Physical Nature of the Processes in Structure Forming, Phase and Chemical Composition of pipe Permanent Joints when MMA Welding

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Abstract. The paper outlines peculiarities of structure formation, phase and chemical composition in regard to heat content in molten electrode metal beads when pipe steel (steel 09G2S) welding using power sources with various energy characteristics. Mathematical calculations indicate an inverter power source provides minor heat content into the bead of electrode metal when welding. Experimental research has pointed at 4 -9 % increase in impact strength of joints produced using an inverter power source in comparison with samples produced applying a diode rectifier. The following factors can possibly give rise to the increasing impact strength: difference in microstructures of weld joints, up to 50% shortening ferritic plates in metal of weld joint, change in dimensions of ferritic grains in the heat-affected zone by as much as 17.5 %, and decrease in the extent of heat-affected zone by 50%.

1. Introduction

The service properties of welded structures, processing strengths of weld metal and heat-affected zone are conditioned by thermal-deformation processes, phase and structural transformations when welding. As the materials used for main pipeline welding are regulated their composition can hardly be changed. However, improvement of service properties is possible provided that various types of allowed welding equipment are used.

In conditions of constantly changing spatial position of a weld pool sufficient dynamic behavior of a current source is required for proper welding of non rotatable joints of pipelines, as well as it necessitates quickly rising voltage from short circuit to arcing, the reasonable rate of current change in order to reduce spattering while beads of melted electrode are transferred into the weld pool; other requirements are to be met too [6].

The authors of this paper deal with studying the influence of heat content into the bead of molten electrode metal on the microstructure and strength properties of a weld joint, which involves application of power sources for arc welding with various energy characteristics.

2. Materials, research procedures and results

For comprehensive analysis we produced pipe welded joint samples Ø159 ×6 of steel 09G2S with electrodes: root - LB-52U (d=2.6 mm), welding current I = 50-60 A, filling - LB-52U (d=3.2 mm), welding current I = 80 – 90 A; power sources are different (diode rectifier VD-306 and inverter Nebula-315).

The set of methods [1, 2] adapted to manual arc welding by means of computer software MatLab was used to calculate the heat content of electrode metal bead according to energy characteristics of welding. Calculation procedure is outlined in Table 1.

Table 1. Procedure to specify the heat content of electrode metal bead when welding with various types of power sources [3]

Procedure to specify the heat content of a bead in software MatLab	Heat content when welding with Nebula 315, Q_{hc}, J,	Heat content when welding with diode rectifier VD 306, Q_{hc}, J,
u1=[u1; u2; u3; u4; u5; u6;…..]; i1=[i1; i2; i3; i4;…..]; [U1,I1]=meshgrid(u1,i1); t1=t1; t2; t3; t4;…….; Q_{hc}=sum(trapz(0,2…0,3*U1.*I1.*t1)), where $u_1, u_2 \ldots u_n$; $i_1, i_2, \ldots i_n$ – instantaneous values of voltage, V; those of current, A per unit of time $t_1, t_2, \ldots t_n$.	113.25 10^5	125.03 10^5

The difference in heat content is the reason for varying dimensions and mass of transferred beads, which can be estimated by the following formulae:

Mass of transferred beads in conditions of short circuits [4] can be calculated according to equation:

$$m = a \cdot \tau_{k.z.}^3 \qquad (1)$$

where $\tau_{к.з.}$ – time a bead is on the electrode tip, s.
a – coefficient $0.3*10^{-4}$ g/s^3.

