Consistent Patterns of Change in Energetic and Fabrication Characteristics of Arcing in Inert Gas Mixtures

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Abstract. The influence of the shielding gas composition and the non-consumable electrode construction on the total and effective efficiency of welding was studied. It was found that value total efficiency is at minimum at 25 % helium content and is increasing with the He concentration growth in the gas mixture. The alteration of arc force impact on the welded metal depending on the current rate, shielding gas composition and cathode processing history was demonstrated. It was found that the arcs with a focused cathode spot feature higher value of the integral forced impact on the welded metal, comparing to the arcs with a diffuse cathode spot, regardless the shielding gas composition.

1. Introduction
The study [1] of fabrication characteristics of arcing with the non-consumable electrodes of different constructions in argon and helium showed that the penetration area $S_p$ depends minimally on the shielding gas composition, when helium content in the mixture amounts to 25–30 %, which is due to the alteration of arc force impact on the weld pool metal. This effect is the most prominent when hollow and composite electrodes are used for arcing with a diffuse cathode spot. At the same time, for arcing with traditional conical cathodes, $S_p$ decreases less significantly. This is due to the fact that arcing with a focused cathode spot features more intensive stirring of the weld pool melt and more efficient heat transfer.

However, the origin of the described minimum for $S_p$ is undetermined, and its existence can be associated both with thermal and with force impact of the arc.

2. Experimental part
To solve this problem a series of experiments was performed to determine total efficiency $\eta_p$ and effective efficiency $\eta_e$ depending on the electrode construction and shielding gas composition.

The constructions of the non-consumable electrodes used for the experiments provide different conditions for cathode processes. The traditional conical electrode (figure 1, a) was used to produce the focused cathode spot, and for arcing with a diffuse cathode spot the hollow cathodes and composite bimetal electrodes (figure 1, b and c) were used.
3. Results and discussion
During the calorimetric study the voltage temporal variations were recorded and the effective arc voltage \( U_{\text{arc}} \) (figure 2) was calculated in order to exclude the influence of considerable fluctuations on \( \eta_e \) measurement results. It is shown that when helium content increases the effective arc voltage always increases but the increase pattern is different for the different electrode constructions. Given the same current level, the lowest \( U_{\text{arc}} \) is observed for the hollow cathodes and the highest – for composite electrodes, both in argon and helium.

![Figure 1. Electrode constructions: conical (a), hollow cathode (b), composite bimetal (c): W - tungsten; Cu - cooper](image)

![Figure 2. Effective arc voltage \( U_{\text{arc}} \) and its fluctuations depending on the electrode construction and helium content in the shielding gas: \( I_{\text{arc}} = 300 \, \text{A}; \, l_{\text{arc}} = 2 \, \text{mm}; \, Q_{\text{gas}} = 20 \, \text{l/min.} \)](image)
The variation of $\eta_p$ with respect to the mixture composition (figure 3) is at minimum at 25 % helium content and is increasing with the He concentration growth in the gas mixture. The total efficiency of the hollow cathode arc decreases dramatically due to the considerable voltage increase when the helium concentration is over 75 %, which results in increased effective arc power, whereas the penetration area changes insignificantly [1].

As noted above, the arc voltage with the hollow cathode in pure helium is lower than for the composite or conical electrode (figure 2), so this total efficiency decrease should be attributed to specific features of the arc with a diffuse cathode spot. All the considered electrode constructions feature the tendency to reduce $\eta_p$ when passing from Ar to 50 % Ar + 50 % He mixture. However the functions have a clearly defined maximum, associated with 75 ‑ 80 % He content. The value of effective efficiency in the maximum area depends to an extent on the cathode working area construction (figure 4). The highest value $\eta_e = 0.77$ occurs for composite electrodes and cathodes with working area sharpened at 90°, the lowest $\eta_e = 0.73$ – for hollow cathodes. The electrode with $d_e = 4$ mm, $\alpha = 45^\circ$ features medium value of effective efficiency $\eta_e = 0.75$.

