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ESTABLISHING RELATIONSHIP BETWEEN WELDING CURRENT AND WELD METAL DEPOSITION RATE FOR SOLID WIRE IN SUBMERGED ARC WELDING PROCESS

Bashkar R[1], *Balasubramanian V[1] and Mani C[2]

[1]Department of Manufacturing Engineering, Annamalai University, Tamil Nadu- 608002, India
[2]Quality Management Division, Consolidated Contractors Company Ltd (CCC), Abu Dhabi, United Arab Emirates

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ABSTRACT

Submerged Arc Welding (SAW) process is used to weld large, heavy metal deposition jobs with critical requirements, and this metal joining process alone is used to weld approximately 10% of the deposited weld metal worldwide. Any augmentation in productivity of SAW process, will immensely benefit the welding industry, as this process is widely used on variety of common metals and alloys. This paper focusses on establishing relationship between welding current and productivity (in terms of weld metal deposition rate as an index), for a given filler wire diameter. Productivity rates of most common solid filler wire sizes were studied, at different preset current values, covering full current range through bead-on-plate experiments. At each preset current value, the bead was first optimized for acceptable visual quality, by varying arc travel speed and voltage, then wire feed rate (of acceptable beads) was noted. The current density, heat input and corresponding weld metal deposition rate were calculated for establishing relationships. The established relationships can be effectively used, to estimate productivity from the preset current values, for a given solid wire diameter.

Keywords: *Submerged Arc Welding, Carbon Steel, Solid Wire, Weld Metal Deposition Rate, Productivity, Heat Input and Current Density.*

1. Introduction

Conventional arc welding processes are helpful in meeting large percentage/volume of common welding needs of engineering industry. Engineering industry employ various arc welding processes, such as shielded metal arc welding (SMAW), flux cored arc welding (FCAW), gas tungsten arc welding (GTAW), gas metal arc welding (GMAW) and submerged arc welding (SAW) in varying percentages during fabrication of engineering components. While SMAW, FCAW processes are used almost on all jobs involving common engineering materials, GTAW, GMAW processes are used for some special needs/materials [1]. SAW is preferred where heavy weld deposition (like in Pressure Vessels, Heat Exchangers, Columns, Reactors, Offshore structures, Ship building, Steel Structures,) is needed, and where joints can be welded in flat/horizontal positions [2]. There are many reasons for the popularity of SAW process in welding industry, some are: SAW process is versatile, scalable, can be mechanized, acceptability of moderately skilled welders achieving more reliable, high quality welds at higher productivity with deeper penetration and excellent surface finish without spatter/flash/fumes/radiation resulting in reduced overall welding time and cost, improving welding cost economy [3]. Hence, SAW is the first process industry use for "heavy and critical" welding applications and approximately 10% of weld metal is deposited by SAW, all over the world [4].

Hari OM et al. [5] state direct-current electrode positive (DCEP) is most often used for wider beads and more penetration depth. The traditional single solid wire, direct current electrode positive (DCEP) SAW process has seen lot of developments, since its inception in 1930s, making SAW process more productive, and now many variations of SAW process are available. Important variations are "Tiny Twin SAW" (using two small dia wires and both sharing current from single power source), or "Two/multi wire SAW Tandem" (two/more wires – each wire powered by its own independent power source), adding deposition rates from each wire to make large deposition rate SAW [6]. In the past decades, welding industry has brought out and adapted mandatory procedures to meet the technical requirements of common and critical materials, being welded. But the need and pressure to find more effective

**Corresponding Author - E- mail: visvabalu@yahoo.com*

welding methods, to improve the overall productivity, so that acceptable quality welds are achieved using least resources/time is increasing every day, to stay/win in the current competitive environment [7].

Though many variations of SAW (such as Tubular wire, Tiny Twin Wire, Tandem, Twin Tandem) have been explored/established in the welding industry for decades, still the traditional single solid wire DCEP SAW is used even now by most, for its simplicity, adaptability, low cost, compact equipment size, easy to use package even by moderately skilled welders, depositing large percentage of weld metal every day [8]. So, any incremental improvement in productivity/economy in this basic SAW process will result in significant improvement in overall output of welding industry [9]. Though fabrication industry employ SAW (to achieve large weld metal deposition and high quality), there is every possibility that SAW is used with very limited choice of wire size and parameter in each company [10]. One company may be using different set of wire size and parameter which is different from other company usage for the same/similar kind of jobs, achieving totally different (higher/lower) levels of productivity [11].

It has been reported that SAW usage is continued with particular wire size and parameters even when the job diameter or joint thickness vary from component to component [12]. When job size, joint thickness, weld bevel configuration changes so much from job to job (like in Pressure vessel, Piping, Offshore, Structural steel welding shops), they are being welded by SAW with one size wire and limited parameter range (suitable for that particular wire size) [13]. It suggest that even though right process is employed, the welding technique that is being used, is not at its highest productivity/economical potential levels [14], and this forced to take up this current investigation: focusing on various diameter solid filler wires and parameter optimization for reducing the welding time and or cost, while improving/maintaining the weld quality.

