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Technological properties of non-consumable electrodes in welding aluminium alloys with an alternating current arc with right-angled pulses

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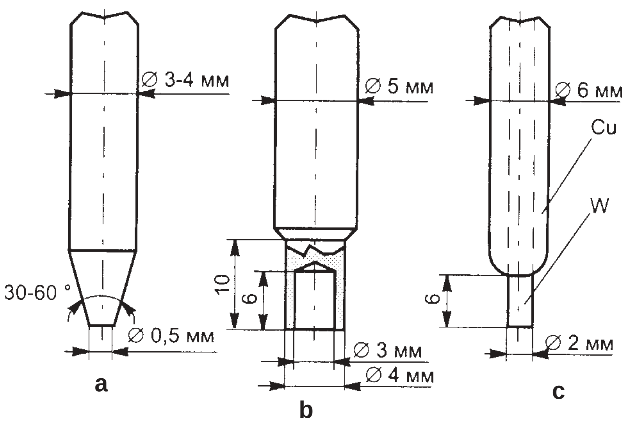
The results of examining thermal conditions of the operation of non-consumable electrodes in welding aluminium and its alloys using alternating current with right-angled pulses (RAP arc)[1] indicate that the electrode may operate without melting of the working section in a range of welding currents (at a specific ratio of the duration of the current pulses with the straight, τ_s and reversed τ_r polarity). This increases the possibility for the application of electrodes in welding with alternating current.

Investigations were carried out into the conditions of effective application and technological possibilities of three types of electrodes, with the conical tip of the working section (Fig. 1**a**), a cavity in the working end (Fig.1**b**), and bimetallic composite electrodes (Fig. 1**c**), in welding aluminium and its alloys with an RAP arc. The experiments were carried out using a power source developed at the Volgograd State Technical University, ensuring stable arcing in the frequency range of 30–250 Hz, and current in the range of 6–350 A, with the possibility of separate regulation of τ_s and τ_r. In individual experiments, the components were penetrated with the arc of sinusoidal alternating current using UDG-501 equipment and EVL electrodes with a diameter of 3 mm, ground to a hemisphere.

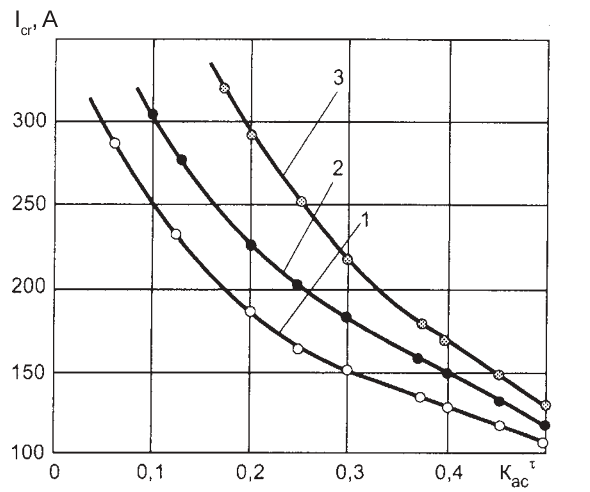
Positive features of the electrodes with a conical tip at the working section are the simple procedure of production and the ease of restoring the initial shape by means of additional grinding. Additionally, the application of electrodes with a small angle of grinding greatly increases the degree of constriction of the arc in the working section and, consequently, increases the concentration of the heat flow into the welded material. This is also accompanied by an increase in the arc pressure at the centre of the weld pool, which greatly increases the degree of penetration (in comparison with electrodes with a working section in the form of a hemisphere).[2]

At the same time, the conical tip of the electrode results in high-density heat flow leading to a highly stressed thermal regime in the working section. Consequently, the working section rapidly loses the initial form; repeated grinding of the electrode is required to restore the initial form. For this reason, electrodes of this type are seldom used in welding with alternating current of industrial frequency with the sinusoidal curve of variation of the current. The RAP arc is used in these cases.

