stated that thermochemical analysis of diatomic gas dissociation in welding arc plasmas can provide insight into the mechanisms of gas absorption during welding.

There are some alloying elements that are very volatile. These alloying elements tend to vaporize [11] and as a result are lost from the weld metal. Some of the non volatile alloying elements are gained in the weld metal from the combined amounts present in the electrodes, the base metal, and the flux material (in the case of covered electrodes).

Block-Bolten and Eagar [12] enumerated that loss of alloying elements from the weld pool due to vaporization could impair the mechanical properties of the weld. This loss also causes the composition of welding arc plasma to influence the temperature of the arc, arc stability, and fume formation. Also, the effect of the shielding gas present during the welding process, on the weld pool formation also contributes in the alteration of the chemistry of the weld metal.

Other authors, who have researched on the effect of thermo-chemical reactions on weld metal chemistry are Mitra and Eagar [13], these authors studied the effect of chemical reactions between slag and metal and the compositional change it has on weld metal chemistry. They were able to show that process parameters have a significant effect on weld metal chemistry. Kanjilal et al. [14] conducted a study to understand the chemical behavior of fluxes in order to control weld metal chemistry. Blander and Olson [15] reported their research work on the effect of electro-chemical reaction on weld pool chemistry in submerged arc welding. However, in this study, the thermo-chemical reactions in mild steel weld pool and its resultant chemistry upon solidification is investigated.

2. Materials and Methods

A GMAW machine utilizing a combination of 75%Ar + 25% CO_2 shielding gas with a flow rate of 18 l/min was used to make weld deposits on mild steel base metals that are welded. The base metals were measuring 50 mm × 30 mm × 8 mm in dimension and welded with 3.2 mm mild steel electrodes. Spectrometer was used to determine the chemical composition of the base metal, wire and weld metal. Also the Avery Brinell hardness tester was used for determining the hardness number of the base metal, wire and weld metal. The weld microstructure was determined using the metallurgical microscope.

2.1. Theoretical Equations

Measurements of parameters used for calculations were made and the following equations used by other investigators as shown here under were adopted. Thermochemical reactions controlled by the application of heat input, 0.05 kJ in the welding process. During the welding process, heat losses usually occur. This claim was supported by Kim et al. [16] who wrote that heat losses occur via conduction in the solid rod, radiation exchange with the environment, convection to the shielding gas and evaporation at the weldpool surface. Heat input is presented as a Gaussian distribution heat flux and is given as [17],

$$Q_{arc} = \frac{\eta_d EI}{3\pi\sigma_q^2}\exp^{\left[\frac{-r^2}{3\sigma_q^2}\right]}, \quad r < \sigma_q \tag{1}$$

Where σ_q is the heat flux distribution parameter of the welding arc, given as 3.5 - 4.5 mm [18]. It is defined as the radial distance from the arc center to the position where heat flux decays to 5% of heat flux maximum. For this study $\sigma_q = 4.0$ mm. However, Cho et al. [19] calculated the Gaussian heat distribution parameter as $\sigma_q = 1.533I^{0.2941}$. Lateral distance from the heat source to the weldpool (measured), $r = 3.25$ mm, I is the welding current = 280A, E is the arc voltage = 29V, η_d is the coefficient of the efficiency of welding heat source, Q_{arc} is the heat flux distribution of welding arc.

The convective heat loss, which is responsible for the heat losses at the center of the weldpool, is given by Radaj [20] as

$$q_c = h_c(T - T_0), \ \mathrm{W/m^2} \tag{2}$$

Where q_c is the convection loss, T is the surface temperature of solid = 1480°C, T_o is the temperature in the medium = 1460°C and h_c is the coefficient of convective heat transfer which is given by Goldak et al. [21] as

$$h_c = 24.1 \times 10^{-4} \times 0.9 \times T^{1.61} \tag{3}$$

Where T is the preheat temperature of 300°C.