The published information on SAW is very minimum and few investigations carried out work related to this area is briefly described. Ogborn et al. [1] opined that if same magnitude of current can be supplied with two different electrode diameters, the smaller electrode will produce the higher deposition rate. Swain et al. [3] reported that the welding current or amperage controls the deposition rate, the depth of penetration, and the amount of base metal melted. Hinal B. Thakker [4] stated that welding current plays major role in bead width, penetration, weld reinforcements. It is also shown that welding current controls bead width by about 67%, depth of penetration by approximately 39% (with equal contribution from welding speed). Gunaraj and Murugan [11] carried out an investigation and found that all important bead parameters such as bead penetration, reinforcement, width, dilution, area of penetration, area of reinforcement increased with the increase in welding current (which was adjusted through wire feed rate during experiments). Das and Kumanan [15] stated welding current directly influences the depth of penetration and base metal fusion. Roy et al. [16] reported that as the current value increases, bead penetration, reinforcement, bead width, HAZ width increases. Welding input parameters play a very significant role in determining the quality of a weld joint. Best quality and cost-effective welds can be achieved by proper understanding of the influence of welding parameters and the weld metal properties. SAW is an important metal joining technology specially applied to join metals of large thickness used in heavy industries.

From the literature review, it is understood that most of the published information are focused on bead geometry analysis only and published information on weld metal deposition rate and productivity are very scant. Hence, present investigation is carried out to establish a relationship between welding current and weld metal deposition rate (productivity) for most commonly used solid filler wire sizes in SAW process. The main objective of this work is to bring out the procedure needed to get full range and optimum parameters for common wire sizes used in the industry so that it is possible for the users to decide which wire size and parameter suits best for their production job condition.

2. Experimental Work

The rolled plates of 25 mm thick, ASME IIA specified A36 grade steel, were used as base plates for depositing Bead on Plate (BoP) trials. Solid filler wires, confirming to the specifications of ASME IIC SFA 5.17 and AWS EM12K, were used to deposit the weld metal. Three solid wires having the diameter of 2.4, 3.2, 4.0 mm were chosen for this investigation. Neutral Flux meeting the specifications F7A4-EM12K-H8 as per ASME IIC SFA 5.17 was used in this investigation. Table 1 presents classification and chemical composition of filler wires used in this investigation. Table 2 presents flux composition AWS classification of flux, basicity index and size distribution. Miller Summit Arc 1000/1250 Power source with HDC 1500DX Digital Controller (with capacity 1,000 A at 100% Duty Cycle, with CV+C mode setting, USA) with Column & Boom set up was used in this investigation (Fig. 1a, b).

Table 1 Chemical composition (wt%) of solid electrodes/wire used in this investigation

Specification	Wire Composition (per ASME IIC SFA 5.17) %						
	C	Mn	Si	S	P	Cu	Fe
AWS EM12K	0.15	1.20	0.3	0.02	0.02	0.35	Bal.

Table 2 Chemical composition (%), other information of flux used in this investigation

SiO_2	MnO	MgO	CaF_2	NaO	Al_2O_3	CaO	TiO_2	Others
19	11	12	17	2	32	2	2	3

Basicity Index (BI)	1.1
Density (Gm/cm3)	1.4
Type	Neutral
AWS Flux Wire Classification	F7A4-EM12K
Size Distribution:	
+20 Mesh	40% Max.
-20+60	55% Min.
-60 Mesh	5% Max.

Small lengths (30 cm) of all three wires (Fig. 1b) were cut and measured for its length and weight, to calculate weight of wire/unit length (gm/inch or gm/mm) by linear density measurement method. Top side of the test coupon was thoroughly cleaned by grinding (to white finish condition) so that arc starting and welding (throughout the test length) can be smooth. Power source, digital controller, column and boom, all necessary accessories were connected/controlled for smooth bead-on-plate (BoP) trials. Controller was set up in Miller CV+C mode which allows pre-setting of welding current and voltage directly. Constant Voltage (CV) is the traditional mode of wire feed process which allows to pre-set wire feed speed and voltage and regulate both the values. The amperage is variable and fluctuates based on changes in the electrode stick out. As stick-out increases the current decreases because the wire gets preheated. So, the heat input fluctuates in the welding operation. CV+C is the constant voltage and current mode which allows the operator to pre-set and monitor the voltage as well as amperage. This gives wire feed speed as the variable. Wire feed speed changes with changes in stick-out to maintain the voltage and current at constant level. Thus, heat input remains consistent throughout the welding operation. CV+C mode automatically adjust the wire feed rate (with the help of machine to controller communication software) based on arc and weld pool dynamics, helping in depositing full length weld bead at near uniform current closest to preset value (as shown in Fig. 1d). During welding, wire feed rate values displayed on the controller was recorded, averaged out for calculating average wire burn off rate which has been considered as average weld metal deposition rate (WMDR in kg weld/ arc hour). Current (A), voltage (V), wire feed rate (WFR) were observed and recorded from the welding controller display, the welding arc travel speed (S) value was taken from Column & Boom settings (cross checked by dry run trial runs). These three values (A, V, S) are the experimental input data, with observed WFR data, weld metal deposition rate in Kg/hour (WMDR = Length of the wire fed in one arc hour x wire weight per unit length), heat input in kJ/mm (HI = A x V x 60 / S x 1000), current density in A/mm^2 (CD=Current in Amps / Wire cross section area in mm^2) were calculated, as per standard methodology.

