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High Productivity of Submerged Arc Welding Achieved with Multiple-Wire Technology

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***Abstract*—The paper addresses a comparative analysis between theoretical and experimental results of the deposition rates, achieved by Submerged Arc Welding, when single and multiple wires technologies are applied. Two welding variants have been investigated in the research program, one power source welding on the one hand and two power sources welding (*Tandem* technique) on the other hand. Classical welding current power sources - i.e. standard DC and rectangular waveform AC - and also the most recent inverter power source, which allows waveform modulating, were selected and used in the experimental program. Comparing the deposition rates achieved in the case of using two conventional power sources systems (*Tandem Single* + *Single* wire welding) with values achieved in the case of multiple-wire welding technique (even if a traditional welding system with only one single power source is used), a higher productivity of the welding process has been noticed when multiple-wire technology is applied. Finally, by combination of multiple power sources systems with multiple-wire welding technique, impressive results of the deposition rates values can be obtained. Process limits and experimental data were graphically processed and presented on the same charts to be comparatively discussed and analyzed. Based on the investigations results, relevant conclusions are highlighted at the paper's end.**

***Keywords*—submerged arc welding, Tandem, Twin, ICE™, multiple-wire welding technique, deposition rate**

I. Introduction

Due to the high values of the deposition rates, uniform and esthetical appearance of the welding layers, *Submerged Arc Welding* (SAW) is the main process applied for pressure vessels manufacturing, offshore constructions, shipbuilding and, generally, for the joining of thick sections that involves a large amount of filler material and long welds [1]. Although the process itself is characterized by a high level of productivity, the actual trends in the process development are looking for further growth of the deposition rates. For the conventional SAW, high productivity derives mainly from the high degree of automation, combined with high values of welding current, which can reach values up to 1000 A without additional special precautions.

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By increasing the welding current, further increases in deposition rates are expected. Generally, that means a growth of heat input value, which most of the times leads to a decrease of the mechanical properties. Toughness is in particular negatively affected by the increase of heat input value. This is very important, especially for the high tensile steels such as the types HSLA (High Strength Low Alloy Steel) or HY (High Yield Steel).

A limitation of heat input value can be reached, at least theoretically, by increasing the welding speed. Chandel and Bala [2] showed that, in practice, this option involves another drawback related to excessive increase of the welding speed which may cause welding defects such as undercuts, lack of fusion, etc. Therefore, increasing the deposition rate should be done without increasing the heat input if it is possible.

There are several types of welding systems, well known and widely used in many welding cases, which could lead to significant increase of the deposition rates. One classification criterion is the number of power sources involved in the welding process. From this point of view, SAW welding process can be divided into two main categories:

- Single power source welding systems;
- Two (or more than two) power sources welding systems.

II. Analytical Models for Deposition Rate Calculus

For determining the actual maximum values that can be achieved under normal operating conditions, practical measurements were performed for each process variant under analysis. Based on the measurements results, analytical formulas have been developed in order to establish the process limits and to fix the theoretical values of the deposition rates. According to Chandel [3], when conventional SAW with one single wire is applied, the deposition rate can be estimated using the mathematical equation (1):

$$DR = A \cdot I + \frac{B \cdot I^2 \cdot L}{d^2} + C \tag{1}$$

where the signification of the terms is the following:

DR is the deposition rate;

I - the welding current;

L - free length of the electrode;

d - electrode diameter.

TABLE I. CONSTANTS VALUES VS. WELDING CURRENT POLARITY

Welding DC$^+$	Welding DC$^-$
A = 0.010371	A = 0.016178
B = 2.2426	B = 2.087 x 10^{-6}
C = -0.46 x 10^{-6}	C = -0.643

A, *B* and *C* are constants which are dependent on the current polarity and wire type used in the welding process. For instance, when low alloyed carbon steels are welded, the constants have the values presented in the Table I.

In the multiple-wire welding process, the behaviour and the melting way of the wires depend on the electrical and magnetic phenomena developed in the electric arc column. Tušek reported a formula that can be used to estimate the values of the deposition rates when multiple wires welding technique is applied [4]:

$$DR = \frac{I \cdot n \cdot (U_E + \alpha \cdot L \cdot j \cdot n^{-0.2})}{Q_k + \beta} \qquad (2)$$

where *DR* is the deposition rate;

I - the welding current;

L - free length of the electrode;

n - number of electrodes (wires);

U_E - arc voltage;

Q_k - energy per unit mass of molten metal contained in the droplet after detachment from the welding wire;

U_E, α, j, Q_k and β are values that are obtained through experimental measurements.

