Experimental research on melting and deposition characteristics of wires during gas metal arc welding

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Abstract. The paper presents a comparative analysis related to the melting and deposition characteristics of different welding wires of 1.2 mm diameter, such as solid (ER70S6), basic flux-cored (E70T5CJH4), rutile flux-cored (E71T1MH4), metal-cored (E70C6MH4), and low fume metal-cored (E70C6MH4) used in Metal Active Gas Welding, Flux-Cored Arc Welding and Metal-Cored Arc Welding. Two-gases mixture, comprising 82% argon and 18% carbon dioxide, known as M21 (Corgon 18) shielding gas, was used during experiments to protect the contamination of the molten weld pool against oxygen, nitrogen, and hydrogen. Five weld beads have been deposited on S275N steel sheets in horizontal welding position (1G/PA), by employing the filler metals mentioned above. Based on the experimental results and comparative analysis, significant information on melting and deposition characteristics has been achieved. The experimental results have revealed that the lowest loss ratio was achieved in the case of MCAW with low fume metal-cored welding wire (E70C6MH4).

1. Introduction
Gas Metal Arc Welding (GMAW) refers to Metal Active Gas (MAG) or Metal Inert Gas (MIG) welding and has a great applicability in many sectors of industry, such as shipbuilding, railroad construction and the production of heavy plants and machinery [1], [2]. It is particularly suitable for welding high-alloy steels, non-ferrous metals like aluminium, nickel, copper and magnesium, and special materials such as titanium [3]. Depending on filler metal type, solid wire or flux-cored and metal-cored wires, the arc welding with active gas shielding can be used as MAG welding, Flux-Cored Arc Welding (FCAW) or Metal-Cored Arc Welding (MCAW), respectively. Frequently encountered in the mechanised version (feed rate of the mechanized electrode wire, manual welding speed), the process is easy to automate and even robotize. Arc welding with active gas shield is one of the most used processes in industry, due to the following advantages [4]:

- high speed welding and, consequently, high productivity;
- welding is possible in all positions;
- easy and accurate welding, good control due to the visibility of the arc and welding pool;
- better penetration control for root passes and thin plates;
- using solid wire, a clean weld without slag is achieved, due to lack of coating or flux;
- low amount of smoke;
- low welding stresses and deformations due to low heat input developed by the process;
The process presents several disadvantages and limitations which refer to [1], [2]:
- greater expenses to purchase and to maintenance of the welding equipment;
- loss of filler metals by spatters (5 ... 10%);
- sensitivity to air currents and, consequently, risk of reducing the protection of the weld pool;
- used to welding workpieces with thickness higher than 1 mm;
- high risk of defects formation, such as pores and lack of melting.

Because the FCAW and MCAW combine the high productivity with the benefits of having a flux present from melting the flux-cored or metal-cored wires, the process has several advantages [2]:
- high deposition rates and deeper penetration than shielded metal arc welding (SMAW);
- less operator skill required than for gas-metal arc welding (GMAW);
- simpler and more adaptable than submerged arc welding (SAW);
- more tolerant of rust and mill scale than GMAW.

Disadvantages of the FCAW process include [2]:
- slag must be removed from the weld and;
- more smoke and fume are produced in FCAW than in the GMAW and SAW processes.

In this paper the assessment of the melting and deposition characteristics of different types of welding wires, by employing the Metal Active Gas welding with M21 shielding gas (MAG-M), FCAW and MCAW processes, is discussed in detail. Significant information which is useful for the industry of welded structures is summarized after discussing the experimental data processing.

2. Materials and methods

The experimental programme was carried out in the Welding Advanced Research Center (SUDAV) of the Department of Manufacturing Engineering from Faculty of Engineering, “Dunarea de Jos” University of Galati. The experimental stand, used for MAG-M welding, FCAW and MCAW, is exhibited and described in figure 1.

The materials employed for evaluation of filler metals characteristics are listed and described below.
- base material: S275N steel sheets with dimensions of 200 x 150 x 7, in [mm];
- filler material with 1.2 mm diameter: ER70S6 solid wire, E70T5CJH4 basic flux-cored wire,
E71T1MH4 rutile flux-cored wire, E70C6MH4 metal-cored wire, and E70C6MH4 low fume metal-cored wire;

- shielding gas: M21 that is a mixture of two gases (82% argon and 18% carbon dioxide).

The phases followed in the framework of the experimental programme are listed and described below.

