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## Razvoj matematičnega modela za izračun talilnega učinka pri varjenju z večžično elektrodo

### Development of a Mathematical Model for Calculation of Melting Rate in Welding with a Multiple-Wire Electrode

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*V članku je prikazan razvoj matematičnega modela za izračun talilnega učinka, ki se doseže pri varjenju z večžično elektrodo v zaščitnih plinih ali pod praškom. V prvem delu je zelo splošno in v kratkem predstavljeno varjenje z večžično elektrodo. Opisane so bistvene prednosti in značilnosti ter različice varjenja z večžično elektrodo, ki jih je mogoče uporabiti v praksi za različne konkretnе primere.*

*Glavni del članka je posvečen razvoju matematičnega modela za izračun talilnega učinka na podlagi fizikalnih zakonitosti varilnega obloka, ogrevanja prostega konca žice zaradi prevajanja toka in medsebojnega topotnega vpliva varilnih oblokov.*

*Na koncu članka je prikazana primerjava rezultatov talilnega učinka, pridobljenih s praktičnimi meritvami, z rezultati, pridobljenimi teoretično z matematičnim modelom.*

*The paper deals with the development of a mathematical model for the calculation of melting rates obtained in gas-shielded arc welding with a multiple-wire electrode or in submerged arc welding with a multiple-wire electrode. The first part provides a very general and short description of welding with a multiple-wire electrode, the main advantages and characteristics, as well as options of welding with a multiple-wire electrode applicable in practice to various cases.*

*The major part of the paper treats the development of the mathematical model for calculation of melting rate on the basis of physical principles of the welding arc and of wire extension heating due to current conduction and mutual thermal influence of the welding arcs.*

*Finally a comparison is made between the melting rate results obtained by practical measurements and those obtained theoretically by the mathematical model.*

#### 0 UVOD

Za matematični popis tehnikoških postopkov, kemičnih in fizikalnih ter drugih procesov je v splošnem znanih več različnih metod. Pri varjenju s taljivo elektrodo sta se za izračun talilnega učinka, to je količine pretaljenega dodajnega materiala, uveljavila predvsem dva, med seboj različna postopka.

Pri prvem je uporabljena statistična metoda. Matematični model dobimo na podlagi zelo velikega števila podatkov, dobljenih s preizkusi. V tem primeru nas sam proces ne zanima, zanimajo nas vstopni in izstopni podatki, ki so temelj za statistično obdelavo in izračun statističnih modelov. Pri eksperimentalnem delu moramo paziti, da so preizkusi realni in da dobljeni rezultati pomenijo dejansko verjetnost.

#### 0 INTRODUCTION

In general, the several methods of modelling of technological, chemical, physical and other processes are well-known. In consumable-electrode welding, two different principles have asserted themselves for calculation of the melting rate, i.e. of the quantity of filler material molten.

The first one applies a statistical method. This model is based on a great number of data obtained by means of experiments. In this case, we are not interested in the process itself, but in input and output data which form the basis for statistical processing and calculation of statistical models. In the experimental work, care should be taken to ensure that the experiments concerned are real and that the results obtained represent an actual probability.

Druga metoda temelji na matematično-fizikalnih zakonitostih procesa. V tem primeru je treba zelo dobro poznati sam proces in fizikalne ter kemične zakonitosti v njem.

V našem primeru, pri talilnem obločnem varjenju, bomo uporabili drugo metodo in skušali po fizikalnih zakonitostih matematično popisati proces in na podlagi vstopnih podatkov oziroma, v našem primeru, varilnih parametrov in fizikalnih lastnosti materialov matematično napovedati količino pretaljenega dodajnega materiala pri varjenju z večžično elektrodo.

### 1 KRATEK OPIS VARJENJA Z VEČŽIČNO ELEKTRODO

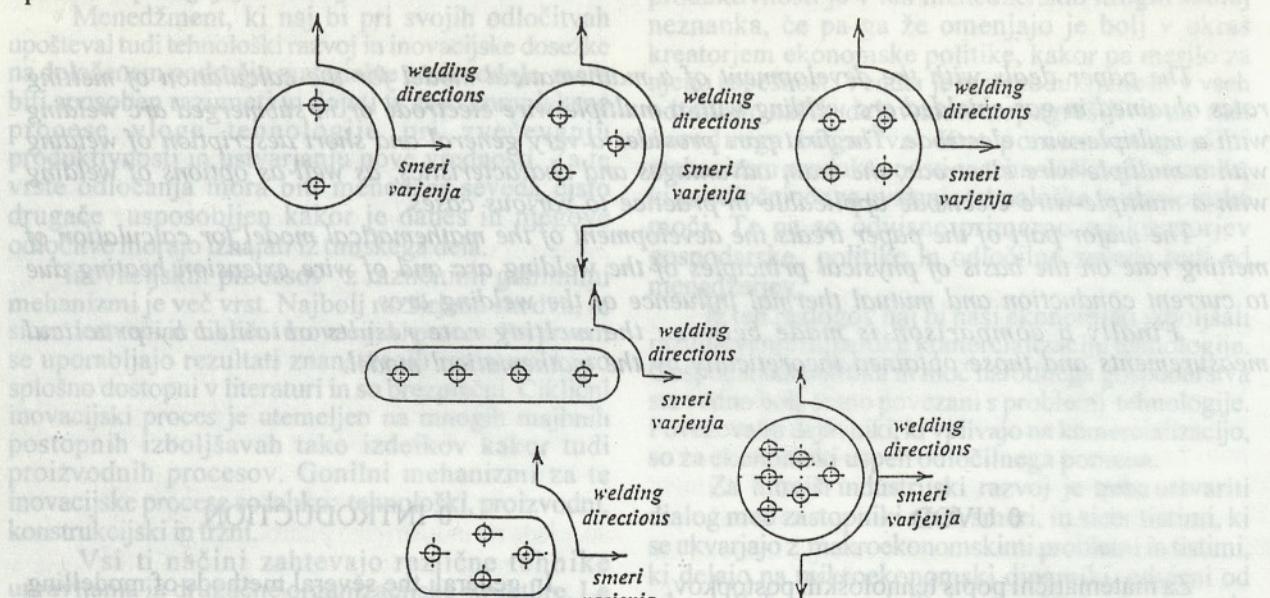
O varjenju z večžično elektrodo govorimo, če skozi kontaktno šobo potuje več ko ena žica hkrati. Vse žice so napajane iz enega vira toka, imajo enako hitrost in isto regulacijo (sl. 2). Žice so v kontaktni šobi lahko razporejene zelo različno, kar je najpogosteje odvisno od namena uporabe in od oblike zvarnega spoja. Nekaj uporabljenih primerov je prikazanih na sliki 1.

The second method is based on the mathematical and physical principles of the process. In this case, one should know very well the process itself, as well as the physical and chemical principles applicable.

In our case, i.e. fusion arc welding, the second method will be applied. On the basis of physical laws we will try to mathematically describe the process, and on the basis of input data, i.e. the welding parameters and physical properties of materials in our case, to predict the quantity of filler material molten in welding with a multiple-wire electrode.

### 1 SHORT DESCRIPTION OF WELDING WITH A MULTIPLE-WIRE ELECTRODE

We have a case of welding with a multiple-wire electrode when two or more wires are travelling simultaneously through the contact nozzle. All the wires concerned are supplied from the same power source, have the same wire feed speed and the same control (Fig. 2). Wires in the contact nozzle can be arranged in a different manner, which is most often dependent on the purpose and on the shape of welded joint. Some cases of application are shown in Fig. 1.



