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IMPROVEMENT OF ENERGY AND MATERIALS EFFICIENCIES BY INTRODUCING MULTIPLE-WIRE WELDING

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The paper deals with a study and comparison between welding with several wires in different shielding atmospheres and single-wire welding. The first part treats the equipment for multiple-wire electrode welding and a comparison between single-wire welding and twin-wire welding. The second part deals with the melting rate as a basis for determining the productivity of welding processes, and the third one with the energy efficiency as a criterion of cost-effectiveness of welding. Some results obtained regarding strength of submerged arc welded joints are shown.

Key words: *arc welding, multiple-wire electrode, energy efficiency, toughness*

Povećanje iskorištavanja energije i materiala uvođenjem zavarivanja s više-žica. U članku je prikazano istraživanje i uspoređenje zavarivanja s više-žičanom elektrodom u različitim zaštitnim atmosferama sa zavarivanjem pomoću samo jedne žice. U prvom je dijelu prikazana oprema za zavarivanje s više-žičanom elektrodom i usporedba sa zavarivanjem s jednom žicom i zavarivanjem s dvije žica (elektroda). U drugom je dijelu prikazan učinak kao osnova za mjerenje produktivnosti svakog postupka zavarivanja i u trećem iskorištavanje energije kao mjerilo ekonomičnosti zavarivanja. Prikazano je i nekoliko rezultata o čvrstoći zavarenih spojeva.

Ključne riječi: *elektrolučno zavarivanje taljenjem, više-žičana elektroda, iskorištavanje energije, žilavost*

INTRODUCTION

Welding is a complex multi-disciplinary technology requiring permanent modernisation of manufacture with new machines, permanent education of workers, and introduction of most recent manufacturing processes. A welding personnel should be highly qualified, periodically tested, and in a good physical and mental shape. Productivity in fusion arc welding processes can be increased in several ways. To attain a higher productivity in practice, arc welding with a multiple-wire electrode, welding with several electrodes, welding with an additional cold wire, welding with an additional metal flux, welding with a longer wire extension length, and other processes, are being used.

Single-wire welding in different shielding media has been known for almost a century. Welding with a multiple-wire (twin-wire) electrode and welding with several electrodes, however, have been known for approximately half a century. Both techniques have been primarily used with submerged arc welding processes [1 - 8].

In the 1980s and 1990s, new devices for multiple-wire welding appeared. Important developments were characteristic first of submerged arc welding with twin-wire, triple-wire, and multiple-wire electrodes [9 - 28], and then of gas shielded arc welding with a twin-wire electrode and with two electrodes respectively, the shielding gas being a gas mixture [29 - 34].

The multiple-wire electrode is nowadays mainly used in submerged arc welding of all grades of steel. Gas shielded arc welding with a twin-wire electrode, where two wires are fed through a single contact tube and current is supplied by a single current source, has not established itself because of too strong spatter of the weld pool.

More recent devices for gas shielded arc welding with two electrodes have pulsed-current sources that are computer-synchronised and controlled so that current pulses are supplied to the welding wires alternately, which produces a controlled, periodic, and alternate material transfer from each wire to the weld pool without spatter.

DESCRIPTION OF THE PROBLEM

Based on experimental measurements of the melting rate, of energy consumption per unit of filler material melted and the magnitude of the energy input, a comparison of single-wire welding with multiple-wire welding, the welding parameters per wire being the same, was to be made.

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Experiments were to include submerged arc welding with single-wire, twin-wire and triple-wire electrodes and gas shielded arc welding with two electrodes. Wires of different diameters, i.e., 1,2, 1,6, and 2,0 mm, were to be used. Rutile flux was to be used in submerged arc welding and a gas mixture of 82 % of argon and 18 % of CO_2 in gas shielded arc welding.

DESCRIPTION OF EQUIPMENT

Figure 1.a schematically shows a device for submerged arc welding with a triple-wire electrode. Figures 1.b and 1.c show cross sections of contact tubes containing three wires each. The wires can be arranged in a straight line (Figure 1.b) or in a triangle (Figure 1.c). The device permits welding with the three wires in an optional direction. This means that during welding the wires can be placed one after the other in the direction of welding or side by side or in any optional arrangement between the two (Figure 1.b). In case of wires making a triangle, the triangle may have sides of optional length and the position of the triangle with regard to the direction of welding may be optional (Figure 1.c). The possible directions of welding are marked with an "X".