Before commencing the actual BoP experiments, each size of wire was trial welded at different current values (from lowest to highest in increments of 50 A). Each resultant bead was visually inspected for appearance and quality as per standard norms (AWS D1.1). When needed, voltage and speed values were optimized for getting visually acceptable quality weld beads, at all preset current values. Some of the trial weld beads are shown in Fig. 1e. The BoP experiments carried out on test plate is shown in Fig. 1f.

In the first phase, 2.4 mm diameter solid filler wire was used to deposit the weld bead, varying the current from 300 A to 600 A, at 50 A increments. The welding conditions and parameters used to deposit the weld metal are presented in Table 3.

Table 3 Welding Parameters used and Deposition Rate obtained for 2.4 mm diameter filler wire

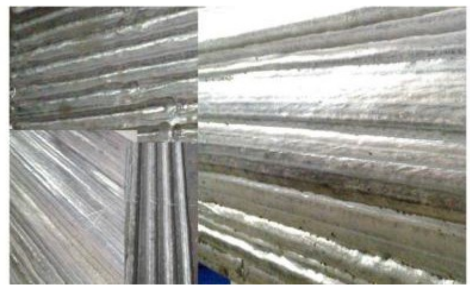
Expt. No.	Current (A)	Voltage (V)	Traverse Speed (mm/min)	Current Density (A/mm^2)	Heat Input (kJ/mm)	Weld Metal Deposition Rate (kg/hour)
1	300	26	290	66	1.6	3.5
2	350	26	290	77	1.9	4.4
3	400	27	290	88	2.2	5.3
4	450	27	495	99	1.5	6.1
5	500	29	495	110	1.8	7.6
6	550	29	495	122	1.9	9.6
7	600	33	495	133	2.4	9.9

(a) Front view of the SAW Machine

(b) Photograph of solid filler wires with wire feed motors, flux feeder set up

(c) Photograph showing Flux Powder used

(d) Photograph taken during bead deposition



(e) Bead on Plate Trials, done for parameter Optimization.

(f) Typical Bead on Plate Experiment Coupon

Fig. 1 Photographs showing the experimental work sequence

Acceptable weld beads (which can be used for single and multiple pass welding application in both fillet and groove joints) could be achieved in this current range. Below 300 A and above 600 A range, welding and beads deposited were not meeting the acceptance criteria for visual inspection, with the wire and flux tried. For all BoP trials, within 300-600 A range in 50 A increments, similar welding sequence/procedure were followed: starting the welding, allowing the arc to stabilize, letting the welding machine ramp up the current to preset ampere, and during smooth welding, recording the displayed wire feed rate (WFR), then moved to the next current setting (i.e. +50 A from previous bead). Whenever the bead was not looking good, arc travel speed (S) and or voltage (V) were adjusted till acceptable quality bead was achieved and the corresponding WFR value was recorded. Similar procedure was employed to evaluate the WMDR (productivity) for 3.2 mm and 4.0 mm diameter solid filler wires. The stick out, flux height, flux width, wire angle (at 90^{0} to job) were maintained same/similar for all BoP trials. The welding parameters used to deposit the weld metal are presented in Table 4 and 5 for 3.2 mm and 4.0 mm diameter filler wires, respectively.