Sl. 1. Kontaktna šoba, v kateri so žice razporejene na poljuben način

Fig. 1. Contact nozzle in which wires are arranged optionally

Z napravo za večžično varjenje se večinoma vari pod praškom ali pod žlindro, mogoče pa je variti tudi pod zaščitnimi plini. V tem primeru morajo biti zelo skrbno izbrani varilni parametri, pogon žic mora biti konstanten, brez nihanj, žice morajo dotečati na varilno mesto vedno v isto točko. To pomeni, da morajo biti dosežene zelo stabilne razmere, ker se v nasprotnem primeru pojavi močno brizganje, pride do neenakomernega gibanja taline in dobimo neravno teme zvara ter obrobne zajede [1] do [3].

The device for a multiple-wire welding is mostly applied in submerged arc welding or electro-slag welding, and possibly also in gas-shielded arc welding. In the latter case, welding parameters should be selected very carefully, wire feed should be constant, without oscillation, the wires should be fed always to the "same" welding spot. This means that very stable conditions should be maintained. In the opposite case, strong spatter, irregular motion of the molten pool as well as irregular final layer and undercuts may occur [1] to [3].

Tehnološko-ekonomske značilnosti varjenja z večično elektrodo pod praškom so bile že dokaj dobro raziskane, rezultati pa objavljeni v številnih člankih, revijah in zbornikih ter v dokumentih Mednarodnega inštituta za varjenje [4] do [10].

## 2 OPIS RAZISKOVALNEGA DELA

Že v uvodu smo zapisali, da bo matematični model za izračun talilnega učinka nastal na podlagi fizikalnih procesov, ki se odvijajo med varjenjem z večično elektrodo. Ker je talilni učinek količina pretaljenega dodajnega materiala v časovni enoti, je torej treba popisati tiste energije z upoštevanjem izkoristkov, ki se porabijo za taljenje varilnih žic. Za taljenje se pri obločnem varjenju porabi topotna energija, ki nastane iz dveh različnih virov. V prostem koncu žice se prevaja električni tok, ki jo po znanem Ohmovem zakonu ogreva. Količina ustvarjene toplote je odvisna od jakosti varilnega toka, od premera žice, od njene dolžine in od vrste materiala. Drugi del energije, ki se porabi za taljenje dodajnega materiala, se razvije v električnem obloku. Varilni oblok je prav tako električni vodnik z veliko električno upornostjo in z visoko temperaturo. Z raziskavami in s teoretičnimi izračuni je dokazano, da se za taljenje porabi topota, ki se razvije v prielektrodnem področju varilnega obloka [11] do [13]. Ko raztaljena kapljica po odtrganju potuje skozi varilni oblok, je že v tekočem stanju in se s tem samo pregreva ter poslabšuje izkoristek varilnega procesa.

V splošnem bi lahko energijsko enačbo za talilni učinek napisali v termodinamični obliki:

$$(Q_o + Q_z) \cdot \eta = M \cdot c_p \cdot \Delta T + H \quad (1)$$

Ta enačba (1) pove, da topoti, ki se razvijata v obloku  $Q_o$  v W in v prostem koncu žice  $Q_z$  v W, raztalita dodajni material  $M$  v kg/h s specifično topoto  $c_p$  v kJ/kgK. Izgube toplote v okolico, prašek ali zaščitni plin in druge izgube, so zajete v izkoristku ( $\eta$ ), z latentno topoto pa so popisane izgube v materialu pri segrevanju zaradi različnih transformacij idr.

Če želimo rešiti enačbo (1), moramo poznati topotno energijo, ki se razvije v prostem koncu žice, topotno energijo v prielektrodnem področju obloka, termični izkoristek teh dveh energij in, kar je še najtežje, poznati funkcionske odvisnosti  $c_p(T)$ ,  $H(T)$  in  $\rho(T)$  za uporabljeni dodajni material.

Za izračun topotne energije v prostem koncu žice je seveda najpomembnejša tista, ki se razvije zaradi ohmske upornosti. V splošnem lahko to topotno energijo popišemo z:

$$Q_z = \frac{I^2 \cdot L}{s} \rho_r(T) \quad (2)$$

The technological and economic characteristics of submerged-arc welding with a multiple-wire electrode have been investigated in great detail, and the results published in numerous papers, journals and documents of the International Institute of Welding [4] to [10].

## 2 DESCRIPTION OF RESEARCH WORK

It was stated in the introduction that the mathematical model for calculation of the melting rate would be based on the physical processes going on during welding with a multiple-wire electrode. Since the melting rate is expressed by the quantity of filler material molten per unit of time, it is necessary to define the energies consumed in welding-wire fusion while taking efficiencies into account. The thermal energy consumed in arc welding fusion is generated in two different ways. Electric current flows through the wire extension and heats it in accordance with Ohm's law. The quantity of heat generated is a function of welding current intensity, wire diameter, wire extension length and the kind of material. The second part of the energy consumed in filler material fusion is generated in the welding arc. The welding arc is also an electric conductor with high electrical resistance and high temperature. Investigations and theoretical calculations show that, in order for fusion to occur, the heat generated in the electrode region of the welding arc needs to be consumed [11] to [13]. Having detached from the wire, a droplet is already in a liquid state. Its travelling through the welding arc only overheats it and reduces the efficiency of the welding process.

In general, the energy equation for the melting speed could be written in a thermodynamic form:

Equation (1) tells that the heat generated in the arc  $Q_o$  in W and in the wire extension  $Q_z$  in W melts the filler material  $M$  in kg/h with specific heat  $c_p$  kJ/kgK. The heat losses in the environment, the powder or the shielding gas and other losses are contained in the efficiency ( $\eta$ ), while material losses in heating due to various transformations are contained in the latent heat.

If Equation (1) is to be solved, one should know the heat energy generated in the wire extension, the heat energy in the electrode region of the arc, the thermal efficiency of these two forms of energy and - which is the hardest - the functional relations of  $c_p(T)$ ,  $H(T)$ , and  $\rho(T)$  for the filler material used.

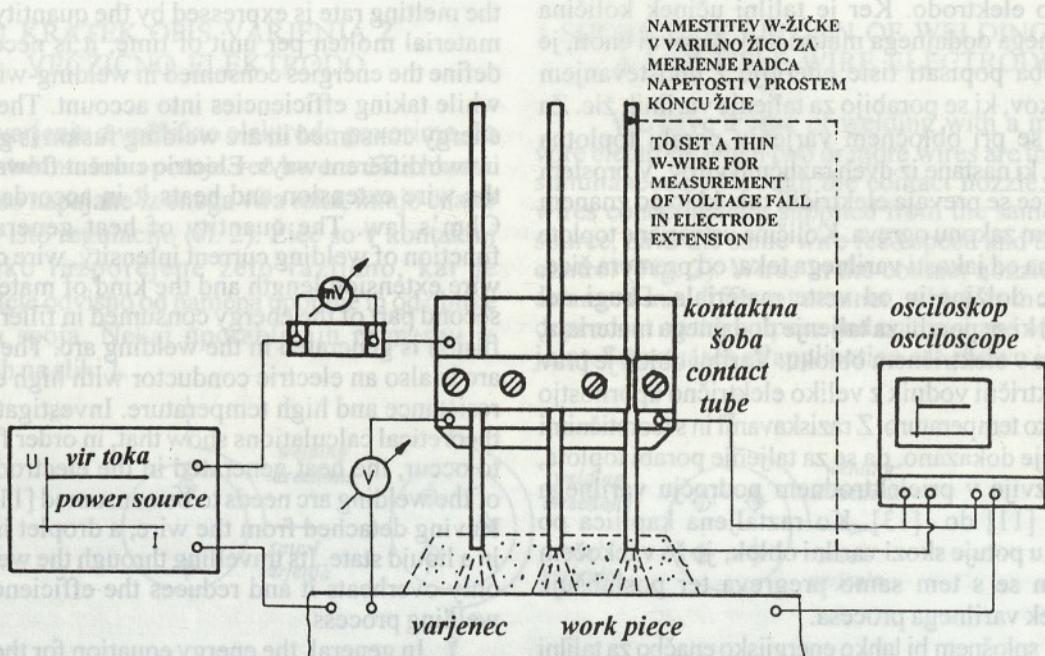
For the calculation of the heat energy in the wire extension, the most important heat is that which is generated due to Ohmic resistance. In general, this heat can be defined by:

kjer pomenijo:  $I$  - jakost toka v A,  $L$  - dolžino prostega konca žice v m,  $S$  - prerez žice v  $\text{m}^2$ ,  $\rho_r$  - specifično upornost v  $\Omega$ .