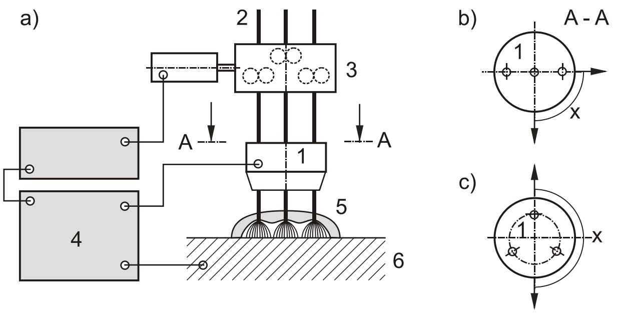

Figure 1. **Schematic representation of device for triple-wire welding (a), wires in the contact tube being arranged in a line (b) and in a triangle (c), and possible directions of welding (*x*): 1 - joint contact tube for three wires, 2 - welding wires, 3 - feeding system, 4 - joint power source, 5 - welding arcs with cavity, 6 - workpiece**

Slika 1. **Shematski prikaz naprave za zavarivanje s trožičanom elektrodom (a), s linijskim rasporedom žica u kontaktnoj sapnici (b) i u trokutastom obliku (c), te prikazom mogućih smjerova zavarivanja (*x*): 1 - zajednička kontaktna sapnica za sve tri žice, 2 - žice za zavarivanje, 3 - pogonski sustav, 4 - zajednički izvor struje, 5 - električni luk s pukotinom, 6 - radni komad**

Submerged arc welding with a triple-wire electrode knows different applications. Most frequently triple-wire welding is applied to surface worn-out surfaces or to weld larger gaps. Welding with the triple-wire electrode, the wires being arranged in a triangle, is used to join asymmetric joint assemblies and those between workpieces of different thickness. The triple-wire electrode may consist of wires of equal or different cross sections and of the same or different materials.

If one wire is removed from the device shown in Figure 1., a device for twin-wire welding will be obtained, and if one wire is added, a device for quadruple-wire welding will be obtained. The number of the wires in the contact tube and their arrangement there depend on the type and shape of the workpiece to be welded or surfaced [9 - 21, 36, 37].

Figure 2. schematically shows a device for gas shielded arc welding with two electrodes, the shielding gas being a gas mixture. There are two wires in the contact tubes. But in this case each wire is in a separate contact tube, i.e., they are electrically insulated, each has its own power source, feeding system, which means that the wire velocities may be different, that current intensities in the wires may be equal or different. It is common with such devices that both power sources and both feeding systems are interconnected through a special control unit synchronising the feeding systems of the two wires and their currents. With more recent power sources, pulsed welding current is often used [30 - 34].

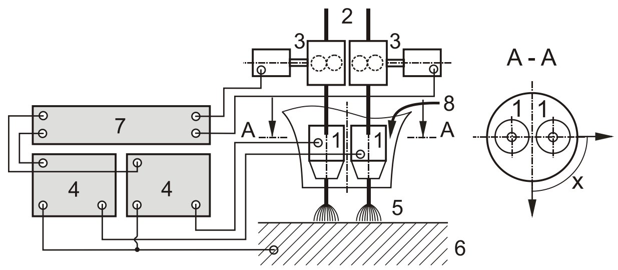

Figure 2. **Schematic representation of device for welding with two electrodes and possible directions of welding (*x*): 1 - contact tubes, 2 - welding wires, 3 - feeding systems, 4 - power sources, 5 - welding arcs, 6 - workpiece, 7 - control unit for feeding the two wires and their supply with pulsed welding current, 8 - supply of shielding gas to gas nozzle, *x* - possible directions of welding**

Slika 2. **Shematski prikaz naprave za zavarivanje s dvije elektrode i s prikazom mogućih smjerova zavarivanja (*x*): 1 - kontaktne sapnice, 2 - žice za zavarivanje, 3 - pogonski sustavi, 4 - izvori struje, 5 - električni lukovi, 6 - radni komad, 7 - komandni ormarić za pogon obje žice i za napajanje obje žice s pulsnom strujom zavarivanja, 8 - dovod zaštitnog plina u plinsku sapnicu, *x* - mogući smjerovi zavarivanja**

Welding with two wires can be used for surfacing and welding of thinner plates, for example in manufacture of pressure vessels, tanks, shorter tubes and other products in mass production. It can be used for all steel grades and aluminium alloys.

