INFLUENCE OF CATHODE TEMPERATURE ON IONIC CURRENT DURING WELDING WITH TUNGSTEN ELECTRODE

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This study presents results for the ratio of the ionic and electronic currents during welding with tungsten electrode obtained by numerical modelling of the processes in the cathode area. The defined task is solved by the finite element method. It was found that the indicated ratio as a function of the temperature passed through a maximum. Also the maximum of the electric field and the space charge density also pass through the maximum. The results obtained show that the magnitude of the cathode area is in the range of 0.01 [mm] and outside of it in the arc column the charge density is close to zero, which corresponds to thermodynamically equilibrium plasma.

Keywords: welding, modelling, welding arc, cathode area.

1. INTRODUCTION

When the welding processes with non-consumable electrode (TIG and plasma welding) are modelled (*Fig. 1*), it is usually assumed that the welding current source maintains a stable current or modifies it by a certain program in pulse arc processes. The thermal and/or deformation task is typically solved to determine thermal cycles, temporary and residual stresses in welded parts. Often the impact of the welding arc on the product is replaced by a heat source, distributed over the surface of the parts or in a given volume (*Fig. 2*). Usually Gaussian distribution of the power is used. In some studies the welding arc and welding pool are modelled simultaneously [1, 2].

Modelling the processes in the welding arc is done in two basic ways. The first one is to examine the movement of particles into plasma and reactions between them [3]. The second is to model the processes by solving thermal, electric and fluid tasks [4÷9], as well as electromagnetic task [4÷7, 9]. In this case,

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Fig. 1. General scheme of modelling the process of arc welding

Fig. 2. Heat sources used to simulate heating during welding

analytical dependencies for concentration, temperature and particle (electron and ion) velocities necessary to determine the electron and ionic currents are often used in addition to the differential equations. Several methodologies have been developed to determine the ionic current. The current density across the cathode surface has two components – electron and ionic current. Since in the contact between the plasma and cathode surface current density can be determined by solving the electrical task it is sufficient to know the ratio of ion to electron current to determinate the magnitude of the ion current.

The aim of this publication is to consider the determination of this ratio by modelling the processes in the cathode region.

2. MODEL DESCRIPTION

In modelling the processes in the cathode region, it is often divided into two sub areas (*Fig. 3*). The first one, which is in direct contact with the cathode, is of small size (approximately the Debye radius) and no interactions between particles are observed here. The second is an ionization zone (the size is from several microns to 0.1 [mm]) between first zone and arc column. This zone is important for processes between electrons and heavy particles. For these interactions cross section data for reactions are used [3, 11÷13]. The processes involved in this area are determinant of the magnitude of the ionic current

Fig. 3. Cathode zone

which is responsible for the cathode heating. The magnitude of this current depends on both the geometric dimensions of the welding arc and the temperature and potential field. Examination of the geometry close to the welding arc does not allow the analysis of the influence of the individual parameters due to the large gradients of temperature and electric potential in the welding arc as well as the substantial change of the surface temperature of the cathode with the distance from the welding arc symmetry axis. This is why we use a one-dimensional task to analyze the impact of basic process parameters on the magnitude of the ionic current. Within this study, gas protection is seen as a multi-component fluid including electrons, neutral atoms (Ar), ions (Ar⁺) and excited atoms (Ar^(s)). Processes are considered at pressure of 1 [atm] and external electric field 2÷4 [V/mm] (arc voltage 12÷24 [V]) and with reference to the space charge density; arc length 2 [mm]). The plasma temperature is 6300 [K] and the cathode temperature is in the range of 1500 to 28000 °C. These values are being selected in accordance with the results set forth in [14]. The cathode is tungsten, and for the electron emission the Richardson equation is used. The Schottky correction of work function is applied [14]. The electric field is being obtained in the process of solving the task. When constructing the geometry the cathode is located at the coordinate $x = 0$ and the anode at $x = 2$ [mm]. The reactions used to describe the processes in the cathode region, are:

In plasma	
Elastic interaction	$e + \text{Ar} \Rightarrow e + \text{Ar},$
Excitation	$e + \text{Ar} \Rightarrow e + \text{Ar}^{(s)} - 11.5 \text{ [eV]},$
Superelastic	$e + \text{Ar}^{(s)} \Rightarrow e + \text{Ar} + 11.5 \text{ [eV]},$
Ionization	$e + \text{Ar} \Rightarrow e + \text{Ar}^+ - 15.8 \text{ [eV]},$
Ionization	$e + \text{Ar}^{(s)} \Rightarrow e + \text{Ar}^+ - 4.427 \text{ [eV]};$
On cathode	
Recovery	$\text{Ar}^{(s)} \Rightarrow \text{Ar},$
Deionization	$\text{Ar}^+ \Rightarrow \text{Ar}.$

The following basic equations describing particle motion and energy transfer are used to model the plasma processes:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \mathbf{\Gamma}_e = R_e, \quad (1)$$

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla \cdot \mathbf{\Gamma}_\varepsilon + \mathbf{E} \cdot \mathbf{\Gamma}_e = R_\varepsilon, \quad (2)$$

$$\rho \frac{\partial w_k}{\partial t} = \nabla \cdot \mathbf{j}_k + R_k. \quad (3)$$