Table 4 Welding Parameters used and Deposition Rate obtained for 3.2 mm diameter filler wire

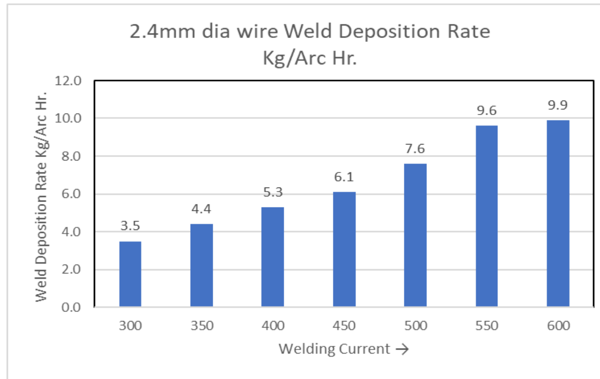
Expt. No.	Current (A)	Voltage (V)	Traverse Speed (mm/min)	Current Density (A/ mm^2)	Heat Input (kJ/mm)	Weld Metal Deposition Rate (kg/hour)
1	300	26	290	37	1.6	3.3
2	350	26	290	44	1.9	3.8
3	400	26	290	50	2.2	4.7
4	450	26	495	56	1.4	5.3
5	500	27	495	62	1.6	6
6	550	27	495	68	1.8	6.9
7	600	28	495	75	2	8.2
8	650	28	605	81	1.8	9.8
9	700	31	605	87	2.2	10.4
10	750	31	605	93	2.3	11

Table 5 Welding Parameters used and Deposition Rate obtained for 4.0 mm diameter filler wire

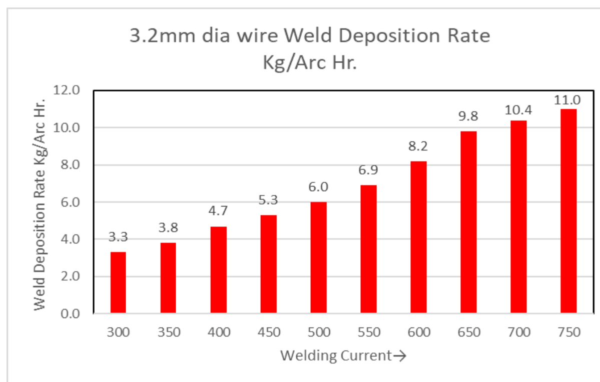
Expt. No.	Current (A)	Voltage (V)	Traverse Speed (mm/min)
1	350	28	290
2	400	28	290
3	450	28	290
4	500	28	290
5	550	30	495
6	600	30	495
7	650	30	495
8	700	30	495
9	750	32	605
10	800	32	605

3. Results

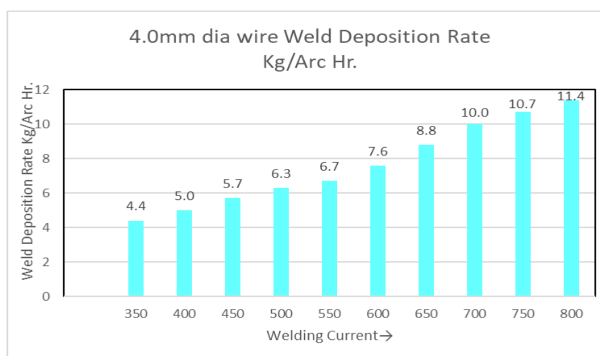
In this investigation, 27 BoP experiments were conducted to evaluate the effect of welding current on WMDR (productivity) of 3 wire sizes. 7 BoP experiments were conducted using 2.4 mm diameter solid filler wire and the results are presented in Table 3. Similarly, 10 BoP experiments were conducted using 3.2 mm diameter solid filler wire and the results are presented in Table 4. Another 10 BoP experiments were conducted using 4.0 mm diameter solid filler wire and the results are presented in Table 5.



(a) For 2.4 mm diameter solid filler wire



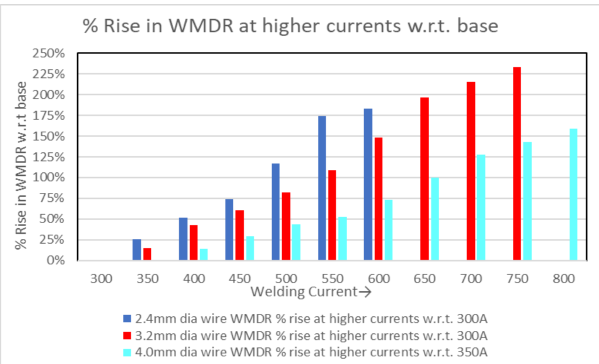
(b) For 3.2 mm diameter solid filler wire



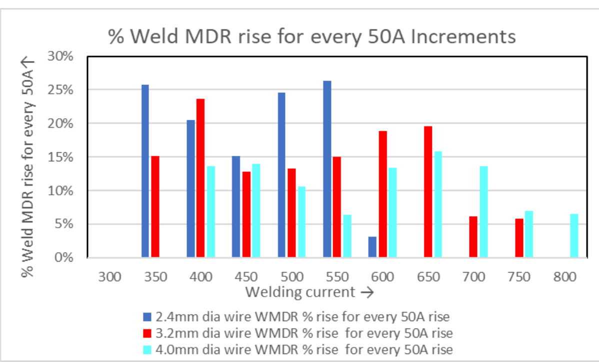
(c) For 4.0 mm diameter solid filler wire