EXPERIMENTAL PROCEDURE AND RESULTS

The above-mentioned systems were used to study the influence of the number of wires used on the melting rate, and energy and material efficiencies. The device for triple-wire electrode welding was employed for submerged arc welding with a single wire, two wires and three wires in a joint contact tube, the welding parameters being different.

The device for welding with two electrodes, however, was used for gas shielded arc welding with a single wire and two wires, the shielding gas being the gas mixture.

Melting rate

The experimental results were then employed to calculate the melting rate, i.e. the length or mass of the filler material melted per unit time, the efficiency of energy consumed, and the quantity of the material lost due to spatter.

Figure 3. shows the melting rate as a function of the current intensity and the number of the welding wires employed in submerged arc welding and in gas shielded arc welding. The wire diameter was 1,2 mm. The wires were arranged in a line in the direction of welding.

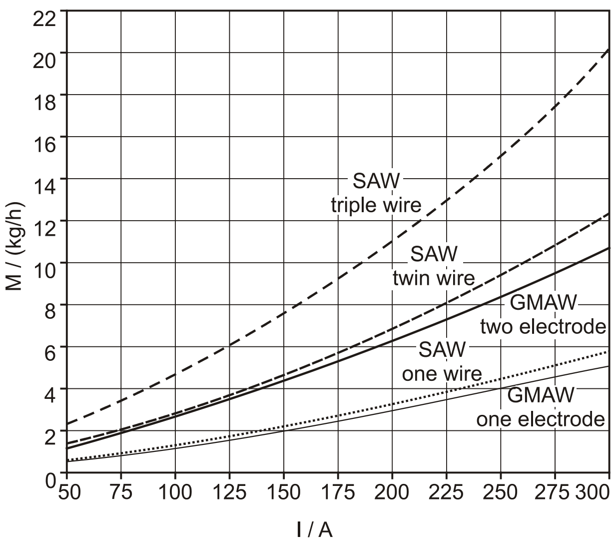

Figure 3. **Melting rate as a function of welding current and number of wires in submerged arc welding (SAW), (rutile flux) and in gas shielded arc welding (GMAW), (82Ar + 18CO_2); wire diameter: 1,2 mm, wire extension length: 20 mm, distance among wires: 7 mm**

Slika 3. **Učinak brzine topljenja u ovisnosti od jačine struje i broja žica kod zavarivanja pod zaštitnim praškom (SAW), (rutilni) i u zaštitnom plinu (GMAW), (82Ar + 18CO_2); promjer žice: 1,2 mm, slobodni kraj žice: 20 mm, udaljenost između žica: 7 mm**

The energy input was uniform per unit of weld length. The device shown in Figure 1. was employed for submerged arc welding with single-wire, twin wire, and triple-wire electrodes. The device shown in Figure 2. was employed for gas shielded arc welding with one electrode and with two electrodes, the shielding gas being the gas mixture mentioned under heading 2.

In gas shielded arc welding with several electrodes, however, no increase as a function of the number of wires in the melting rate occurred. In multiple-wire welding where there is a single power source, a much stronger current will flow through the wire extension for a very short period of time than in welding with several electrodes where each electrode has its own power source. This is true with the same average current intensity calculated per wire. The effect of the short-time high current in the wire extension is stronger than that of the long-time low current. This is true even if the product of time and current ($I \times t =$ const.) flowing through the wire extension is in both cases the same [37, 41, 42]. The energy of the welding current conducted through the wire extension can be described by Equation (1):

$$E = I^2 \cdot \frac{t}{S} \cdot \int_0^L \rho(L) \cdot \mathrm{d}L, \tag{1}$$

where:

I - the current intensity /A,
t - the time /s,
L - the wire extension length /mm,
S - the cross section of the wire /mm^2,
ρ - the resistibility /Ω·mm.

The diagram in Figure 3. shows that the melting rate in submerged arc welding increases with increases in the current intensity and in the number of wires used. With a current increase the melting rate does not increase in a linear manner but in a slightly exponential manner.

It can also be noticed that the melting rate in submerged arc welding is, under the same conditions, somewhat higher than in gas shielded arc welding.

Figure 4. shows the melting rate obtained in submerged arc welding with the triple-wire electrode, the diameters of the welding wires being different. The diagram indicates that the melting rate is strongly affected by the wire diameter, i.e., current density in the wire extension. This means that with the same current and with a smaller wire diameter, a larger quantity of the filler material will be melted. This is quite logical from the viewpoint of physics.