Ker je specifična upornost odvisna od temperature, ta pa od dolžine prostega konca žice, smo z eksperimentalnim delom izmerili padec napetosti v prostem koncu žice od kontaktne šobe do varilnega bloka. Glede na to, da v dostopni literaturi takšnih meritev nismo zasledili, smo izdelali prilagojeno kontaktno šobo za varjenje s trojno žično elektrodo in sistem merjenja padca napetosti (sl. 2) [7].

where:  $I$  - current intensity in A,  $L$  - wire extension length in m,  $S$  - wire cross section in  $\text{m}^2$ ,  $\rho_r$  - specific resistance in  $\Omega$ .

Specific resistance being dependent on temperature, and temperature being dependent on wire extension length, the voltage drop in the wire extension, i.e. between the contact nozzle and the arc, was measured experimentally. In the literature available, no such measurements could be found, therefore, a contact nozzle was adapted to welding with a triple-wire electrode, and a system for voltage drop measurement shown in Fig. 2 [7].

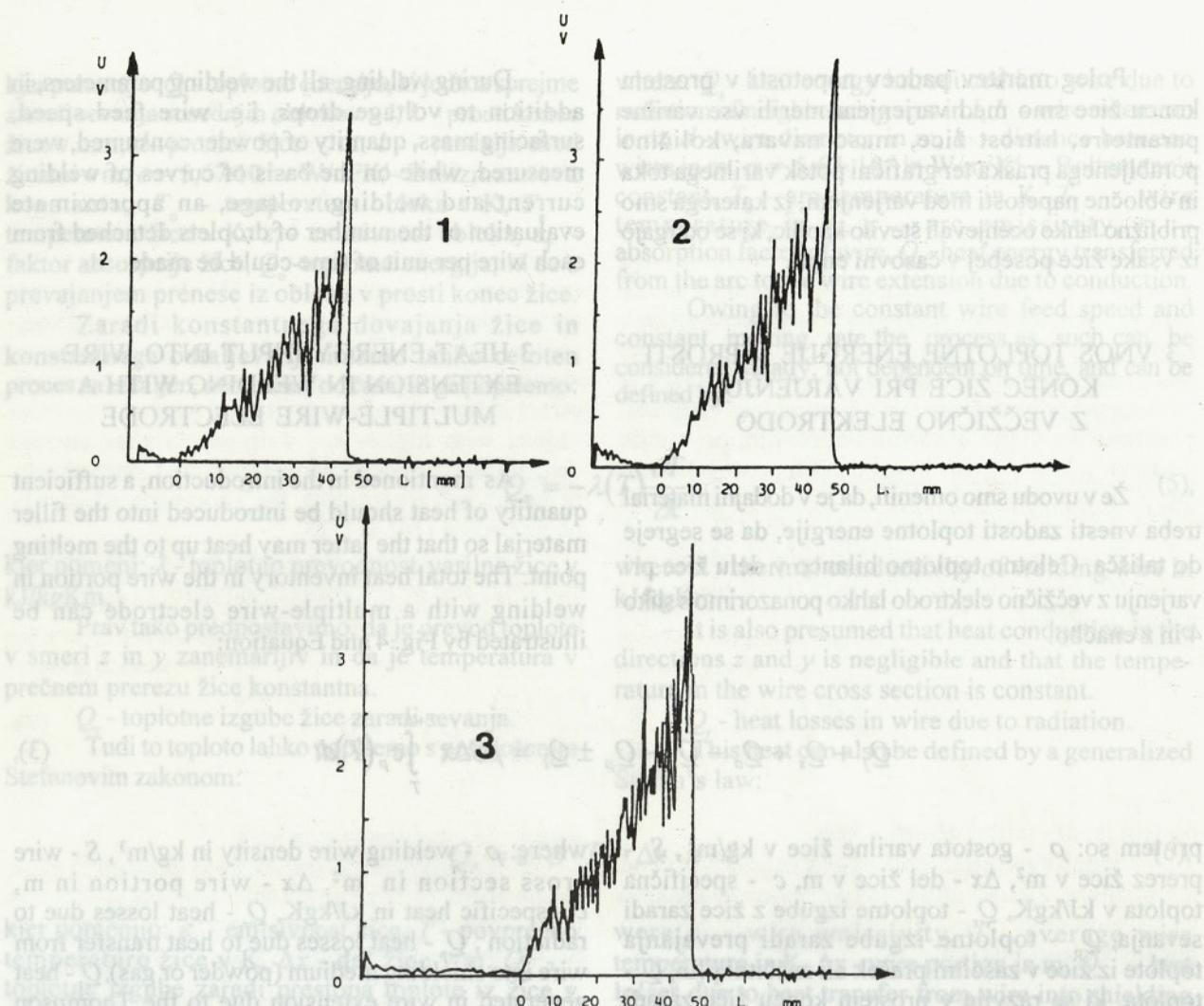


Sl. 2. Shematski prikaz naprave za merjenje padca napetosti v prostem koncu žice pri varjenju z večkratno elektrodo.

Fig. 2. Schematic representation of an apparatus for voltage drop measurement in wire extension in welding with a multiple-wire electrode

Na sliki 2 je shematsko prikazana kontaktna šoba, skozi katero potujejo tri žice hkrati z enako hitrostjo. Vse žice so napajane iz enega vira. Za meritev padca napetosti v prostem koncu žice smo kontaktno šobo prerezali, kakor prikazuje slika 2, da je skozi režo lahko potovala volframova žička, ki smo jo pred varjenjem trdno pritrudili na žico, na mesto, označeno na sliki. Volframova žička je med varjenjem potovala skupaj z varilno žico do kontaktne šobe in naprej do bloka. Ko je žička dosegla kontaktno šobo, se je meritev padca napetosti pričela in je trajala, vse dolej, da je volframova žička dosegla oblok. V obloku se žička ni raztalila, ampak je le odpadla in meritev je bila s tem končana. Potek padcev napetosti v prostem koncu žice, od kontaktne šobe do obloka, so za varjenje z enojno, dvojno in s trojno žično elektrodo prikazani na sliki 3.

Fig. 2 shows a scheme of the contact nozzle through which three wires travel simultaneously at the same speed. The three wires are supplied from one power source. In order to be able to measure the voltage drop in the wire extension, the contact nozzle was cut as shown in Fig. 2 so that a tungsten wire, which was fixed to the wire before welding at the spot also shown in Fig. 2, could travel through the gap. During welding the tungsten wire travelled together with the welding wire to the contact nozzle and then to the arc. When the tungsten wire reached the contact nozzle, voltage drop measurement was started and continued till the tungsten wire reached the arc. In the arc, the tungsten wire did not melt but fell off; the measurement was thus ended. Curves of voltage drops in the wire extension, i.e. between the contact nozzle and the arc, in welding with single-wire, double-wire and triple-wire electrodes are shown in Fig. 3.