Fig. 2 Effect of welding current on weld metal deposition rate

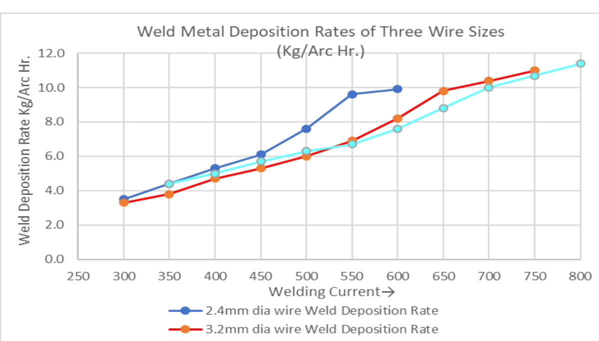
Fig. 2 (a to c) presents the weld metal deposition rate of all the three wires for different preset current values. Fig. 3a presents the percentage increase in WMDR achieved at different preset current values with respect to the base WMDR level (300 A weld metal deposition rate level for 2.4 mm and 3.2 mm diameter wires and 350 A WMDR for 4.0 mm diameter wire). Fig. 3b depicts the percentage of increase in WMDR of all three wire sizes, for every 50 A increments, at different preset current values, as compared to WMDR levels of lower current value (50 A) levels. Fig. 3c gives WMDR of all three wires at different preset current values (within its full current range in increments of 50 A). Fig. 4a displays the current density of all three wire sizes at all current preset values (within the range) tried. Fig. 4b reveals the same information (three wire sizes current density values at different current values) in graphical form. Fig. 4c gives deposition rate divided by current at different preset current values of all three wires.



(a) Improvement in weld metal deposition rate w.r.t base (250A WMDR)

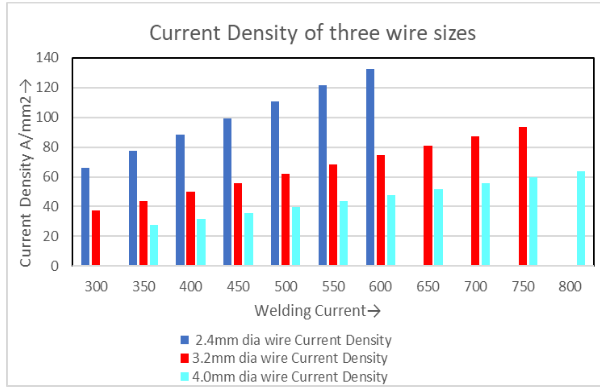


(b) Improvement in WMDR for every 50 A current increments

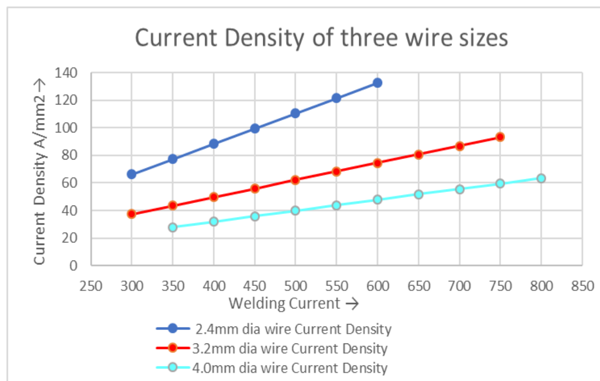


(c) Welding current Vs Weld metal deposition rate for all the three wires

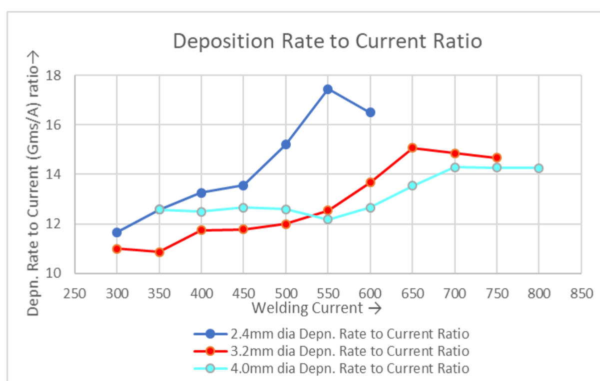
Fig. 3 Effect of welding current on improvement in weld metal deposition rate



(a) Welding Current Vs Current Density



(b) Welding Current Vs Current Density (Line graph)



(c) Deposition Rate to Current Ratio of three sizes solid filler wire

Fig. 4 Relationship between welding current and current density

4. Discussion

4.1 Effect of Welding Current on WMDR

For 2.0 mm diameter wire, WMDR of 3.5 kg is achieved at 300 A welding current, and it increases gradually at every incremental current value (4.4 kg at 350 A, 5.3 kg at 400 A, 6.1 kg at 450 A, 7.6 kg at 500

A, 9.6 kg at 550 A, 9.9 kg at 600 A). With the same wire, flux, machine, welder, infrastructure/accessories, compared to 300A deposition rate (3.5), increase in applied current gives 26% increase in deposition rate at 350 A, 51% increase at 400 A, 74% at 450 A, 117% at 500 A, 174% at 550 A, 183% at 600 A. 26, 20, 15, 25, 26, 3 are the % improvement in deposition rate when current is increased to next 50 A value compared to previous preset current value.