This maximum is attributable to arc voltage growth (approx. 1 ‑ 2 V) at 75 ‑ 80 % helium content, while the arcing is highly unstable in regards to $U_{arc}$. According to the research [2], at argon-helium...
ratio ¼ 4 \text{ effective ionization potential of the gas mixture} \text{ dramatically increases, which governs the arc voltage growth. This voltage growth is attributed [3] both to cathode and anode potential drop and is attended with increased heat liberation on the anode. The efficiency values in pure He decrease due to significant increase of the arc effective power while the penetration area changes marginally. The latter is apparently due to the increase in plasma temperature which results in high energy input for the discharge radiation and marginal increase of anode potential drop with helium content increase in the abovementioned range [4-6].}

However, these findings do not answer how \( \eta_{a} \) alteration influences the decrease of the penetration area \( S_{p} \) at 25 \% He content.

To prove the above assumptions a series of experiments was performed to reveal how the force impact of the power discharge on the melt depends on the shielding gas components ratio and cathode processes behaviour. The study of arc force impact for DC straight polarity welding in inert gases has also a practical significance as its value defines the melt movement pattern in the weld pool, the joint formation and formation of undercuts, splashes, pores and lacks of fusion and eventually the weld quality [6, 7].

The gravimetric analysis of arc force impact on the weld pool [8] showed, that the functions \( F_{arc} = f(I_{arc}) \) in the quadratic scale of currents are rectilinear, and their slope (coefficient \( k = \tan \alpha \)) defines the change rate of \( F_{arc} \) (figure 5).

![Figure 5. Dependence of the arc force impact \( F_{arc} \) on the electrode construction, shielding gas composition and current rate \( I_{arc} \): 1, 2 – focused cathode spot (conical electrode \( \alpha = 45^\circ, d_{c} = 4 \text{ mm} \)); 3, 4 – diffuse cathode spot (hollow cathode); 1, 3 – Ar; 2, 4 – He.](image)

The arcs with a focused cathode spot feature higher value of force impact on the welded metal regardless of the shielding gas composition. For the welding in argon the value of \( k = 5.12 \times 10^{-7} \text{ N/A}^2 \), which is consistent with the results of the research [9]. For the welding in helium the arc force impact on the welded metal is considerably lower, and with the current increase the change rate \( F_{arc} \) is characterized with the coefficient value \( k = 3.6 \times 10^{-7} \text{ N/A}^2 \).

The arcing with a diffused cathode spot provides lower change rates of the force impact, when \( I_{arc} \) is growing. For the arc discharge in argon \( k = 3.27 \times 10^{-7} \text{ N/A}^2 \), which is lower than that for welding in helium with conical cathode. When helium is used for electrodes providing arcing with a diffuse cathode spot, this coefficient takes on a value of \( 1.6 \times 10^{-7} \text{ N/A}^2 \) and is the lowest for all the studied types of electrodes and shielding gas mixtures.

Thus, with changing the non-consumable cathode construction and gas mixture components ratio, the ratio \( k_F = \frac{k_{\text{max}}}{k_{\text{min}}} \), describing the change of the force impact increase rate with welding current growth, amounts to \( k_F = 3.2 \).

It follows that at the same value of \( F_{arc} \) different results can be obtained regarding the welded joint quality. The force impact about \( 4.4 \times 10^{-3} \text{ N} \) can be implemented at arc welding with a focused cathode...
spot in argon and helium with current 300 and 350 A, respectively. At the same time, the earlier studies [1] had proved that in the first case the welded joint has multiple defects, and the second case features high-quality formation. For welding in argon with a diffuse cathode spot when the force impact exceeds the specified value (at $I_{\text{arc}}$ over 360 ÷ 370 A), the resulted joint is also defect-free, regardless the increased welding rate.

Thus, it was found that the value of the discharge force impact on the melt in itself is not a determinative factor for the formation of a high-quality weld joint. It also requires the information on the arcing conditions governing the pressure distribution pattern on the weld pool surface.

4. Conclusion
The total efficiency for all constructions of non-consumable electrodes depends minimally on the shielding gas ($\text{Ar} + \text{He}$) composition at minimal content of helium 5 % and increases with the growth of He content in the gas mixture.

All the considered electrode constructions feature the tendency to reduce the effective efficiency when passing from Ar to 50 % Ar + 50 % He mixture, and the following increase of He content results in growing efficiency a clearly defined maximum at He concentration = 75 ÷ 80 %.

The arcs with a focused cathode spot feature higher value of the integral forced impact on the welded metal, comparing to the arcs with a diffuse cathode spot, regardless the shielding gas composition, but this parameter is not a determinative factor for the formation of a high-quality weld joint, s it also requires the information on the pressure distribution pattern on the weld pool surface.

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