The radiation loss which is considered to be the most dominant form of heat loss in the welding process was given by ZhongQin et al. [18] as

$$q_r = \varepsilon C_0\left(T^4 - T_0^4\right) \tag{4}$$

Where C_0 is the Stefan-Boltzmann constant = 5.669 × 10^{-8} W/m^2. T^4 and ε is the radiation emissivity = 0.4 [22].

Cho et al. [19] gave an empirical equation for Gaussian current density parameter, σ_c, as

$$\sigma_c = 0.5342I^{0.2684} \tag{5}$$

Where, the melting current, I for base metal, wire and weldment are 150A, 220A and 280A respectively.

Kim et al. [16] and Kays [23] reported a governing thermal energy equation for the wire and droplet in cylindrical coordinates as

$$\frac{\partial\rho l}{\partial t}+\rho u\frac{\partial H}{\partial x}+\rho v\frac{\partial H}{\partial r} = \frac{\partial}{\partial x}\left(kr\frac{\partial T}{\partial x}\right)+\frac{l}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+qG \tag{6}$$

Where the dependent variables are the enthalpy (H) and the specific internal thermal energy (l), v is the

Table 1: Chemical composition and Brinell hardness number (BHN) of mild steel materials.

Element	V	Ti	O	P	N	S	C	Si	Mo	Mn	Ni	Cr	Nb	BHN
Percent by weight (% by wt)														
Basemetal	0.002	0.015	0.029	0.004	0.013	0.001	0.038	0.25	0.23	1.04	2.48	0.078	0.017	328
Wire	0.013	0.009	0.010	0	0.006	0	0.021	0.35	0.17	0.08	2.92	0.089	0.018	286
Weldment	0.001	0.018	0.037	0.002	0.0135	0.001	0.016	0.42	0.24	0.09	2.67	0.056	0.021	256

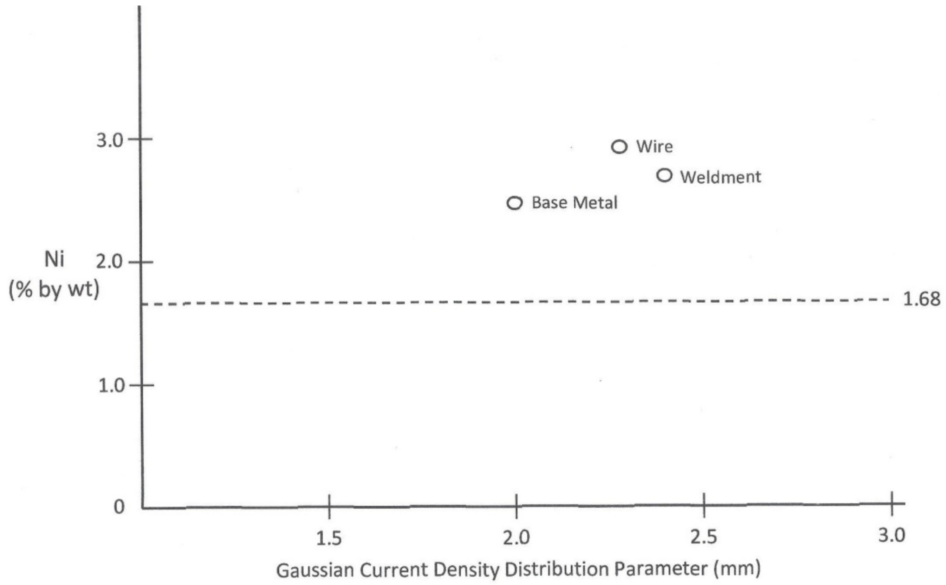

Figure 1: The influence of current density distribution on Ni alloying element.