Sl. 3. Poteki padcev napetosti v prostem koncu žice pri varjenju z enojno (1), dvojno (2) in s trojno žično elektrodo (3):  $U = 30 \text{ V}$ ,  $L = 50 \text{ mm}$ ,  $b = 9 \text{ mm}$ ,  $I = 400 \text{ A/žico}$ ,  $d = 3 \text{ mm}$ , (+) pol na elektrodi

Fig. 3. Curves of voltage drops in wire extension in welding with a single-wire electrode, (1), double-wire electrode (2), and triple-wire electrode (3):  $U = 30 \text{ V}$ ,  $L = 50 \text{ mm}$ ,  $b = 9 \text{ mm}$ ,  $I = 400 \text{ A/wire}$ ,  $d = 3 \text{ mm}$ , (+) electrode positive

Iz zapisa potekov padcev napetosti lahko ugotovimo, kakšna je ta napetost v odvisnosti od kontaktne šobe in neko frekvenco nihanja napetosti, ki se spreminja in je enaka številu odtrganih kapljic. Prav tako lahko opazimo razliko v padcih napetosti pri enojni, dvojni in trojni žični elektrodi. Padec napetosti se veča z večanjem števila žic in tudi frekvenca nihanja napetosti je višja pri trojni kakor pri dvojni ali enojni.

Iz povedanega lahko sklepamo, da se upornost v žicah veča z večanjem števila žic pri enakih preostalih varilnih parametrih na eno žico. Razlog za povečanje upornosti sta dva. Prvi je toplotni vpliv. Medsebojni vpliv varilnih oblokov dodatno ogreva žice, kar vpliva na zvišanje temperature in s tem električne upornosti. Drugi je medsebojni elektromagnetski vpliv, ki prav tako poveča električno upornost v prostem koncu žice.

The curves of the voltage drops show what the voltage is a function of the contact nozzle and also indicate the voltage oscillation frequency which is changing and dependent on the number of the droplets detached. A difference in the voltage drops can be observed in the case of the single-wire, the double-wire and the triple-wire electrodes. The greater the number of wires, the greater is the voltage drop. Voltage oscillation frequency is also higher in the case of triple-wire electrode than in the case of single-wire or double-wire electrode.

Consequently it can be concluded that resistance in the wires increases with the increase in the number of wires when other welding parameters per wire are maintained constant. There are two reasons for the increase in resistance. The first is thermal influence. The mutual influence of the welding arcs additionally heats the wires, which results in temperature increase, and consequently in an increase of electric resistance. The second is mutual electromagnetic influence, which also increases electric resistance in the wire extension.

Poleg meritev padcev napetosti v prostem koncu žice smo med varjenjem merili vse varilne parametre, hitrost žice, maso navara, količino porabljenega praška ter grafični potek varilnega toka in obločne napetosti med varjenjem, iz katerega smo približno lahko ocenjevali število kapljic, ki se odtrgajo iz vsake žice posebej v časovni enoti.

### 3 VNOS TOPLITNE ENERGIJE V PROSTI KONEC ŽICE PRI VARJENJU Z VEČŽIČNO ELEKTRODO

Že v uvodu smo omenili, da je v dodajni material treba vnesti zadost toplotne energije, da se segreje do tališča. Celotno toplotno bilanco v delu žice pri varjenju z večžično elektrodo lahko ponazorimo s sliko 4 in z enačbo:

During welding, all the welding parameters, in addition to voltage drops, i.e. wire feed speed, surfacing mass, quantity of powder consumed, were measured, while on the basis of curves of welding current and welding voltage, an approximate evaluation of the number of droplets detached from each wire per unit of time could be made.

### 3 HEAT ENERGY INPUT INTO WIRE EXTENSION IN WELDING WITH A MULTIPLE-WIRE ELECTRODE

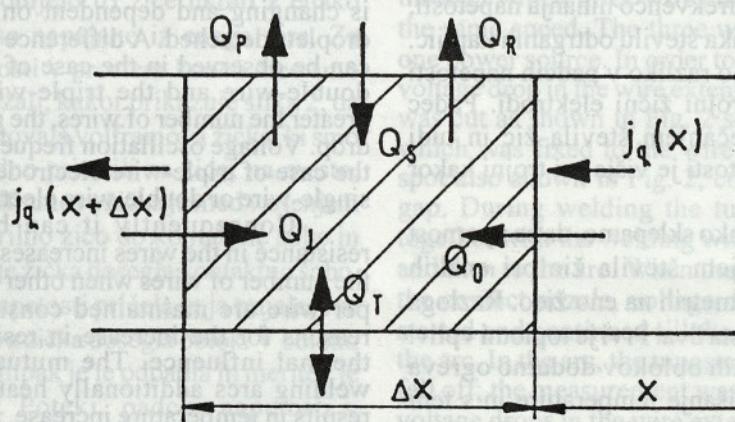
As mentioned in the introduction, a sufficient quantity of heat should be introduced into the filler material so that the latter may heat up to the melting point. The total heat inventory in the wire portion in welding with a multiple-wire electrode can be illustrated by Fig. 4 and Equation:

$$Q_j + Q_s + Q_o - Q_r - Q_p \pm Q_t = \rho S \Delta x \int_T^{T+\Delta T} c_p(T) dt \quad (3)$$

pri tem so:  $\rho$  - gostota varilne žice v  $\text{kg/m}^3$ ,  $S$  - prerez žice v  $\text{m}^2$ ,  $\Delta x$  - del žice v m,  $c$  - specifična toplota v  $\text{kJ/kgK}$ ,  $Q_r$  - toplotne izgube z žice zaradi sevanja,  $Q_p$  - toplotne izgube zaradi prevajanja toplote iz žice v zaščitni prašek ali zaščitni plin,  $Q_t$  - toplota, ki se razvije v prostem koncu žice zaradi Thompsonovega pojava,  $Q_j$  - toplotna energija, ki se razvije v prostem koncu žice zaradi ohmske upornosti, in

$$Q_s = \frac{L \cdot d}{6} \cdot \sigma \cdot (T_o^4 - T_z^4) \left[ \frac{1}{\frac{1}{\varepsilon_1} + \left( \frac{1}{\varepsilon_2} - 1 \right)} \right] \cdot \left[ \sqrt{1 + \left( \frac{b}{d} \right)^2} - \frac{b}{d} \right] \quad (4)$$

where:  $\rho$  - welding wire density in  $\text{kg/m}^3$ ,  $S$  - wire cross section in  $\text{m}^2$ ,  $\Delta x$  - wire portion in m,  $c$  - specific heat in  $\text{kJ/kgK}$ ,  $Q_r$  - heat losses due to radiation,  $Q_p$  - heat losses due to heat transfer from wire into shielding medium (powder or gas),  $Q_t$  - heat generated in wire extension due to the Thompson effect,  $Q_j$  - heat energy generated in wire extension due to Ohmic resistance, and



Sl. 4. Shematski prikaz dela prostega konca žice s toplotno bilanco

Fig. 4. Schematic representation of wire extension with heat inventory

kjer pomenijo:  $Q_s$  - toplotno energijo, ki jo žica sprejme zaradi sevanja sosednjih oblokov v J,  $L$  - prosti konec žice v mm,  $d$  - premer žice v m,  $b$  - razdalja med žicami v m,  $\sigma = 5,67 \cdot 10^{-8}$  W/m<sup>2</sup>K<sup>4</sup> - Boltzmannova konstanta,  $T_o$  - temperatura obloka v K,  $T_z$  - temperatura žice v K,  $\varepsilon_1$  - emisivnost obloka,  $\varepsilon_2$  - faktor absorpcije žice,  $Q_o$  - toplotna energija, ki se s prevajanjem prenese iz obloka v prosti konec žice.