In addition to experimental measurements, data on the melting rate in submerged arc welding and in gas shielded arc welding can be obtained also by calculations using different mathematical models [19, 20, 27, 41 - 54, 58].

Welding - process efficiency

The melting rate is only one of the indicators of the characteristics of a welding process. Another very important factor is the energy efficiency, i.e. the welding-process efficiency. In the literature various definitions may be find describing the welding-process efficiency, the welding-arc efficiency, the material efficiency or any other efficiency [35 - 40].

It is generally true that the welding-process efficiency is meant to be the efficiency of electric energy transformation into heat energy and the transfer of heat to the workpiece. In arc welding processes this can range between 50 and 98 %.

But it is known that the heat energy transferred from the arc to the workpiece is not consumed entirely for making the weld. During welding a great deal of heat energy, namely, gets "lost". Some of the heat energy propagates through the workpiece by conduction, and some of it is transferred to the workpiece environment by radiation. The quantity of the energy lost in this way depends on the type and thickness of the material welded, the welding parameters, the weld shape, and the type of shielding medium.

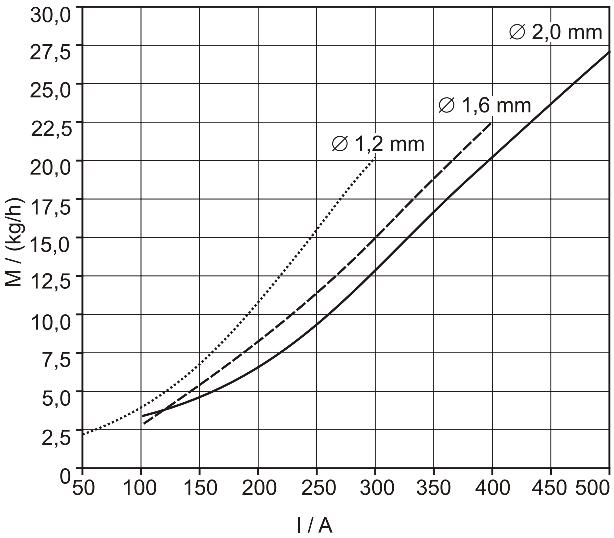

Figure 4. **Melting rate as a function of welding current and wire diameter (ø) in submerged arc welding with triple-wire electrode; wire extension length: 20 mm, distance among wires: 7 mm**

Slika 4. **Učinak brzine topljenja u ovisnosti od jačine struje i promjera žice (ø) za zavarivanje pri zavarivanju pod zaštitnim praškom s trožičanom elektrodom; slobodni kraj žice: 20 mm, udaljenost između žica: 7 mm**

According to some literature estimates it is more suitable to describe the welding efficiency as the efficiency of the energy consumed and call it the melting efficiency [35 - 39]. It can be calculated using Equation (2):

$$\eta_e = \frac{1340 \cdot M}{I \cdot U} \cdot 100, \quad (2)$$

where:

1340 J is the energy theoretically required to melt 1 g of the welding wire, and

M - the quantity of the filler material melted /(g/s),

I - the current intensity /A,

U - the arc voltage /V.

Equation (2) provides an efficient comparison of the energy efficiency with the individual welding processes. As in multiple-wire welding the energy loss to the environment is comparatively smaller than in single-wire welding, it can be expected that in multiple-wire welding the energy efficiency will be higher.

Figure 5. shows the melting efficiency of the energy as a function of the welding current and the number of the wires used. Equation (2) was used in calculations. The diagram