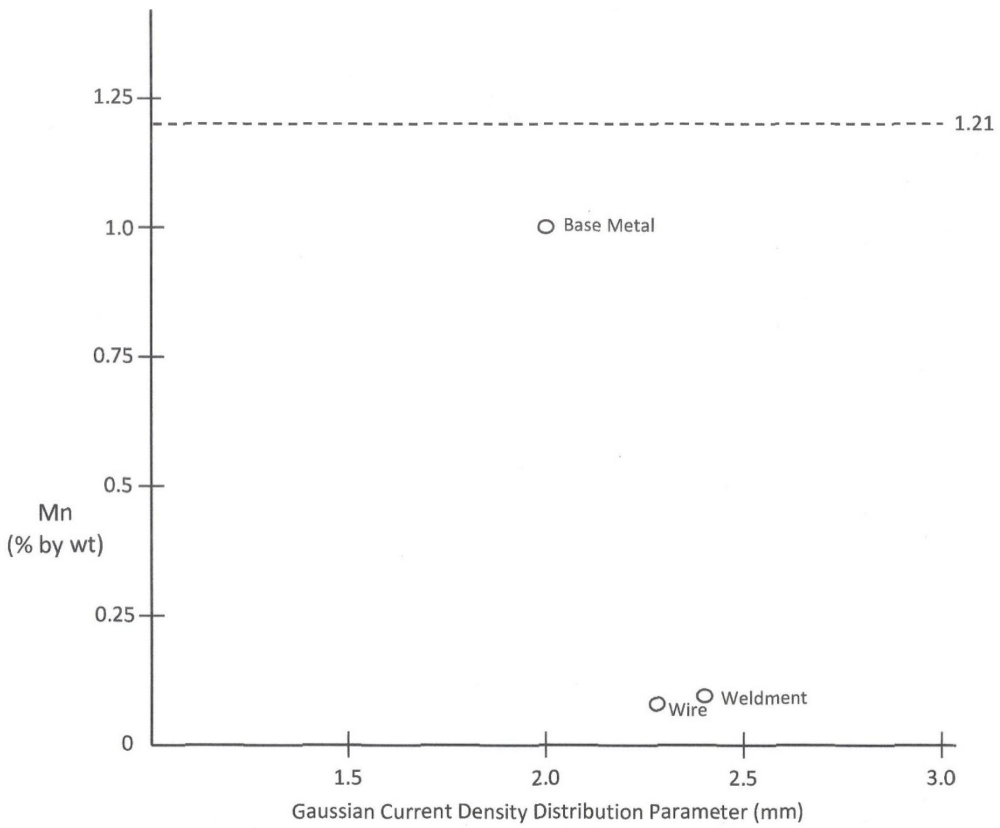

Figure 2: The influence of current density distribution on Mn alloying element.