Zaradi konstantnega dovanjanja žice in konstantnega odtaljevanja imamo lahko celoten proces za ustaljen, neodvisen od časa, in ga popišemo:

$$Q_o = -\lambda(T) \frac{\partial T}{\partial L} \quad (5)$$

kjer pomeni:  $\lambda$  - toplotno prevodnost varilne žice v kJ/kgKm.

Prav tako predpostavimo, da je prevod toplotne v smeri  $z$  in  $y$  zanemarljiv in da je temperatura v prečnem prerezu žice konstantna.

$Q_r$  - toplotne izgube žice zaradi sevanja.

Tudi to toplotno lahko popišemo s posplošenim Stefanovim zakonom:

$$Q_r = \varepsilon \cdot \sigma \cdot T^4 \cdot \Delta x \cdot \pi \cdot d \quad (6)$$

kjer pomenijo:  $\varepsilon$  - emisivnost žice,  $T$  - povprečno temperaturo žice v K,  $\Delta x$  - del žice v m,  $Q_p$  - toplotne izgube zaradi prestopa toplotne iz žice v zaščitni medij, ki jih popišemo:

$$Q_p = \alpha_T \cdot \Delta x \cdot 1,5d \cdot (T_z - T_p) \quad (7)$$

pri tem pomenijo:  $\alpha_T$  - toplotno prestopnost v J/m<sup>2</sup>K,  $T_p$  - temperaturo zaščitnega medija v K.

Z eksperimentalnimi meritvami smo ugotovili, da polarnost vpliva na segrevanje prostega konca žice. To ugotovitev, ki v dostopni varilski literaturi sploh ni opisana, lahko pojasnimo s Thomsonovim pojavom in matematično popišemo z:

$$Q_t = \mu(T) \cdot I \cdot \Delta x \cdot \frac{\partial T}{\partial L} \quad (8)$$

kjer sta:  $\mu$  - Thomsonov koeficient v V/K,  $I$  - jakost električnega toka v A.

Thomsonov koeficient  $\mu$  je lahko pozitiven ali negativen. Če električni tok teče v smeri temperaturnega gradiента, je koeficient pozitiven, v nasprotnem primeru pa negativen.

Poleg omenjenih virov toplotne energije, ki segrevajo prosti konec žice, in toplotnih izgub iz žice, so opazni še nekateri drugi, ki na hitrost odtaljevanja dodajnega materiala nimajo posebnega vpliva.

where:  $Q_s$  - heat energy introduced into wire due to radiation of neighbouring arcs in J,  $L$  - wire extension in m,  $d$  - wire diameter in m,  $b$  - distance between wires in m,  $\sigma = 5.67 \cdot 10^{-8}$  W/m<sup>2</sup>K<sup>4</sup> - Boltzmann's constant,  $T_o$  - arc temperature in K,  $T_z$  - wire temperature in K,  $\varepsilon_1$  - arc emissivity,  $\varepsilon_2$  - absorption factor of wire,  $Q_o$  - heat energy transferred from the arc to the wire extension due to conduction.

Owing to the constant wire feed speed and constant melting rate the process as such can be considered steady, not dependent on time, and can be defined by:

where:  $\lambda$  - thermal conductivity of welding wire in kJ/kgKm.

It is also presumed that heat conduction in the directions  $z$  and  $y$  is negligible and that the temperature in the wire cross section is constant.

$Q_r$  - heat losses in wire due to radiation.

This heat can also be defined by a generalized Stefan's law:

were:  $\varepsilon$  - wire emissivity,  $T$  - average wire temperature in K,  $\Delta x$  - wire portion in m,  $Q_p$  - heat losses due to heat transfer from wire into shielding medium defined by:

where:  $\alpha_T$  - heat transfer coefficient in J/m<sup>2</sup>K,  $T_p$  - temperature of shielding medium in K.

By means of experimental measurements it was established that polarity affects wire extension heating. This statement, which is not described in the welding literature available, can be explained by the Thomson effect and mathematically defined by:

where:  $m$  - Thomson's coefficient in V/K,  $I$  - electric current intensity in A.

The Thomson coefficient  $\mu$  can be positive or negative. If electric current is flowing in the direction of the temperature gradient, the coefficient is positive, while in the opposite case it is negative.

In addition to the heat energy sources mentioned, which warm up the wire extension, and heat losses in the wire, there are some more sources and losses which, however, do not particularly affect the melting rate of the filler material.

Na podlagi eksperimentalnih rezultatov, fizikalnih in kemičnih lastnosti materialov ter podatkov iz literature za varjenje z enojno žično elektrodo v različnih zaščitnih medijih, lahko enačbo (3) nekoliko poenostavimo.

Po podatkih iz literature [19] za varjenje po postopku MIG znašajo topotne izgube zaradi sevanja 4 odstotke in zaradi pretoka plinov 5 odstotkov. Za varjenje pod praškom je znano, da so gostote tokov v žicah manjše kakor pri varjenju MIG in zato so omenjene izgube še manjše. Thomsonov pojav je odvisen od polarnosti in neke pomembne vrednosti dosežene pri višjih obločnih napetostih, pri večjih gostotah tokov v žicah in pri daljših prostih koncih žic. Glede na to lahko pri varjenju pod praškom Thomsonov pojav zanemarimo [14] do [18].

Z zanemaritvijo omenjenih virov in ponorov in z upoštevanjem enačb (2), (4) in (5) dobri enačba (3) naslednjo obliko:

$$\lambda \frac{\partial^2 T}{\partial x^2} + \frac{\partial T}{\partial x} \cdot c_p \cdot \frac{M}{S} + \frac{I^2 \rho_r(T)}{S^2} + Q_s(T) = 0 \quad (9)$$

pri tem je:  $M$  - talilni učinek v kg/s.

Specifična električna upornost je odvisna od temperature. Za uporabljeni dodajne materiale smo to odvisnost eksperimentalno dobili sami in jo, nekoliko poenostavljeno, pišemo:

$$\rho_r = K_1 \cdot T_z \quad (10)$$

Tudi topotni vpliv sosednjega varilnega bloka lahko s poenostavljivo zapišemo kot linearno odvisnost:

$$Q_s = K_2 \cdot T_z \quad (11)$$

S preureditvijo enačbe (9) in z upoštevanjem enačb (10) in (11) dobimo:

$$\frac{\partial^2 T}{\partial x^2} + C_1 \frac{\partial T}{\partial x} + C_2 T = 0 \quad (12)$$

Konstanti  $C_1$  in  $C_2$  sta:

$$C_1 = \frac{c_p \cdot M}{S \cdot \lambda} \quad (13)$$

Constants  $C_1$  and  $C_2$  are expressed by:

$$C_2 = \frac{I^2 K_1}{S^2 \lambda} + \frac{K_2}{\lambda} \quad (14)$$

On the basis of experimental results, the physical and chemical properties of materials and literature data concerning welding with a single-wire electrode in various shielding media, Equation (3) can be somewhat simplified.

According to reference data [19] on MIG welding, heat losses due to radiation amount to 4% and those due to gas flow to 5%. It is known that current densities in wires in submerged arc welding are lower than in MIG welding, therefore, the above-mentioned losses are even smaller. The Thomson effect is dependent on polarity and reaches important values with higher arc voltages, higher current densities and increased wire extensions. Consequently, in submerged arc welding, the Thompson effect may be neglected [14] to [18].

By neglecting the above-mentioned sources and sinks and by considering Equations (2), (4), and (5), Equation (3) takes the following form:

where:  $M$  - melting rate in kg/s.