Similarly, For 3.2 mm diameter wire, WMDR of 3.3 kg is achieved at 300 A, and it increases gradually at every incremental current value (3.8 kg at 350 A, 4.7 kg at 400 A, 5.3 kg at 450 A, 6.0 kg at 500 A, 6.9 kg at 550 A, 8.2 kg at 600 A, 9.8 kg at 650 A, 10.4 kg at 700 A, 11.0 kg at 750 A). With the same wire, flux, machine, welder, infrastructure/accessories, compared to 300 A deposition rate (3.3 Kg), increase in applied current gives 15% increase in deposition rate at 350 A, 42% increase at 400 A, 61% at 450 A, 82% at 500 A, 109% at 550 A, 148% at 600 A, 197% at 650 A, 215% at 700 A, 233% at 750 A). The % improvement in deposition rate are 15, 24, 13, 13, 15, 19, 20, 6 and 6% when current is increased to next 50 A value compared to previous preset current value.

For **4**.0 mm diameter solid filler wire, weld metal deposition rate of 4.4 kg is achieved at 350 A, and it increases gradually at every incremental current value (5.0 kg at 400 A, 5.7 kg at 450 A, 6.3 kg at 500 A, 6.7 kg at 550 A, 7.6 kg at 600 A, 8.8 kg at 650 A, 10.0 kg at 700 A, 10.7 kg at 750 A, 11.4 kg at 800 A). With the same wire, flux, machine, welder, infrastructure and accessories, increase in applied current gives 14% increase at 400 A, 30% at 450 A, 43% at 500 A, 52% at 550 A, 73% at 600 A, 100% at 650 A, 127% at 700 A, 143% at 750 A, 159% at 800 A) compared to 350 A deposition rate (4.4 kg). The % improvement in deposition rate when current is increased to next 50 A value compared to previous preset current value are 14, 14, 11, 6, 13, 16, 14, 7, 7%.

It is evident that every 50 A incremental current value, gave considerable % increase in weld metal deposition rate till last two current settings, which is close to its peak current value/deposition rate potential of this wire type/classification/size/flux characteristics. At higher current values, increasing denominator reduces the % increase in WMDR. Any attempts to use this wire/flux above this current value for still higher % improvement results in unstable weld start/arc, peaky bead, undercut, unstable arc control system. Above this point (current value), it would be prudent to go for other type of wire, size and flux combination to increase % improvement any further.

4.2 Effect of Welding Current on Productivity Improvement

For 2.4 mm diameter wire, when the current is increased to 400 A (from base 300 A), 51% productivity can be increased (under same conditions of wire, flux and machine). When the current is increased to 500 A, 117% improvement in productivity can be achieved (with respect to the base productivity levels). When the current is further increased to 600 A, 183% improvement in productivity can be achieved (with respect to the base productivity levels). The 100% increase in current value brings 183% increase in productivity.

Similarly, for 3.2 mm diameter wire, as compared to 300 A (base level) productivity, 400 A gives 42% increase in productivity (under same conditions: same wire/flux/machine). When the current is increased to 500 A, 82% improvement in productivity can be achieved (with respect to base productivity levels). When the current is further increased to 600 A, 148% improvement in productivity can be achieved (with respect to base productivity levels). When the current is increased to 750 A, 233% improvement in productivity can be achieved (with respect to base productivity levels). An increase of 100% in current gives 148% increase in productivity and 150% increase in current value brings 233% increase in productivity.

In the same way, for 4.0 mm diameter solid filler wire, as compared to 350 A (base level) productivity, 450 A gives 30% increase in productivity (under same conditions: same wire/flux/machine). When the current is increased to 550 A, 52% improvement in productivity can be achieved (with respect to base productivity levels). When the current is further increased to 700 A, 127% improvement in productivity can be achieved (with respect to base productivity levels). When the current is increased to 800 A, 159% improvement in productivity can be achieved (with respect to base productivity levels). An 100% increase in current gives 127% increase in productivity and 150% increase in current value gives 159% increase in productivity.