Since the above constant values should be experimentally determined and the number of electrodes (wires) used in most of the practical cases analyzed is 2, the mathematical formula (2) should be rewritten. Besides, it can be assumed that the electric current is equally distributed between the two electrodes that are simultaneously melting without mutual influence. Therefore, the mathematical model becomes similar to the mathematical model used for single wire electrode case. Applying this simplifying principle, the deposition rate can be estimated with acceptable accuracy as follows:

$$DR = 2 \cdot \left(A \cdot \frac{I}{2} + \frac{B \cdot I^2 \cdot L}{4d^2} + C \right) \qquad (3)$$

The parameters from the equation (3) have the following signification:

DR is the deposition rate;

I - the welding current;

L - free length of wire electrode;

d - wire diameter.

A, B and C are constants that depend on the current polarity and type of wire used in the welding process. The constants values are shown in the Table I.

III. Experimental Procedure

The assessment of the deposition rate - computed with the formulas (1), (2), (3) - aims to validate the process limits practically found. In practice, factors as quality and properties of welding fluxes, welding joint geometry and welding process stability have a major influence on the deposition rate. The shape and size of the components which have to be welded, but also the capability of the equipment in use, are crucial and lead to limitations of the welding parameters that ultimately make values to be lower than the process limits for security and comfort of the operator.

The following SAW welding equipments, presented in figure 1, were used for the experimental measurements [5]-[9]:

- ESAB inverter power sources ARISTO® 1000 AC/DC SAW offering the possibility to modify the AC wave balance and frequency [7];
- AC classical power sources with rectangular waveform type TAF 1250 [9];
- DC classical power sources type LAF 1251 [8];
- PEK control units having the possibility to memorize the welding parameters and provide digital data on actual values of welding current and voltage, heat input values and actual consumption of welding wire [6].

The PEK control unit features 255 memory locations, shown in figure 1, can record as many sets of welding parameters (current, voltage, welding speed, polarity, wave balance etc.) [6]. Each weld is registered, by the date and time related to its performing, and a serial number from 100 memory locations, available to store the data, is assigned to it. The data stored within the controller memory can be exported and, further, processed as Xcel or XML files. The *Quality Functions* provide information on welding system parameters, while the *Productivity Functions* give information on the filler material and wire consumption. Figure 2 illustrates the information displayed on the PEK controller, as an example of *Quality* and *Productivity Functions*.

Figure 1. Aristo® 1000 AC/DC SAW and PEK controller [7]

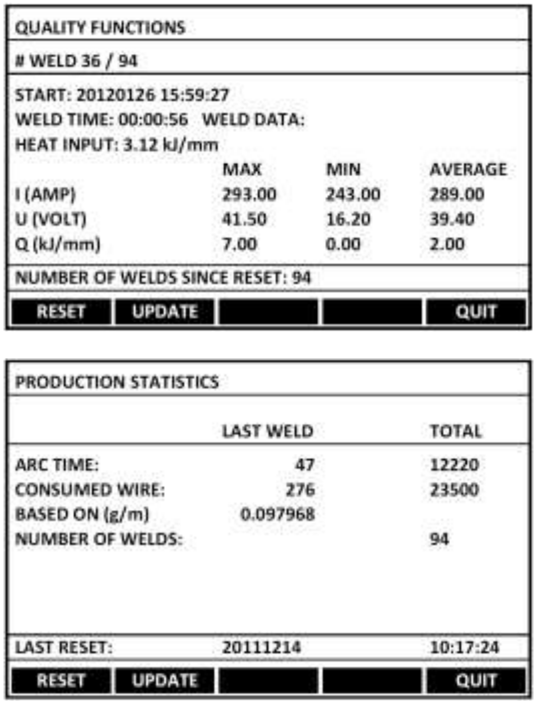

Figure 2. PEK controller’s display showing the quality and production information [6]

The PEK controller can provide the following information about each weld performed in the experimental program:

- minimum, maximum and average welding current;
- minimum, maximum and average welding voltage;
- minimum, maximum and average heat input value;
- amount of welding wire consumption;
- last weld registered.

The investigations included several welding process variants, starting with conventional *Single Wire* SAW, *Twin Arc* welding, *ICE*^{TM} welding, *Tandem* welding and finishing with the combined variant between *Tandem Single* and *ICE*^{TM}. The welding conditions followed in the experimental program are presented below:

A. Welding systems with a single power source:

- *Single Wire* welding, 4.0 mm diameter wire, DC$^+$
- *Twin Arc* welding, 2 x 2.4 mm diameter wires, DC$^+$
- *Single* wire of 4.0 mm diameter, AC welding, 30% positive half cycle and 70% negative half cycle
- *Twin Arc* welding with the addition of "cold" wire - Integrated Cold Electrode ICE^{TM} - 3 x 2.4 mm diameter wires and DC$^+$ polarity
- *Twin Arc* welding with the addition of "cold" wire - *Integrated Cold Electrode ICE*^{TM} - 3 x 2.4 mm diameter wires, AC with balanced square wave.