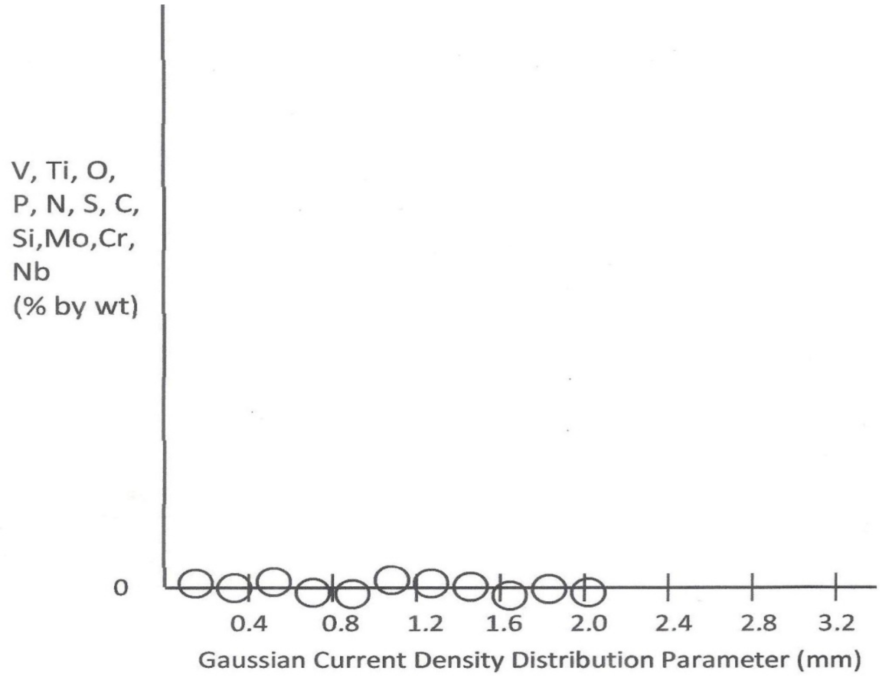

Figure 3: The influence of current density distribution on V, Ti, O, P, N, S, C, Si, Mo, Cr, Nb alloying elements.

radial velocity, u is the axial velocity, V_w is the wire feed speed and qG is the volumetric thermal energy generation rate, G is the electrical resistance heating. Table 1 shows the spectrometric analysis of the chemical compositions and Brinell hardness properties of the basemetal, wire and weldment.

Using MATLAB facility the regression analysis of the values in Table 1 was carried out and a resultant equation, $Y = -2.1672 + 1.2114Mn + 1.6885Ni$ was obtained. Where Y is the dependent variable, in this case Y is BHN.

3. Discussion of Results

This study examines the effect of heat input and thermo chemical reactions on the chemical composition and hardness of mild steel weldment. This reaction is facilitated by the heat supplied by the GMAW machine. Yang and Debroy [24] reported that during fusing welding, the heat from the heat source interacts with the base metal and filler material and this leads to rapid heating, melting and vigorous circulation of the molten metal in the weld pool. The circulation, according to the authors helps to transport heat in the entire weld pool. As the heat source moves away from the molten region, solidification and subsequently a series of solid-state phase transformations occur.

The role of the heat source is very significant to the melting process that forms the droplets which eventually produce a weld pool. During the convective circulation of molten metal in the weld pool, the alloying elements in the filler metal (electrode) and the heat affected zones (HAZ) of the basemetal react to form a weldment in which the alloying elements would be in new proportions, different from those of either the filler metal or basemetal.

The GMAW machine possesses an electric power of 8.12kW and produces a radiation heat loss of 5.76kJ, whereas, the convective heat loss that occurs between the molten metal and the arc column, when the molten metal droplets are transferred to the weldpool by gravity was calculated to be 0.42kJ. The heat transfer coefficient is 21.1 W/m^2.°C. The values of heat losses obtained in this study shows that radiation heat loss dominated the welding process. The arc heat is the lowest and is highly localized, was calculated to be 0.05kJ. The combined effect of the heat input on the chemical composition of the weldment were investigated by conducing spectrometric examination on the base metal, the welding wire, as well as the weldment to determine their various chemical compositions which is presented in Table 1. From Table 1, it can be seen that 6.67% of V was available in the weldment whereas 93.33% of V introduced from the basemetal and wire into the weldment were lost as a result of the applied heat input. Of the available Ti in the entire welding process, only 25% of Ti was lost, whereas a significant quantity of Ti (75%) were present in the weldment. 95% of oxygen content in the entire welding process were retained in the weldment. This further indicates that the weldment must have been oxidized by this level of entrapped oxygen. Half the quantity of P available in the entire welding process is present in the weldment. About 71% of N was