The radius of transferred electrode metal beads [5]:

$$R = \sqrt[3]{\frac{-1}{27}\cdot\left(\frac{-\pi\cdot\gamma\cdot\cdot r_0^2}{4a\cdot\tau_0^3\cdot 10^3}\right)^3 + \left(\frac{-3a\cdot\tau_{k.z.}^3\cdot 10^3}{8\cdot\pi\cdot\gamma} + \frac{\pi\cdot\gamma\cdot r_0^2}{24\cdot a\cdot\tau_{k.z.}^3\cdot 10^3}\right) - \sqrt{\frac{2}{27}\left(\frac{-\pi\cdot\gamma\cdot r_0^3}{4a\cdot\tau_{k.z.}^3\cdot 10^3}\right)^3 + \left(\frac{-3a\cdot\tau_{k.z.}^3\cdot 10^3}{8\cdot\pi\cdot\gamma} + \frac{\pi\cdot\gamma\cdot r_0^2}{24a\cdot\tau_{к.z.}^3\cdot 10^3}\right)\cdot\frac{1}{4} - \frac{1}{729}\cdot\left(\frac{-\pi\cdot\gamma\cdot r_0^2}{4a\cdot\tau_{k.z.}^3\cdot 10^3}\right)^6}} + \frac{\pi\cdot\gamma\cdot r_0^2}{12a\cdot\tau_{k.z.}^3\cdot 10^3}. \qquad (2)$$

where $\tau_{k.z.}$ – time a bead is on the electrode tip, s;
a – coefficient $0.33\cdot 10^{-4}$ g/s^3;
π – mathematic constant, circumference to diameter ratio 3.14;
γ – density of liquid metal, g/mm^3;
R –radius of bead surface curvature, mm;
r_o – core wire radius, mm.

Table 2. Calculated data on transferred bead mass and specific surface area when using power sources with different dynamic characteristics [5]

Power source	Mean values	$\tau_{k.z.}$, 10^{-3}, s	Bead mass m, g	Bead radius R, mm
Inverter	I=100A; U=22V	10…14	$\frac{0.33-0.9}{0.615}$	$\frac{2.16-3.02}{2.59}$
Diode rectifier	I=100A; U=22V	8…12	$\frac{0.168-0.57}{0.369}$	$\frac{1.72-2.89}{2.305}$

As far as it's known [6, 7], downsizing electrode beads cause increase in their total contact surface with the ambient medium. Therefore, liquid metal of beads completely react with this medium (deoxidation, alloying, oxidation, gas dissolution), but the rate of metallurgical reaction is deteriorated provided that the lifetime of beads is shortened. In papers by N.M. Novozhilov [8] the data is presented: specific surface of electrode beads is approximaly 5 – 22 times greater than it of the weld pool, while specific oxidation velocity of electrode bead metal is about 39 times greater than that of weld pool metal. A.A. Erokhin has stated in his paper [9], chemical reactions of welding stop completely at the time of bead formation, beads intensively react with gas and dross. Therefore, chemical composition of weld joint metal can be controlled via affecting chemical composition of electrode metal beads.

Various heat content of molten electrode metal bead, as well as mass and radius of beads transferred from the electrode into the weld pool are the reasons for different heat input into the product, as the consequence, for change in the microstructure, chemical composition and mechanical properties of a weld joint.

Chemical composition and mechanical properties of a product to be welded were experimentally tested in conditions of various energy impact of power sources when manual arc welding. The analysis of the data presented in Table 3 and 4 reveals the increase in mass concentration of alloying elements: (Mn – 0.02 to 0.28%, Si – 0.24 to 0.48%, Cr – 0.04 to 0.5%) in deposited metal and reduction of oxide concentration (SiO_2, MnO) in a dross phase if inverter is used instead of diode rectifier. Various heat content in electrode metal beads can be a probable reason of it [6] provided that different power sources are used, as one can see in Table 4. This fact is confirmed by the data in paper [10].