Specific electric resistance is dependent upon temperature. As regards the filler materials used, this dependence was established experimentally and can be, in a somewhat simplified form, defined by:

The heat influence of the neighbouring arc can be, somewhat simplified, defined as a linear function by:

By rearranging Equation (9) and by considering Equations (10) and (11), one can obtain:

Enačba (12) je homogena parcialna diferencialna enačba drugega reda, ki je pri znanih robnih pogojih preprosto rešljiva.

Z rešitvijo te enačbe dobimo porazdelitev temperature v prostem koncu žice med varjenjem z večjično elektordjo.

#### 4 CELOTEN VNOS TOPLITNE ENERGIJE V DODAJNI MATERIAL IN IZDELAVA MATEMATIČNEGA MODELA ZA IZRAČUN TALILNEGA UČINKA

Za raztalitev dodajnega materiala se porabita topotna energija, ki se ustvari v prostem koncu žice, in del obločne energije.

Če v enačbi (9) opustimo tisti člen, ki popisuje prevod toplote iz oblaka v prosti konec žice, ta količina toplote je zaradi stalnega odtaljevanja kapljic zelo majhna, dobimo:

$$\frac{c_p}{\rho} \int_0^L dT = \frac{I^2 \cdot L}{M \cdot S} = f(Q_z) \quad (15).$$

V enačbi (15) so zajete fizikalne lastnosti dodajnih varilnih žic, varilni parametri in talilni učinek. Z eksperimentalnimi preizkusi smo na uporabljenih varilnih žicah raziskali dejansko vneseno toploto  $Q_z$  v žico, v odvisnosti od parametrov  $I$  in  $A$ ,  $L$  v m,  $S$  v  $m^2$ ,  $\rho$  v  $kg/m^3$  in  $v_z$  v  $m/s$ .

Toplotno energijo v prostem koncu žice, ki je popisana z enačbo (9), v kateri opustimo tisti člen, ki popisuje prevod toplote iz oblaka v prosti konec žice, lahko popišemo tudi z enačbo:

$$dQ_z = \frac{R \cdot I^2}{S \cdot L} dt \quad (16).$$

Z integriranjem in preuredityjo dobimo:

$$Q_z = \frac{j}{L \cdot \rho} \int_0^t U_L(t) dt \quad (17).$$

S številnimi poskusi smo na osmih različnih tipskih varilnih žicah raziskali funkcionalno povezavo med toploto, ki se vnesе v žico,  $Q_z$  v  $kJ/kg$  in  $f(Q_z)$  v  $kJ/kg\Omega m$ . Za žici s premerom 3 mm, ki se uporablja za varjenje pod praškom, in za stržensko žico s premerom 3,2 mm, ki je prav tako namenjena za varjenje pod praškom, so dobljeni rezultati prikazani v diagramu na sliki 5.

Equation (12) is a second order homogeneous partial differential equation which is easy to solve if the boundary conditions are known.

By solving this equation, one can establish temperature distribution in the wire extension during welding with a multiple-wire electrode.

#### 4 TOTAL HEAT ENERGY INPUT INTO FILLER MATERIAL AND ELABORATION OF A MATHEMATICAL MODEL FOR CALCULATION OF MELTING RATE

For fusion of the filler material, the heat energy generated in the wire extension and a portion of the arc energy are consumed.

If in Equation (9) the member which describes heat transfer from the arc to the wire extension (the quantity of heat being very low due to constant droplet melting) is deleted:

Equation (15) includes the physical properties of welding wires, welding parameters and melting rate. The actual heat input  $Q_z$  into welding wires applied as a function of parameters  $I$  in A,  $L$  in m,  $S$  in  $m^2$ ,  $\rho$  in  $kg/m^3$  and  $v_z$  in  $m/s$  was investigated by experiments.

The heat energy in the wire extension, which is defined by Equation (9), but in which the member describing heat transfer from the arc to the wire extension can be deleted, can also be defined by:

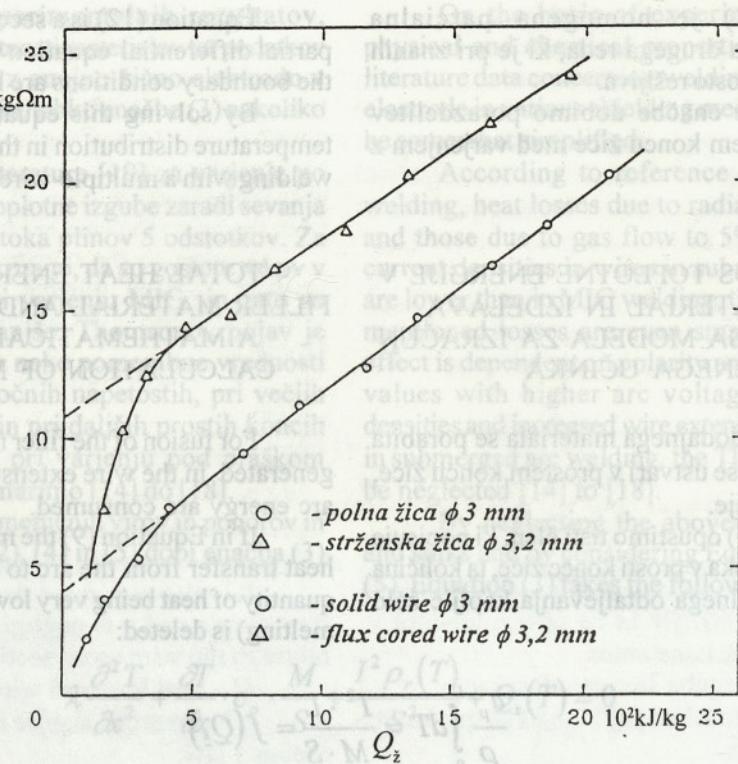
By integration and rearrangement:

The functional relation between the heat introduced into the wire  $Q_z$  in  $kJ/kg$  and  $f(Q_z)$  in  $kJ/kg\Omega m$  was investigated by means of numerous experiments performed on eight different types of welding wires. The diagram in Fig. 5 shows the results obtained with two 3 mm wires used in submerged-arc welding and with a 3.2 mm cored wire also used in submerged-arc welding.

Po podatkih v literaturi je znano, da topotno izgubo zaradi sevanja je odstotke in zaradi pretoka v plinu (vzdušna stran) do 5 odstotkov. Po podatkih MIG postopku MIG znašajo topotno izgubo zaradi sevanja 4 odstotke in zaradi pretoka v plinu 5 odstotkov. Zato je vpliv na topotno izgubo zaradi sevanja na celotno topotno izgubo zelo pomemben.

Za nepravilno uporabo varilne žice je vpliv na topotno izgubo zaradi sevanja zelo pomemben. Če je varilna žica premerna ali pa je naročna, je vpliv na topotno izgubo zaradi sevanja zelo pomemben.

Za pravilno uporabo varilne žice je vpliv na topotno izgubo zaradi sevanja zelo pomemben. Če je varilna žica premerna ali pa je naročna, je vpliv na topotno izgubo zaradi sevanja zelo pomemben.



Sl. 5. Povezava med vneseno topoto v varilno žico in parametri, ki to topotno energijo povzročijo, za stržensko žico s premerom 3,2 mm in masivno žico s premerom 3mm pri varjenju pod praškom.

Fig. 5. Relationship between heat input into welding wire and parameters which generate this heat for 3.2 mm cored wire and 3 mm solid wire in submerged arc welding.