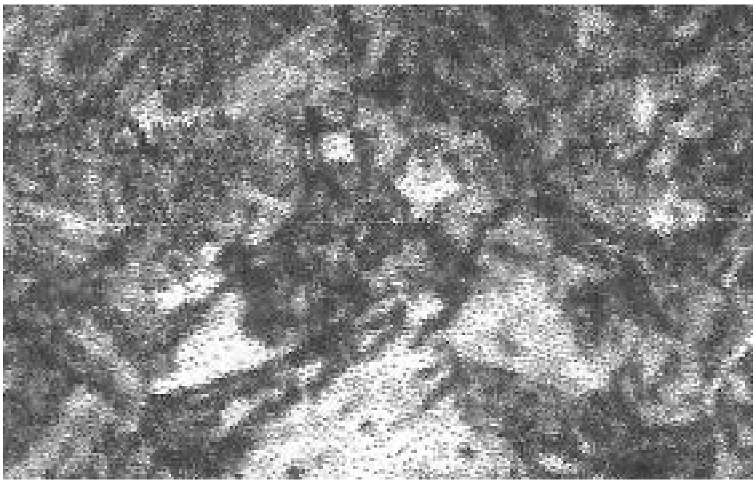

Figure 4: The influence of current density distribution on Ni alloying element.

retained in the weldment whereas, the entire quantity of S is available in the weldment.

For alloying elements C, Mn and Cr, their diffusion into the weldment was minimal, constituting about 27%, 8% and 33.5% respectively. Whereas, the alloying elements Si, Mo and Nb made gains by diffusing more into the weldment in percentages of 70%, 60% and 60% respectively but half the amount of Ni is present in the weldment. This analysis, clearly shows that Ti, O, N, S, Si, Mo and Nb were introduced more in quantity into the weldment, whereas, V, C, Mn and Cr were lost and available in the weldment in small proportions, as a result of the chemical reactions facilitated by the application of heat. For alloying element P, 50% of the entire proportion available, was present in the weldment. While 100% of S available in the entire welding process, was present in the weldment.

A regression analysis, was conducted using the MATLAB software to determine the optimum amount of alloying elements that would produce a weldment with improved mechanical properties. Figures 1 to 3 show the effect of current density on the alloying element content (wt %) of the base metal, wire and weldment. It can be seen from these figures that the quantity Ni present in the basemetal, wire and weldment are higher than the optimum quantity of 1.68. The values for Mn available in the basemetal, wire and weldment are less than the optimum quantity of 1.21. However, the other alloying elements present in Table 1 fall within the expected optimum values. To further confirm the effect of thermo chemical reaction on the weldment chemical composition, the Brinell hardness numbers of the basemetal, wire, and weldment were determined to be 328, 286 and 254 respectively. These values show that the weldment has the lowest value of 254. This low value of the Brinell hardness value could be attributed to the loss of Carbon content in the weldment. From Table 1, it was found that about 73% of C introduced into the welding process was lost as a result of the applied heat. Other strength enhancing alloying elements such as Mn and Cr were also lost. The losses of these alloying elements are responsible for the reduction in the hardness number of the weldment. The low amount of surfur, contributed to the improvement of the strength and toughness of the weldment.

The weldment is subjected to prolonged heating. This localized heat treatment is the major cause of loss of carbon. The absence of carbon is significantly responsible for the loss of strength in the weldment. Also the introduction of oxygen in the weld may have affected its ductility, but Fig. 3 confirms that the oxygen content is within its optimum quantity. This indicates that, the quantity of O_2 is not large enough to reduce the weldment's load carrying capacity, or high enough to affect the ductility of the weldment. Figure 4, is the magnified version of the white spots of the weld metal microstructure that show the parts that have been affected by O_2 contamination of the weld metal. The degree of contamination is not significant enough to affect its weld quality.

4. Conclusion

An electric arc welding process was carried out to study the effect of heat inputs in stimulating thermo-chemical reactions that could alter the chemical composition of mild steel weld chemistry. During the welding process, the convective and radiative heat losses were calculated and the arc heat energy, including the power used by the electric arc welding machine. From the results, it was found that the application of the heat, especially the prolonged heat treatment of the weldment lead to the losses and gains of some of the alloying elements. Most of the significant elements responsible for weldment hardenability such as C, Mo, and Cr were drastically reduced in quantity during the prolonged welding process.

This study has shown that thermochemical reactions can be simulated and induced by the application of intense, localized and prolonged arc heating. This heat treatment has been confirmed in this study to have a significant effect on the weld metal chemistry. Therefore, the level of heat input could to some extent determine the level of the alloying elements present in the eventual weldment.

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