Here n_e and n_ε are electron density and electron energy density, respectively; $\mathbf{\Gamma}_e$ and $\mathbf{\Gamma}_\varepsilon$ – are the electron flux vector and the electron energy flux vector; R_e and R_k are the electron rate and rate expression for species k ; R_ε is energy loss/gain due to inelastic collisions; w_k is the mass fraction of the k^{th} species; $\mathbf{j}_k$ is the diffusive flux vector for k^{th} species (Ar^+ and $\text{Ar}^{(s)}$); $\mathbf{E}$ is the electric field. Mass fraction of the neutrals is determined as $w_{\text{Ar}} = 1 - (w_{\text{Ar}^+} + w_{\text{Ar}^{(s)}})$. The electron flux vector is determined by electric field, electron mobility μ_e , electron density and electron diffusivity $D_e = \mu_e T_e$ through electron temperature T_e . Similarly, the energy flow is defined using $\mu_\varepsilon = (5/3) \mu_e$:

$$\mathbf{\Gamma}_e = -\mu_e \mathbf{E} n_e - \nabla (D_e n_e), \quad (4)$$

$$\mathbf{\Gamma}_\varepsilon = -\mu_\varepsilon \mathbf{E} n_\varepsilon - \nabla (D_\varepsilon n_\varepsilon). \quad (5)$$

Electron mobility is determined by electrical conductivity of argon σ , electron density and charge:

$$\mu_e = \sigma / (n_e \cdot e). \quad (6)$$

The diffusive flux vector for heavy species is calculated using their mobility charge and electric field.

Initial conditions include gas density, electron concentration, and average energy. For the determination of average particle velocities the Maxwell distribution was used and the concentration of electrons was determined by the degree of ionization in accordance with the Saha–Langmuir equation.

3. RESULTS AND DISCUSSION

The ratio of ion to electronic current for two different arc voltages is shown in *Fig. 4*. In both cases, this dependence, as a function of temperature, goes through a maximum. The maximum is shifted to higher temperatures at the higher arc voltage. Also, as the voltage increases, the maximum value of this ratio increases.

The electric field in front of the cathode is shown in *Figs 5* and *6*. The behavior of the electric field with the change of temperature in the two cases considered is analogous. At a distance of about 0.01 [mm] from the cathode surface it takes very low values. As the cathode temperature increases, the absolute value of the electric field increases first (the negative values indicate that the vector is directed back to the positive direction of the Ox axis, i.e. towards cathode), and then decreases. This means that the intensity of the field in front of the cathode goes through extremum. The position of this extremum compared to the position of the maximum ratio of the ionic to the

Fig. 4. Ratio of ion to electron current

Fig. 5. An electric field in front of the cathode for different surface temperatures T [°C] and $U_{arc} = 12$ [V]

electronic current is moved to the lower temperatures. Considering the fact that the electric field above the cathode has high values in the result of the ionic charge, it can be said that in this case the magnitude of the cathode region is in the order of 0.01 [mm]. The reason for the decrease in the electric field is the significantly higher amount of emitted electrons at higher temperatures. This increased amount of electrons leads to a decrease in the space charge

Fig. 6. An electric field in front of the cathode for different surface temperatures T [$^{\circ}\text{C}$] and $U_{arc} = 16$ [V]

Fig. 7. Space charge density in front of the cathode for different surface temperatures $T_{plasma} = 6300$ $^{\circ}\text{C}$, $U_{arc} = 12$ [V]

density and as a result the energy of the electrons entering the ionization zone decreases. The latter in turn causes difficulties in ionization and ion current reducing. In order to trace this relationship, we examine the behavior of the space charge density in front of the cathode (*Figs 7 and 8*). It is also reached the maximum with temperature increase. Furthermore, the result

Fig. 8. Space charge density behind cathode for different surface temperatures $T_{plasma} = 6300^{\circ}\text{C}$, $U_{arc} = 16$ [V]

obtained shows that the maximum number of electrons in the unit volume is greater than the ionic one (negative space charge density) at the maximum temperatures considered directly in front of the cathode. The position of the space charge density and the ratio of the ionic to electronic currents coincide. This coincidence, together with the passage of the ion-to-electron ratio to the maximum, indicates that an internal mechanism of self-regulation in the cathode region is possible.

CONCLUSIONS

1. Digital data for ion to electron current during welding with tungsten electrode are obtained. It was shown that this ratio as a function of temperature goes through a maximum.
2. The transition of this function through a maximum is explained by the processes in the cathode region and the transition through a maximum of both the electric field and the space charge density depending on the temperature.

3. On the basis of the data obtained about the electric field and the space charge density in front of the cathode it can be stated that the magnitude of the cathode area in the case considered is in the order of 0.01[mm].

The conclusions outlined here are made only on the basis of the simulation results obtained in this study and do not necessarily have a universal character.

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ВЛИЯНИЕ НА ТЕМПЕРАТУРАТА НА КАТОДА ВЪРХУ ЙОННИЯ ТОК ПРИ ЗАВАРЯВАНЕ С ВОЛФРАМОВ ЕЛЕКТРОД

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Резюме. В това изследване са представени резултати за съотношението на йонния и електронния ток при заваряване с волфрамов електрод, получени чрез числено моделиране на процесите в катодната област. Дефинираната задача е решена по метода на крайните елементи. Установено е, че посоченото съотношение, като функция от температурата, преминава през максимум. Също така през максимум преминават напрегнатостта на електрическото поле и плътността на обемния заряд. Получените резултати показват, че големината на катодната област е от порядъка на 0,01 [mm] и извън нея, в стълба на дъгата, плътността на заряда е близка до нула, което съответства на термодинамично равновесна плазма.

Ключови думи: заваряване, моделиране, заваръчна дъга, катодна област.

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