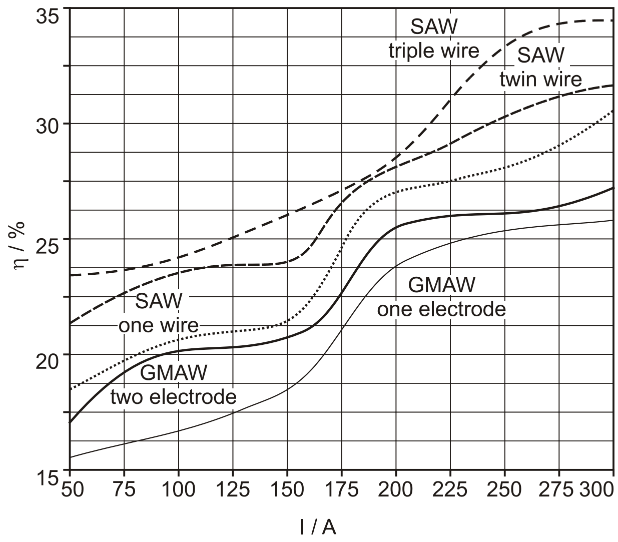

Figure 5. **Energy efficiency as a function of welding current and number of wires in submerged arc welding (SAW) and in gas shielded arc welding (GMAW); wire diameter: 1,2 mm, wire extension length: 20 mm, distance between wires: 7 mm**

Slika 5. **Iskorištavanje energije u ovisnosti od jačine struje i broja žica kod zavarivanja pod zaštitnim praškom (SAW) i kod zavarivanja u zaštitnom plinu (GMAW); promjer žice: 1,2 mm, slobodni kraj žice: 20 mm, udaljenost između žica: 7 mm**

indicates similar findings as stated above for the melting rate. The diagram also indicates that the melting efficiency is higher in submerged arc welding than in gas shielded arc welding, and that the melting efficiency is the higher, the higher the number of the wires in the contact tube is.

In addition to the energy efficiency, the efficiency of filler-material remelting indicates how much of the welding wire got "lost" during welding. This is the material, i.e., small burning droplets, spatter or sparks, that has been blown off the burning wire or the weld pool into the environment. In submerged arc welding this type of efficiency almost always amounts to 100 %. In gas shielded welding, however, it depends mostly on the type of shielding gas used, the welding current, the polarity, and the type of material welded [40 - 57].

MECHANICAL PROPERTIES OF WELDS OBTAINED USING THE MULTIPLE-WIRE ELECTRODE

It has already been found that in multiple-wire welding less energy is introduced into the workpiece per unit of the material melted, that. It is because of the lower energy input that it can be anticipated that the heat-affected zone surrounding the weld metal will be narrower and that the entire weld will, consequently, show more favourable mechanical properties.

Impact toughness test

The impact toughness test is one of better indicators of mechanical properties of a welded joint. The welded joints were made on low-alloy steel showing good weldability. The workpiece dimensions, the type of welded joint, the location where test pieces were taken, the shape and size of the toughness test piece are shown in Figure 6. A single-V butt weld was produced with a thickness of 12 mm. The impact toughness tests were performed only with submerged arc welded joints. The welding parameters were chosen so that with all the welds the energy input per unit of weld length was the same, i.e., 36 kJ/cm. The other welding parameters were as follows: I = 460 A/wire, U = 35 V, v(1x) = 0,57 m/min, v(3x) = 1,14 m/min, v(3x) = 1,71 m/min, the wire diameter was 2 mm, and the wire extension length 30 mm.

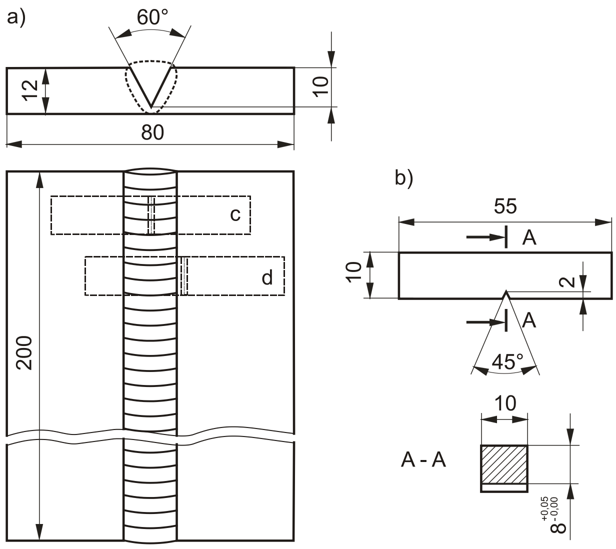

Figure 6. **Dimensions of workpiece (a) and test specimen (b) and locations of taking test pieces; c - test specimen for toughness testing in all-weld metal, d - test specimen for toughness testing in heat-affected zone of parent metal**

Slika 6. **Dimenzije radnog komada (a) probe (b) i mjesta uzimanja uzoraka; c - proba za utvrđivanje žilavosti u čistom zavaru, d - proba za utvrđivanje žilavosti u prelaznom području toplinskog utjecaja na osnovnom materijalu**

Figure 7.a shows the results of toughness testing of all-weld metals at a temperature of +20 °C. The welds were obtained in submerged arc welding with single-wire, twin-wire, and triple-wire electrodes and with the parameters stated above.