- Evaluation of sheets and wires’ weight before welding;
- Deposition welding of weld beads on S275N steel sheets;
- Recording the main welding parameters (current - I_s, arc voltage - U_s) and the welding time, t;
- Evaluation of sheets and inconsumable wires’ weight after welding.
- Evaluation of efficiency of the arc welding with active gas shield process.

Evaluation of the steel sheets’ weight, m_p, and m_psd, before and after welding, using a specific Denver Instrument, is presented in figure 2. The sheets surfaces were polished and machined by milling before starting the deposition welding. Also, five different types of welding wires [7], used for deposition welding by MAG-M FCAW and MCAW, having 1.2 mm diameter and 10000 mm length, were measured, in order to assess the total weight and the inconsumable wires weight, mso and msn, respectively. These weight values, determined for the sheets and the welding wires employed in the experiments, will be introduced in the mathematical equations used for assessing the melting and deposition characteristics of the solid, flux-cored and metal-cored welding wires.

Figure 2. Evaluation of the sheets and wires weight before and after welding, respectively.

Figure 3 shows images recorded during and after deposition welding. Five weld beads have been achieved by melting and depositing several solid, flux-cored, metal-cored and low fume metal-cored welding wires on five S275N steel sheets. The welds were performed in horizontal position (PA), by applying reverse polarity (DC+) welding and swinging the welding torch. The process parameters which were maintained constant the entire experimental programme are presented in the table 1. The samples achieved after deposition welding by MAG-M, FCAW and MCAW techniques are shown in figure 4a. The slag and the spatters were removed, by brushing, and the samples presented in figure 4b were prepared for the evaluation of the weight.

Table 1. Process parameters maintained constant during the experimental programme.

| Parameters of the deposition welding process | Values          |
|--------------------------------------------|-----------------|
| wire feed speed, v_e                       | 6 m/min         |
| swinging width, L_p                        | 5 mm            |
| swinging speed, v_p                        | 5 mm/s          |
| welding speed, v_s                         | 35 cm/min       |
| gas protection flow, Q_G                   | 18 l/min        |
| nozzle-plate distance, h_dp                | 15 mm           |
Figure 3. Images recorded during and after deposition welding on S275N steel sheets.

Figure 4. Weld beads deposited by welding on the S275N steel sheets (a) and after removal of slag and spatters (b).

During the experiments, the welding current, $I_s$, arc voltage, $U_a$ and welding time, $t$, were recorded and, further, used in the calculus of the melting and deposition characteristics of the filler metals. The values of theses process parameters are presented in the table 2. Besides, the weight values of the samples, $m_{po}$ and $m_{pd}$, determined before and after the deposition welding, were centralised in the table 2. Also, the total weight of filler metals and the inconsumable filler metal, $m_{so}$ and $m_{sn}$, respectively, was assessed and centralised in the table 2. Introducing the experimental values recorded and measured in the analytical mathematical relations (1) to (6), filler metal characteristics - such as melting and deposition rate, $P_T$ and $P_D$, efficiency, $R_N$, melting and deposition ratio, $\alpha_T$ and $\alpha_D$ and, finally, the loss ratio $\Psi$ – can be assessed and comparatively discussed.

Melting rate of filler metal, $P_T$

$$P_T = \frac{m_{so} - m_m}{t}$$  \hspace{1cm} (1)

Deposition rate of filler metal, $P_D$

$$P_D = \frac{m_{pd} - m_{po}}{t}$$  \hspace{1cm} (2)

Nominal efficiency of filler metal, $R_N$

$$R_N = \frac{m_{so} - m_{po}}{m_{po}}$$  \hspace{1cm} (3)
The typical chemical composition of the rutile and basic flux causes by the loss through spatters, as well as by the metallic oxides which are transferred from the welding metal. As well as by the welding current. These characteristics range from 0.23 to 0.29 g/A·min and from 0.20 to 0.26 g/A·min, respectively. A difference between melting and deposition ratios is noticed and that is caused by the loss through spatters, as well as by the metallic oxides which are transferred from the welding metal.

The nominal efficiency of the welding wires employed in the experiments is plotted in figure 6 and supports the results discussed above. This parameter increases from 80% to 99%, the lowest value being computed for the E71T1MH4 rutile flux-cored wire and the highest for the solid wire ER70S6. An acceptable efficiency (85%) was noticed in the case of FCAW welding with E70C6MH4 low fume metal-cored wire, too.