Table 3. Chemical composition of weld joint metal, produced from pipe Ø159×6 (steel 09G2S) with electrodes LB 52U [11]

Power source	Element concentration, mass %							
	C	Si	Mn	S	P	Cr	Ni	Cu
Diode rectifier	0.10± 0.012	0.52± 0.03	1.03± 0.05	0.010	0.014	0.03±0.01	0.05 ±0.01	0.03
Inverter	).09±0.00 5	0.60±0.03	1.23±0.05	0.010	0.014	0.03±0.01	0.06 ±0.01	0.03

Table 4. Typical chemical composition of dross [11]

Electrodes	Power source	CaO, %	SiO_2, %	TiO_2, %	NbO, %	MnO, %	Fe_2O_3, %	Cr_2O_3, %	Al_20_3, %
LB-52U	Diode rectifier	38.66	25.37	9.57	0.10	7.21	18.31	0.17	3.61
	Inverter	36.27	24.187	8.74	0.05	7.48	13.89	0.15	3.66

The results presented above are the consequences of heterogeneous reactions of equilibrium, which dross MnO, SiO_2 and base metal enter into, they depend on heat content of beads and their temperature (they are different for various sources of power Table 3 and 4):

Interacting dross and metal components in the course of oxidation-reduction reaction on the interface can be both viewed as a heterogeneous reaction or electrochemical process [12]:

Dross: (MnO) (FeO)

$$\begin{matrix} (MnO) & & & & (FeO) \\ \updownarrow & & & & \updownarrow \\ [MnO] & + Fe & \leftrightarrow & [Mn] + & [FeO] \end{matrix} \quad (3)$$

Metal:

Dross: (SiO_2) 2(FeO)

$$\begin{matrix} (SiO_2) & & & & 2(FeO) \\ \updownarrow & & & & \updownarrow \\ [SiO_2] & + Fe & \leftrightarrow & [Si] + & [FeO] \end{matrix} \quad (4)$$

Metal:

$$\Delta G^0 = \Delta H - T\Delta S \quad (5)$$

where ΔG^0- Gibbs energy, kJ/ mole;

ΔH – enthalpy change, kJ/ mole;

ΔS – entropy change, kJ/ mole;

T – temperature of electrode metal bead heating, ^{0}K. As it is specified in paper [5] the data are as follows: for inverter T= 2213^0 K, for diode rectifier T=2283^0 K.

$$\Delta H = \Delta H_{FeO} - \Delta H_{MnO} \quad (6)$$

$$\Delta S = \Delta S_{FeO} - \Delta S_{MnO} \quad (7)$$

We specify Gibbs energy (5) given in Table 5 making use of reference data [13, 14] ΔH_{FeO}= -265 kJ/ mole; ΔH_{MnO}= -385.1 kJ/ mole; ΔS_{FeO}= 60.8 kJ/ mole K^{-1}; ΔS_{MnO}= 61.5 kJ/ mole; ΔH_{SiO2}= -908 kJ/ mole; ΔS_{SiO2}= 42.7 kJ/ mole K^{-1} in formulae 6, 7.

Table 5. Calculated Gibbs energy of chemical reactions in metallurgical processes when welding

	ΔG^0 for reaction 6, kJ/ mole	ΔG^0 for reaction 7, kJ/ mole
Inverter	121.649	180.129
Diode rectifier	121.708	219.415

In the area affected by high temperatures there is equilibrium direction shift of processes (3,4) towards oxidation of Si, Mn, moreover, the process velocity increases as the temperature goes up, the data given in Tables 3 – 4 confirm this fact.

The change in chemical composition of deposited metal is to cause changing structure and phase composition, as the consequence, operating properties of deposited metal.

Table 6. Mechanical properties of weld joints produced of pipe Ø159×6 (steel 09G2S) with electrodes LB 52U [11]

Power source	Limit of temporary tensile strength σ_B, MPa	Angle of root, inward, and edgewise bend, grad.	Impact strength KCU, J/cm^2 (cut along the center of a weld)			
			+20ºC	0ºC	-20ºC	-40ºC
Diode rectifier	$\frac{541-543}{542}$	$\frac{120-120}{120}$	$\frac{201-220}{210}$	$\frac{212-223}{216}$	$\frac{200-233}{219}$	$\frac{143-230}{182}$
Inverter	$\frac{550-560}{555}$	$\frac{120-120}{120}$	$\frac{208-226}{217}$	$\frac{215-254}{235}$	$\frac{224-250}{237}$	$\frac{150-258}{193}$

The analysis of data given in Table 6 reveals 4 -9 % growth of impact strength of joints produced using an inverter power source in comparison with the samples produced by diode rectifier at various temperatures. The following factors can possibly give rise to the increasing impact strength: difference in microstructures of weld joints (Figure 1), up to 50% shortening ferritic plates in metal of weld joint, change in the dimensions of ferritic grains in the heat-affected zone by as much as 17.5 %, and decrease in the extent of heat-affected zone by 50%.