With 2.4 mm solid filler wire, when the current is increased to 350 A, 26% increase in productivity is achieved. First 50 A rise (300 to 350A) give 26% rise in productivity, next 50 A rise gives 20%, next 50 A rise gives 15%, next 50 A rise gives 25%, then 26% and then the % improvement for the same 50 A flattens to just 3%. i.e. when the current is increased from 550 to 600 A, the % incremental productivity is just 3%, beyond this current value, any increase in current gives issues like unstable start, arc instability, undercut. This is the point, next larger sized wire at higher current levels to be used for further % increased productivity.

The trend is similar in 3.2 mm solid filler wire. From 300A, a rise of 50 A increment in current gives 15%, 24%, 13%, 13%, 15%, 19%, 20%, then the % increment drops to 6% and 6% for the same 50A increase, further effort to increase the current meets with same issues. Same trend is seen in 4.0 mm solid filler wire too, initially the % incremental productivity is 14%, 14%, 11%, 6%, 13%, 16%, 14%, then flattening to 7%, 7% (at 800 A) and further increase in current gives unacceptable welding arc/beads.

Welding current is the most influential parameter because it affects weld bead shape and controls the rate of melting of filler wire and therefore also controls the deposition rate. The SAW arc welding processes use constant current (CC) output in which welding current is the main presettable parameter. Increase in welding current results in increase in heat input. So, there is more melting of filler wire at the joint. This in turn gives rise to arc voltage. The increase in voltage increases controls the automatic wire feed unit to increase the wire feed speed. Thus, the weld metal deposition rate increases with increase in welding current. Excessive current causes the filler wire to overheat causing arc instability, a deterioration in weld profile and, sometimes, undercutting. Below a minimum current level, arc instability will also occur giving arc wander and poor penetration.

4.3 Effect of Current Density on Productivity

Current density is increasing as the welding current is increased, because while the cross section of filler wire (denominator) remains constant when the current value (numerator) is increasing. It can also be noted that between 350 A and 600 A, at every current value tested, the current density difference between 2.4 mm and 3.2 mm diameter wires is much higher than the difference between 3.2 mm and 4.0 mm diameter wires. Also, the slope of line 2.4 mm filler wire is higher than the other two. This is because, when the same magnitude of current (or the current difference) passes through the different cross sections, the effect is more pronounced in smaller cross section than larger cross sections. So, 2.4 mm diameter wire passes more current (per unit area) at same current than larger wires. This higher current density of the 2.4 mm diameter filler wire (up to 600 A), higher slope indicates the higher productivity rise of 2.4 mm diameter wire. Similarly, higher current density of 3.2 mm diameter filler wire (over 4.0 mm diameter wire) up to 750 A infers the higher productivity rise.

As the same amount of welding current passes through each wire, the current density is greater in the smaller diameter wire (2.4 mm) than in the larger diameter wire (4.2 mm). As a result of this higher current density, the smaller diameter wire will have greater weld metal deposition than the larger diameter wire. However, the wire diameter has a maximum current density before the welding arc tends to become unstable and erratic. So, when the welding current reaches to a certain level, it is necessary to increase the wire diameter.

4.4 Optimizing Filler Wire Diameter and Parameters for Higher Productivity

Increase in welding current in the range of 300-600 A (100% increase) for 2.4 mm filler wire, increases the productivity by 183%. Whereas the same 300-600 A (100% increase) in 3.2 mm filler wire, only 148% improvement in productivity is achieved. However, for 4.0 mm filler wire, the 100% increase in current (350-700 A) gives 127% improvement only in productivity. From this simple comparison, it is possible to derive strategy for wire size and parameter selection for production welding: i.e. if larger diameter filler wire is chosen for higher productivity in SAW, then the welding current usage should be far more higher than the current that can be applied on smaller wire size to match or beat smaller diameter filler wire productivity. In case, if the joint design, location of the pass in the joint (say hot pass on thin root/backing), or pipe/plate/section thickness/bevel/location of welding is such, much higher current usage is not possible, it may be worth selecting smaller wire size, and weld at slightly lower/equal current levels, which would give higher productivity values (than the larger sized wires at same or just little higher current levels). If the welding current is too high at a given welding speed, the depth of fusion or penetration will also be too high so that the resulting weld may tend to melt through the metal being joined. High current also leads to wastage of electrode wires in the form of excessive reinforcement and produces digging arc and undercut. This overwelding increases weld shrinkage and causes greater distortion. The higher level of welding current is also not desirable from the point of view of mechanical properties. It would lead to the more formation of coarser grains and deteriorate the joint strength and impact toughness.