Figure 3. *Tandem Single + ICE®* welding system configuration [5]

B. Welding systems with two power sources:

- Classical *Tandem* welding, with single wire of 4.0 mm diameter for each welding torch
- *Single Wire* + *Twin-Tandem* welding, with 4.0 mm diameter wire for the leading torch and 2 x 2.4 mm welding wire the trailing welding torch
- *Tandem-Twin* Arc welding with 2.4 mm diameter
- *Tandem* welding with *Single* + *ICE*^{TM}, using single 4.0 mm wire diameter on the leading torch and 3 x 2.4 mm wire diameters (*ICE*^{TM}) for trailing welding torch (Figure 3)
- Since the applicability of DC$^-$ polarity welding is limited by the low values of penetration, no experiment has been performed in these joining conditions.

The *Twin Arc* multiple-wire welding system, with two wires of 2.4 mm diameter, and the most recent *ICE*^{TM} welding system, with three wires of 2.4 mm diameter, launched by ESAB Company, have been used in the investigations[5]. The *ICE*^{TM} acronym comes from *Integrated Cold Electrode* and refers to the fact that the third wire is electrically insulated and is melted due to the heat generated by the electric arc during the welding process.

As shown in the figure 4, an additional amount of filler material is obtained without changing the relevant welding parameters (welding current and voltage). This is a recent breakthrough, developed by ESAB Company, and it is based on the classic *Twin Arc* welding technique. In this new process alternative, in order to improve the deposition rate, a so-called "cold wire" is included between two wires connected to the power source.

The process is monitored through a software routine, included in the PEK process controller, and also through additional hardware components that are used to handle the additional “cold electrode”. The welding parameters applied to acquire the theoretical values of the deposition rates, for various configurations analyzed, are presented in the Table II. A typical flux and wires (*AUTROD OK 12.20* and *OK Flux 10.71*) combination, recommended for mild steel alloys welding, has been used in the experimental program.

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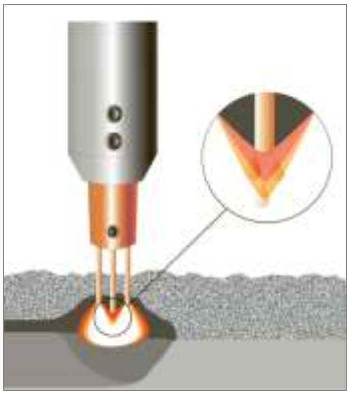

Figure 4. *ICE*^{TM} operating principle [5]

TABLE II. WELDING PARAMETERS

No. wires x diameter	Polarity of current	Welding current [A]
1 x 4.0 mm	DC$^+$	900
1 x 4.0 mm	AC 30% positive	900
2 x 2.4 mm	DC$^+$	1100
3 x 2.4 mm	DC$^+$	1100
3 x 2.4 mm	AC 50% positive	1100

Process limits and experimental results related to heat input and respectively to the deposition rate, achieved in different welding conditions, are clearly illustrated in the graphs shown in the figures 5 and 6.

IV. Results and Discussions

Process limits and experimental values - obtained for different combinations and configurations of the welding systems - represented in the figures 5 and 6 reveal the following phenomena:

- The value of the deposition rate increases with the increase of the current density applied to the welding wire.
- Using the multiple-wire welding technique, a higher deposition rate is achieved in comparison with single-wire welding technique [4];
- By increasing the negative half cycle ratio in single wire (AC) welding, a growth of the deposition rate can be achieved, maintaining an acceptable level of the penetration and, above all, maintaining the stability of the welding process;
- By adding an auxiliary "cold" wire (*ICE*^{TM} process), a substantial increase of the deposit rate, up to 50% higher than the second most productive welding process with a single power source (*Twin Arc*) is obtained. The main advantage of the process derives from the fact that the amount of deposited material increases, without changing the heat input value.

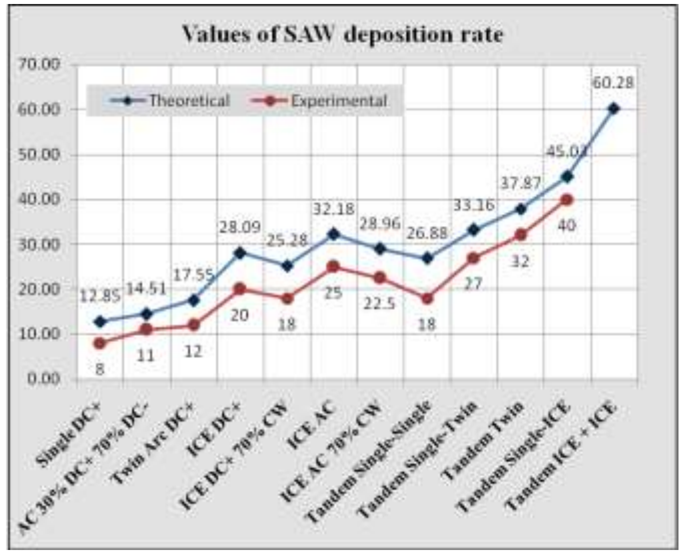

Figure 5. Deposition rates for different process alternatives showing the process limits