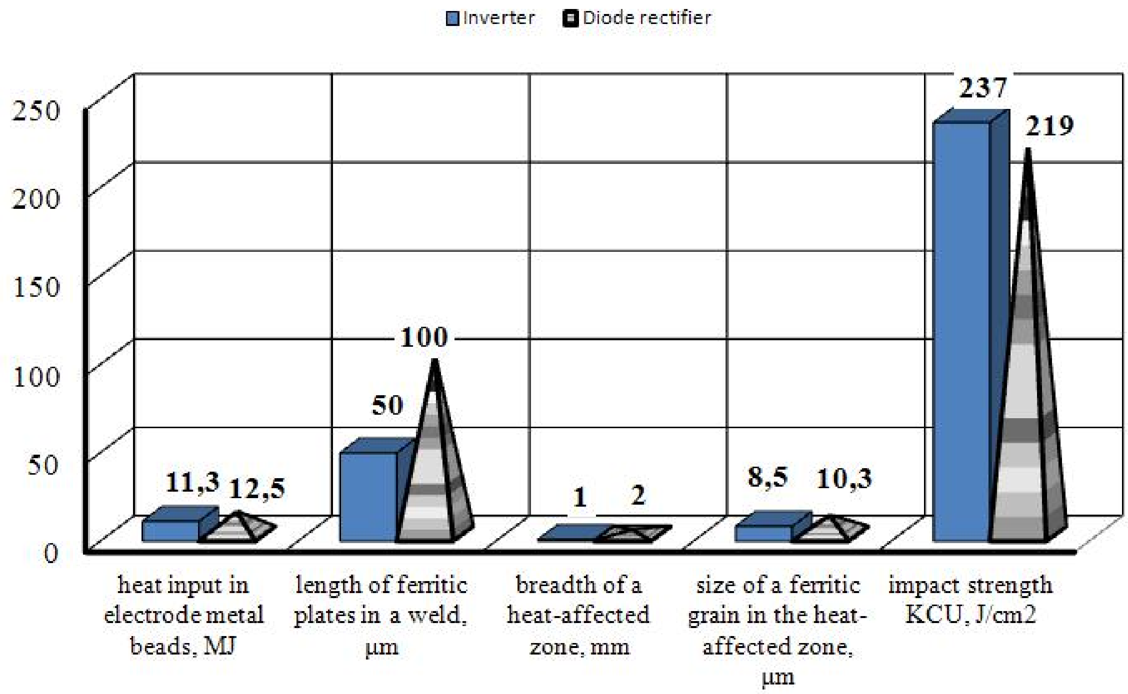

Figure 1. Histogram of changes in weld joints with respect to the type of power source

Conclusions

The experiments have revealed an inverter power source provides minor heat content into the bead of electrode metal when MMA welding as compared with the diode rectifier. The mass concentration of alloying elements goes up: Mn 0.02 to 0.28%, Si 0.24 to 0.48%, Cr 0.04 to 0.5%) in deposited metal, whereas the share of oxides (SiO_2, MnO) is reduced in the doss phase when inverter using instead of a diode rectifier. Impact strength of joints produced using an inverter power source increases by 4 -9 %

IOP Conf. Series: Materials Science and Engineering **125** (2016) 012010 doi:10.1088/1757-899X/125/1/012010

in comparison with the samples produced by diode rectifier due to difference in microstructures of weld joints, up to 50% shortening ferritic plates in metal of weld joint, change in the dimensions of ferritic grains in the heat-affected zone by as much as 17.5 %, and decrease in the extent of heat-affected zone by 50%.

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