Funkcijska povezava med  $Q_z$  in  $f(Q_z)$  je od določene vrednosti, ki je za prakso tudi uporabna in pomembna, linearna in jo lahko popišemo:

$$Q_z = \alpha \cdot f(Q_z) - \beta \quad (18).$$

Vrednosti za konstanti  $\alpha$  in  $\beta$  v  $\Omega m$  in  $\text{kJ/kg}$  je za uporabljene materiale mogoče dobiti iz diagramov, kakor je za dve varilni žici prikazano na sliki 5 [1], in za nekatere druge varilne žice, podane v preglednici 1.

Konstanta  $\alpha$  je v največji meri odvisna od vrste materiala in pomeni specifično električno upornost dodajnega materiala pri višjih temperaturah oziroma na koncu prostega konca žice. Prav tako je konstanta  $\alpha$  odvisna tudi od polarnosti in premera žice. Nadalje lahko ugotovimo, da je vrednost konstante  $\alpha$  mnogo večja pri strženskih kakor pri masivnih žicah. Strženska žica ima namreč nizko specifično topoto in je s tem kovinski plašč strženske žice segret na višjo temperaturo in ima zato višjo električno upornost.

Druga konstanta v enačbi (18) je  $\beta$  v  $\text{kJ/kg}$ , ki pomeni topotno energijo v žici pri sobni temperaturi. Glede na teoretični razmislek naj bi bila konstanta  $\beta$  odvisna samo od vrste materiala. Preizkusi so pokazali, da je odvisna tudi od premera in tipa varilne žice.

The functional relation between  $Q_z$  and  $f(Q_z)$  is linear up to a certain value which is still applicable in practice and important. It can be defined by:

Values of constants  $\alpha$  in  $\Omega m$  and  $\beta$  in  $\text{kJ/kg}$  for the materials applied can be obtained for two welding wires from the diagrams in Fig. 5 [1] and for some other welding wires from Table 1.

Constant  $\alpha$  is mainly dependent on the kind of material, and represents specific electric resistance of the filler material at higher temperatures, i.e. at the wire extension tip. Constant  $\alpha$  is also a function of polarity and of wire diameter. It can be further established that the value of constant  $\alpha$  is much higher with cored wires than with solid ones. Since a cored wire has low specific heat, the sleeve of the cored wire is consequently heated to a higher temperature and has a higher specific resistance.

The second constant in Eq. (18) is  $\beta$  in  $\text{kJ/kg}$ , which is the heat energy in the wire at room temperature. Following theoretical considerations, constant  $\beta$  should be dependent only on the kind of material used. Experiments, however, have shown that this constant is also dependent on wire diameter and welding wire type.

Drugi del energije, s katero talimo dodajni material, dobimo iz varilnega obloka. Količinsko vrednost obločne energije je mogoče določiti tudi eksperimentalno. V primeru, da se za taljenje dodajnega materiala porabi samo obločna energija, kar pomeni, da varimo brez prostega konca žice, lahko vneseno energijo v enoto dodajnega materiala določimo z:

$$Q_v = \frac{U_E \cdot I}{M} \quad (19).$$

Če v enačbo (18) vnesemo:

$$f(Q_z) = \frac{L \cdot j^2 \cdot S}{M} \quad (20)$$

in k dobljeni enačbi prištejemo enačbo (19), upoštevamo število žic in zapis preuredimo, dobimo matematični model za izračun talilnega učinka pri varjenju z večžično elektrodo:

$$M = \frac{I \cdot n \cdot (U_E + \alpha \cdot L \cdot j \cdot n^{-0.2})}{Q_k + \beta} \quad (21).$$

V tej enačbi (21)  $n$  pomeni število žic,  $Q_k$  v  $\text{kJ/kg}$  energijo na enoto mase dodajnega materiala, ki jo kapljica vsebuje takoj po odtrganju od žice, in  $U_E$  v V padec napetosti v anodnem ali katodnem področju varilnega obloka.

Podobno kakor konstanti  $\alpha$  in  $\beta$ , sta tudi vrednosti  $Q_k$  in  $U_E$  pridobljeni eksperimentalno. Te vrednosti so za varjenje z enojno žico za nekatere uporabljene dodajne materiale navedene v preglednici 1, za varjenje z dvojno in s trojno žično elektrodo, za žico s premerom 3 mm, pa v preglednici 2.

Preglednica 1: *Eksperimentalno dobljene vrednosti za faktorje za nekatere uporabljene dodajne materiale za varjenje z enojno žično elektrodo pod praškom*

Table 1: *Experimentally obtained values of factors for some of the filler materials used in submerged arc welding with a single-wire electrode*

Premer žice Wire diameter mm	$\alpha$ $\Omega\text{m}$		$\beta$ $\text{kJ/kg}$		$U_E$ V		$Q_k$ $\text{kJ/kg}$	
	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)
A $\phi 3$	1,19	1,08	505	505	4,96	8,2	1705	1870
B $\phi 2$	1,22	1,22	586	586	4,92	8,0	1705	1870
C $\phi 1.6$	1,26	1,26	610	610	4,8	7,8	1705	1870
D $\phi 1.2$	1,26	1,26	615	615	4,75	7,7	1705	1870
E $\phi 1.2$	1,22	1,22	625	625	4,75	7,7	1705	1870
F <sub>1</sub> $\phi 3.2$	1,38	1,30	1430	1430	5,6	9,4	1705	1870
F <sub>2</sub> $\phi 3.2$	1,47	1,47	1080	1080	/	/	/	/

The second portion of heat by which the filler material is melted, is obtained from the welding arc. The quantitative value of arc energy can also be determined experimentally. In cases where only arc energy is consumed for melting of the filler material, i.e. welding is carried out without the wire extension, the energy input into a unit of the filler material can be determined by:

Entering into Equation (18):

and Equation (19) is added up to the equation obtained, the number of wires is considered, and the record is rearranged; then a mathematical model for calculation of the melting rate in welding with a multiple-wire electrode is obtained:

In Eq.(21),  $n$  is the number of wires,  $Q_k$  in  $\text{kJ/kg}$  is the energy per unit of mass of the filler material which is contained in the droplet right after its detachment from the wire, and  $U_E$  in V is the voltage drop in the anode and cathode regions of the welding arc.

Similarly to constants  $\alpha$  in  $\beta$ , the values  $Q_k$  and  $U_E$  are also obtained experimentally. Table 1 shows these values for some of the filler materials used in welding with a single-wire electrode, while Table 2 shows them for a 3 mm wire used in welding with double-wire and triple-wire electrodes.

Preglednica 2: Eksperimentalno dobljene vrednosti faktorjev  $\alpha$ ,  $\beta$ ,  $Q$  in UE za varjenje z dvojno in s trojno žično elektrodo pod praškom

Table 2: Experimentally obtained values of factors  $\alpha$ ,  $\beta$ ,  $Q$  and UE in submerged arc welding with double-wire and triple-wire electrodes

Premer žice Wire diameter mm	$\alpha$ $\Omega\text{m}$		$\beta$ $\text{kJ/kg}$		$Q$ $\text{kJ/kg}$		$U_E$ V	
	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)
A $\phi$ 3 double	1,34	1,19	505	505	1560	1795	5,5	8,7
A $\phi$ 3 triple	1,56	1,35	505	505	1490	1705	6,1	9,6