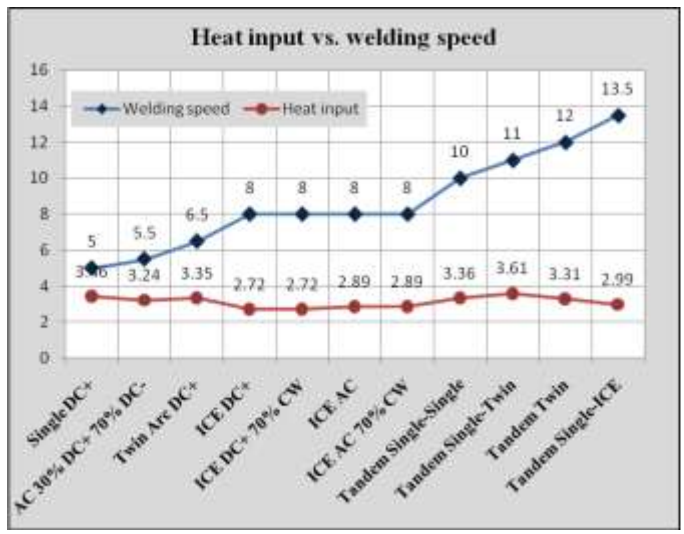

Figure 6. Heat input vs. welding speed

- Due to the additional quantity of filler material, introduced in the process, the welding speed could increase and the heat input will decrease, while all the other relevant welding parameters (current/voltage) do not change. In these welding conditions, the effect is mostly beneficial to the resilience of the welded joints.
- It is important to notice that in a comparative analysis referred to the system with a single power source (*ICE*^{TM}) and the traditional welding system with two independent power sources (*Tandem Single + Single)*, the new "cold wire" welding process leads to higher deposition rates (Figure 5). This happens due to the multiple-wire technology that uses an increased current carrying capacity, compared to the single wire one. The experimental tests revealed that for a single 4.0 mm diameter wire, both single and tandem

welding, the process limits the current up to 900 A, while for 2 x 2.4 mm wires (*Twin Arc*), the current reaches 1100 - 1200 A. Furthermore, in the *ICE*™ welding process, the additional of the third “cold” wire favourites the stabilization of the welding process and an increase of the current more than 1400 A.

- The benefits of using the multiple wires welding systems are significant in terms of welded joints performances. Due to the possibility of increasing the welding speed, because of higher deposition rates achieved with multi-wire technology, the heat input value can decrease (Figure 6). It is well-known that applying a lower heat input in the joining process, the welding effects on the alteration of the base material’s mechanical properties are more reduced and the distortions are lower.

V. Conclusions

Considering the deposition rate as a main estimator of the productivity, the paper deals with a comparative study on the deposition rate values, achieved in various combinations and configurations of welding systems, derived from the conventional *Submerged Arc Welding*. The investigations included theoretical research on process limits and experimental tests to determine the “comfortable” deposition rate values. Process limits and experimental results were graphically processed and represented on the same charts, in order to be compared and analysed.

The main relevant conclusions are listed and explained below:

- ✓ Efficiency of welding process increases, both in terms of quantity - by increasing the deposition rates - and in terms of quality - by reducing the heat input – by using an increased number of welding wires;
- ✓ A welding system based on a single current power source, but using several wires can be more productive than a welding system based on two welding power sources, but using single wire welding heads. Economic benefits coming out from the energy consumption, which is reduced by about 50% for a single welding power source system compared with two welding power sources, are obvious;
- ✓ The only noticeable drawback is, to some extent, the reduced penetration achieved with multiple-wire welding technique, in comparison to single wire welding variant. Under normal circumstances, when the high penetration is of secondary importance while a high deposition rate is desired, more than two thirds of the welder’s job are dedicated to the filing of joint. A high penetration level is mostly required for the root runs.
- ✓ However, when it is needed to perform greater penetration, the technical solution is to use the multiple-wire welding system in a *Tandem* configuration with a leading welding head connected to a DC power source. In this case, the leading welding head will carry out the desired penetration, while the trailing welding head, having multiple wires incorporated in the torch, will perform faster filling of joint.

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