2.4 mm diameter filler wire, between 300-400 A range, deposits 12-13 gm of weld metal for every ampere of welding current applied, but from 450-600 A range, the same wire deposits higher weld metal (14-17 gm/A) for every ampere of welding current. Based on the quantity of weld metal deposited (per ampere current applied), 2.4 mm diameter wire in 450-600 A range, performs far superior than the higher diameter 3.2 mm and 4.0 mm diameter wires, in that or even at higher current ranges. For comparison, at 550 A current, 2.4 mm diameter filler wire deposits 17 gm per ampere and

3.2 mm diameter wire deposits 13 gm per ampere which is 4 gm higher on 13 gm. This means that if 2.4 mm diameter filler wire is chosen and used at 550 A current, the deposition of weld metal will be 23% (3/13 x 100) more with the same application of heat into the job. Conversely, while depositing same weld metal quantity (say finite weld size on finite length on the same/identical job), 2.4 mm diameter would need at least 23% lesser current application than larger sized 3.2 mm diameter (or 4.0 mm diameter) wires.

During heavy fabrication, due to application of heat, job undergoes linear and or angular distortion. Sometimes distortion can lead to even rejection of job. Most of the time, fabricators are forced to go for elaborate pre-setting, load application to reduce the distortion extent or go for extensive/expensive distortion (heat) correction post-welding activities to correct the distorted job. Under these circumstances, if the applied current (or hear input) is lower, then the distortion also will be correspondingly lower. The reduction in distortion % is related and directly proportional to reduction in heat input to deposit the same quantity of weld metal. Application of 2.4 mm diameter at 550 A, depositing same weld quantity using 23% lesser current (or heat input) means, the distortion issues with 2.4 mm diameter wire at 550 A will be very much lower, when other parameters/conditions are identical.

4.5 Establishing Relationship between Welding Current and WMDR.

All the 27 WMDR values are related with preset welding current (A) values in the form of graph as shown in Fig. 5. The data points are connected using a best fit line concept and the straight line is governed by the following equations (1-3).

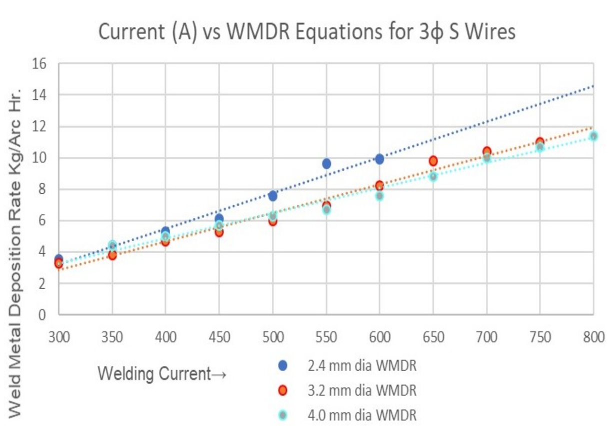


Fig. 5 Relationship between Welding Current and Weld Metal Deposition Rate

$$WMDR_{(\text{for 2.4 mm dia wire 350-600A range})} = (0.0228 \text{ x } A) - 3.625 \quad (1)$$

$$WMDR_{(\text{for 3.2 mm dia wire 350-750A range})} = (0.0183 \text{ x } A) - 2.643 \quad (2)$$

$$WMDR_{(\text{for 4.0 mm dia wire 350-800A range})} = (0.0161 \text{ x } A) - 1.595 \quad (3)$$

The WMDR (kg/hour) for any of the three-filler wire size (2.4, 3.2, 4.0 mm diameter) can be predicted for any preset welding current value (A, within the specified range) for the same/similar wire/flux combinations, at 90 % confidence level using respective equation. It is well established that increase in welding current increases the weld metal deposition rate. The developed relationship shows that the weld metal deposition rate is higher for small diameter wire (2.0 mm) and requires comparatively less (23%) amount of welding current to attain the improved productivity than large diameter filler wires (3.2-4.2 mm diameter wires). This would reduce the cost of energy consumption and processing time. The larger diameter filler wires can carry more current than a smaller filler wire, and produce a higher deposition rate at higher amperage.

5. Conclusions

(i) Welding current is the most influential parameter because it controls the rate of melting of filler wire and therefore also controls the deposition rate.
(ii) Using the 27 experimental results, the relationship between welding current and WMDR for three wire sizes have been established.
(iii) The developed relationship can be effectively used to predict the weld metal deposition rate for a given welding current at 90% accuracy. Conversely, it can also be used to estimate the preset welding current values for a required weld metal deposition rate at 90% accuracy.
(iv) It is found that 100% increase in welding current for 2.4 mm filler wire, increased the productivity by 183%. Whereas the same 100% increase in welding current for 3.2 mm filler wire, increased the productivity only 148%. However, in 4.0 mm filler wire, the same 100% increase in current yielded 127% improvement only in productivity.
(v) The small diameter filler wire is best suitable to improve the productivity of the process for a given industrial application. It requires comparatively less amount of welding current than the larger diameter filler wires to attain higher weld metal deposition rate.

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