## 5 PRIMERJAVA MED EKSPERIMENTALNO IZMERJENO IN TEORETIČNO Izračunano vrednostjo talilnega učinka

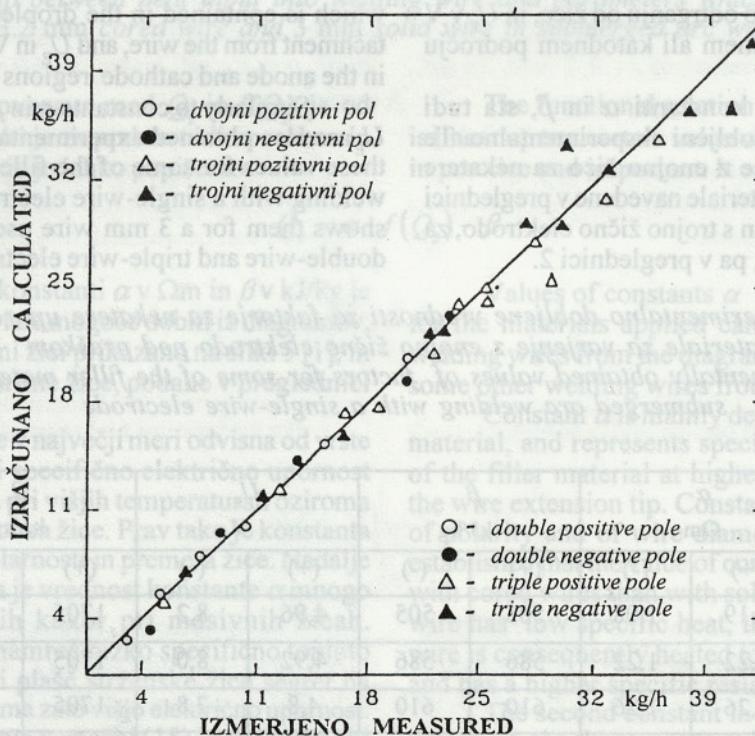
Po številnih preizkusih in na podlagi znanih fizikalnih lastnosti dodajnih materialov smo izdelali matematični model za izračun in napoved talilnega učinka pri varjenju z večkratno elektrodo, ki je popisan z enačbo (21). S ponovnimi praktičnimi varjenji v različnih varilnih razmerah smo opravili večje število preizkusov in dobljene rezultate primerjali z izračunanimi, primerjavo pa prikazali v diagramih.

Na sliki 6 je podan diagram odvisnosti med izmerjenimi in izračunanimi talilnimi učinki pri varjenju z dvojno in s trojno žično elektrodo pod praškom z obema polarnostima.

## 5 COMPARISON OF EXPERIMENTALLY MEASURED AND THEORETICALLY CALCULATED VALUES OF MELTING RATE

On the basis of numerous experiments and on the known physical properties of the filler materials, the mathematical model for calculation and prediction of melting rate in welding with a multiple-wire electrode, as defined by Equation (21), was elaborated. A larger number of repeated experiments in welding under various welding conditions was carried out. The results obtained were compared to the calculated ones. The comparison is shown in the diagrams.

The diagram in Fig. 6 shows the functional relations between the measured melting rates in submerged arc welding with double-wire and triple-wire electrodes using different polarities and the calculated melting rates.



Sl. 6. Primerjalni diagram teoretično in praktično dobljenih rezultatov talilnega učinka pri varjenju pod praškom z dvojno in s trojno žično elektrodo s premerom 3 mm, s pozitivnim in z negativnim polom na elektrodi

Fig. 6. Comparative diagram of theoretically calculated melting rates in submerged arc welding with double-wire and triple-wire electrodes (diameter of 3 mm, electrode positive and electrode negative) and of the experimental rates

Iz diagrama lahko ugotovimo zelo dobro podobnost med izmerjenimi in izračunanimi vrednostmi za talilni učinek. Še posebno dobra povezava je pri varjenju s pozitivnim polom na elektrodi pri varjenju z dvojno in tudi pri varjenju s trojno žično elektrodo. Nekoliko slabše rezultate oziroma nekoliko večji raztros opazimo le pri varjenju s trojno žično elektrodo z negativnim polom na elektrodi in pri večjih vrednostih talilnega učinka.

## 6 SKLEP

Na podlagi prikazanih rezultatov lahko ugotovimo, da je matematični model za izračun talilnega učinka pri varjenju z večžično elektrodo dovolj natančen za praktično uporabo. Edina pomanjkljivost modela je v tem, da je za uporabljene dodajne materiale treba poznati štiri različne koeficiente. Za dodajne materiale je treba te koeficiente ugotoviti eksperimentalno, ti pa potem veljajo za vedno, neodvisno od serije.

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The diagram shows a very high degree of likeness between the measured values of melting rate and the theoretically calculated values. A particularly high degree of likeness can be observed in welding with a double-wire electrode positive and also in welding with a triple-wire electrode. Somewhat less favourable results, i.e. a somewhat stronger discrepancy in results, is observed only in welding with a triple-wire electrode negative and with higher melting rates. [81]

## 6 CONCLUSION

On the basis of the results obtained, it can be established that the mathematical model for calculation of the melting rate in welding with a multiple-wire electrode is accurate enough for practical application. The only weakness of the model is the fact that four different coefficients should be known for each filler material used. For filler materials, these coefficients can be determined experimentally. They then always remain valid, even independently from the series.

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## 5 PRIMERJAVA MED EKSPERIMENTALNO IN TEORETIČNO VREDNOSTI

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## 5 COMPARISON OF EXPERIMENTAL AND THEORETICAL VALUES

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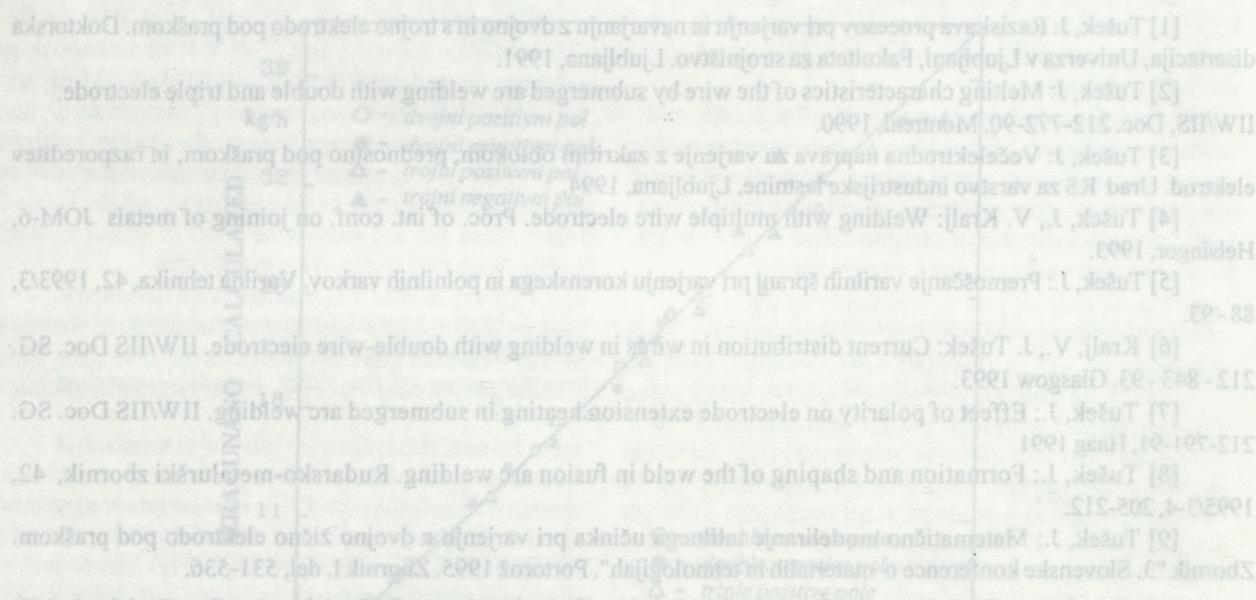


Fig. 6. Comparative diagram of theoretically calculated melting rates in submerged arc welding with double-wire and triple-wire electrodes (diameter of 3 mm, electrode positive and electrode negative) and of the experimental rates