Figure 7.b shows the results of toughness testing of the heat-affected zone at +20 °C. It can be noticed that the toughness is higher than that stated by the manufacturer of the parent metal and the difference between the welded joints is obvious. The toughness in the heat-affected zone of the weld increases with the increase in the number of the wires in the contact tube [58].

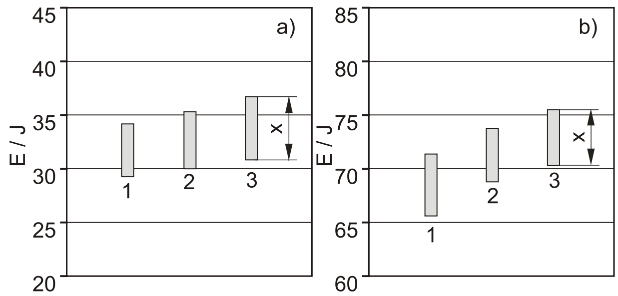

Figure 7. **Toughness of all-weld metals (a) and of heat-affected zone (b) established with standard ISO test specimens**

Slika 7. **Žilavost čistih zavara (a) i prelaznog područja toplinskog utjecaja (b) ustanovljeno standardnim probama po ISO**

Micro-hardness test

Micro-hardness was tested with a Vickers micro-hardness tester with a load of 30 N. The macro sections for testing were prepared from butt joints welded from the same material and with the same parameters as described above and shown in Figure 6.

Figure 8. schematically shows a macro section and a straight line upon it representing the line of micro-hardness testing. The hardness variation in the diagram indicates that with all weld metals hardness in the heat-affected zone

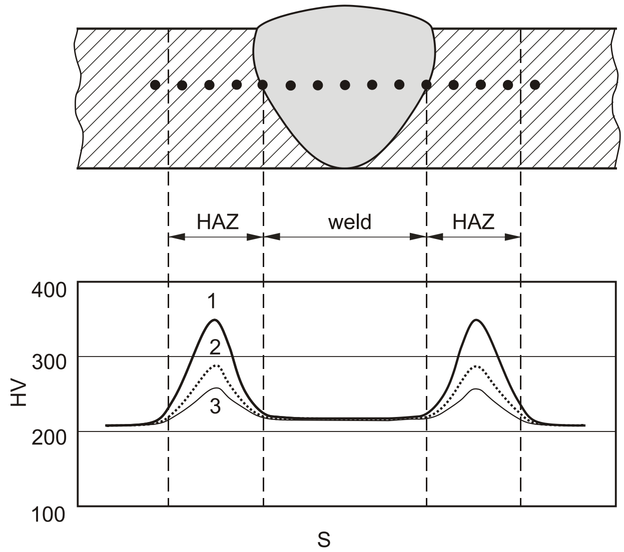

Figure 8. **Hardness variation and hardness measuring points across the entire joint welded with single-wire, twin-wire, and triple-wire electrodes**

Slika 8. **Promjena tvrdoće i mjesta njenog mjerenja preko cjelokupnog zavarnog spoja na spoju zavarenom s jednožičanom, dvožičanom i trožičanom elektrodom** increased. Such a result was expected. It is, however, a more surprising result that the hardness increased most in single-wire welding and least in triple-wire welding. But taking into account the phenomena occurring in multiple-wire welding and described above, the results are quite logic and could be expected [58].

CONCLUSIONS

The experimental measurements performed and the theoretical analysis made permit the following findings:

- the melting rate will increase with the increase of the number of wires in the joint contact tube, with the same energy consumption per wire, by a factor higher than the number of wires;
- in multiple-wire welding, however, a higher number of the wires do not increase the melting rate;
- the melting efficiency in welding will increase with the increase in the number of wires in the joint contact tube, the energy consumption per wire being the same;
- in multiple-wire welding the melting efficiency is independent of the number of the wires;
- heat-energy input in multiple-wire welding, the wires being arranged in a line in the direction of welding, is more favourable than in single-wire welding, the energy input being the same per unit of weld length;
- the mechanical properties of the weld are more favourable if the weld is made by multiple-wire welding than by single-wire welding.

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