The melting and deposition ratios are strongly influenced by the chemical composition as well by the welding current. These characteristics range from 0.23 to 0.29 g/A·min and from 0.20 to 0.26 g/A·min, respectively. A difference between melting and deposition ratios is noticed and that is caused by the loss through spatters, as well as by the metallic oxides which are transferred from the welding metal.

\[ R_M = \frac{m_{pd} - m_{po}}{m_{pd} - m_{so}} \times 100 \]  \hspace{1cm} (3)

Melting ratio of filler metal, \( \alpha_r \)

\[ \alpha_r = \frac{m_{ST}}{l_S t} = \frac{m_{so} - m_{sc}}{l_S t} \]  \hspace{1cm} (4)

Deposition ratio of filler metal, \( \alpha_d \)

\[ \alpha_D = \frac{m_{pd} - m_{po}}{l_S t} \]  \hspace{1cm} (5)

Loss ratio of filler metal, \( \Psi \)

\[ \Psi = 1 - \frac{\alpha_D}{\alpha_r} \]  \hspace{1cm} (6)

Table 2. Samples weight before and after deposition welding and the main process parameters.

| Sample/Process | Wire type/ Wire code | \( m_{po} \) (g) | \( m_{so} \) (g) | \( m_{pd} \) (g) | \( m_{sd} \) (g) | \( m_{sc} \) (g) | \( I_s \) (A) | \( U_s \) (V) | \( t \) (min) |
|----------------|---------------------|------------------|------------------|------------------|------------------|------------------|---------------|---------------|---------------|
| D1 MAG-M       | solid ER70S6        | 1534.89          | 86.65            | 1575.61          | 42.81            | 43.41            | 43.84         | 230           | 26.5          | 0.822         |
| D2 FCAW        | basic flux-cored E70T5CJH4 | 1531.06          | 73.40            | 1565.02          | 36.18            | 33.96            | 39.44         | 170           | 21.0          | 0.823         |
| D3 FCAW        | rutile flux-cored E71T1MH4 | 1538.20          | 75.31            | 1571.59          | 37.12            | 33.39            | 41.92         | 200           | 24.0          | 0.821         |
| D4 MCAW        | metal-cored E70C6MH4 | 1538.37          | 80.20            | 1575.23          | 39.91            | 36.86            | 43.34         | 180           | 32.0          | 0.822         |
| D5 MCAW        | low fume metal-cored E70C6MH4 | 1535.51          | 81.07            | 1573.61          | 40.03            | 38.10            | 41.04         | 180           | 32.0          | 0.823         |

3. Results and discussion

The computed values that characterise the solid, basic and rutile flux-cored, metal-cored and low fume metal-cored filler metals, melted and deposited by MAG-M welding, FCAW and MCAW processes, were graphically processed and comparatively discussed.

From figure 5, it noticed that the deposition and melting rate of the filler metals depends on the wire type – solid, flux-cored - and on the core type (basic, rutile or metal-cored). The melting rate of the welding wires used in the experimental programme is in the range of 47.92...57.72 g/min, the lowest value being specific to the E70T5CJH4 basic flux-cored wire and the highest to the E70C6MH4 metal-cored wire due to the additional metallic powders introduced in the core of the filler metal. As regards the deposition rate that increases from 40.67g/min to 52.81g/min, the experiments revealed that the lowest value was recorded for the rutile flux-cored wire E71T1MH4 and the highest for the solid wire ER70S6. This phenomenon is possibly caused by the typical chemical composition of the rutile and basic flux-cored wires that is characterised by lower amount of metallic compounds, comparing to the solid and metal-cored filler metals.

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pool to the slag formed on the weld surface. The highest ratios were achieved for the E70C6MH4 metal-cored wire and the lowest for the ER70S6 solid wire because of the higher welding current required for deposition welding. Good results were noticed in the case of welding with E70C6MH4 low fume metal-cored wire, too.

According to equation (6), the loss ratio depends on the deposition and melting ratios. It can be noticed that it is increasing from 0.07 to 0.23 value. The highest loss is noticed in the case of FCAW with E71T1MH4 rutile flux-cored wire and the lowest loss is achieved when the E70C6MH4 low fume metallic-cored wire is used in the MCAW process, due to the additional metal powders inserted in the filler metal core.

Figure 5. Melting and deposition rate.

Figure 6. Nominal efficiency of filler metal.

Figure 7. Melting and deposition ratio.

Figure 8. Loss ratio of filler metal.

4. Conclusions
The experimental results have revealed that the lowest loss ratio was achieved in the case of MCAW with E70C6MH4 low fume metal-cored tubular wire. Additionally, due to reduced emissions and fumes during welding, this filler metal represents an appropriate solution to protect the welder health.

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