Figure 2 shows the dependence of critical current, I_{cr} (indicating the start of failure of the working section of the electrode,) on the asymmetry factor of the duration of the pulses $K_{ac}^{\tau} = \dfrac{\tau_r}{\tau_s + \tau_r}$ for the EVL electrodes with a diameter of 3 mm and a different angle tip α. Failure of the working section is represented by the rapidly advancing change of its initial shape. At a low value of $K^{\tau}|_{ac}$ the working section shows the formation of needle-shaped crystals, resulting in instability of the welding arc. In the case of long duration of the current pulses of the reversed polarity, the electrode melts.



1 *The design of non-consumable electrodes.*



2 *The dependence of I_{cr} on K^{τ}_{ac}: 1–3) the value of a 30, 45 and 60°, respectively.*

As indicated by Fig. 2, an increase of α is also accompanied by an increase of I_{cr}, but with an increase of K^{τ}_{ac} this effect becomes smaller and at K^{τ}_{ac} = 0.5 (this corresponds to the alternating current of industrial frequency) the value of a has almost no effect on I_{cr}. For example, at K^{τ}_{ac} = 0.125, the increase of α from 30 to 60° increases the value of I_{cr} from 230 to 360 A, whereas at K^{τ}_{ac} = 0.5 the value of I_{cr} changes only slightly (from 120 to 145 A). However, the electrodes with a conical tip at the working section do not ensure burning of the arc with the de-concentrated cathode spot, these working conditions are preferred in some cases.[3]

The high values of permissible current density are obtained in the case of composite non-consumable electrodes (Fig. 1**b**). For example, in welding with straight polarity, the current density in the working section of these electrodes reaches 130–150 A/mm^2 which is approximately three times higher in comparison with the electrodes with a conical tip. This increases the concentration of energy in the heating spot and the productivity of welding, and also makes it possible to reduce the consumption of electrode material. The cylindrical shape of the working section of these electrodes results in more uniform heating of the electrode, which is one of the main conditions of burning of the arc with the de-concentrated cathode spot.[3] At the same time, in welding with alternating current with the application of standard electric arc equipment, etc, ensuring the sinusoidal form of the output voltage, the burning of the arc with the de-concentrated cathode spot (in pulses of straight polarity) cannot be achieved. This is associated with the fact that the melting of the working section of the electrode takes place at a relatively low current density and the condition in which the heat, generated in the ohmic resistance, plays the controlling role in the thermal balance of the electrode, and a zone with different temperatures appears in the working section, is not reached.

The experimental results show that the durability of the composite electrode at $K^{\tau}_{ac} \leq 0.06$ is not inferior to the durability in welding with a direct current of straight polarity. In this case, the permissible current density in the working section is 150 A/mm^2, which is twice the value for the electrode of the same diameter produced from the material with the working section in the form of a hemisphere.

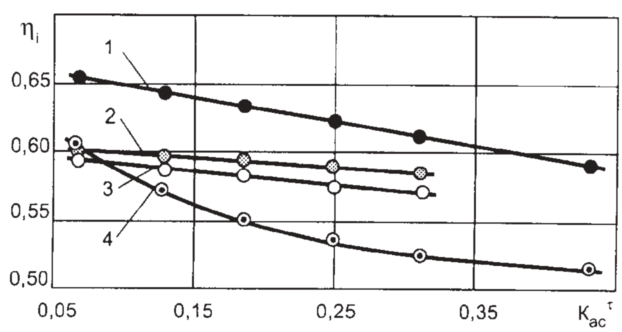
The application of the electrodes with a cavity in the working end[5, 6] makes it possible to ensure quite easily the burning conditions of the arc with the de-concentrated cathode spot in a wide range of current.[5] In this case, the cathode spot is distributed on the wall inside the cavity since the temperature of the internal surface is higher than the temperature on the external surface. Consequently, the arc column is symmetric in relation to the axis of the electrode, and the arc is 'pulled out' from the cavity of the working section. This effect is often referred to as the effect of the hollow cathode. The special feature of these arcs is the absence of compression of the column at the cathode, characteristic of the arc with the concentrated cathode spot. In particular, this special feature determines the main technological advantages of the arc with the hollow cathode: the almost uniform and smaller absolute value of the pressure of the argon on the weld pool, resulting in a large increase of current and welding speed.

In regard to the working efficiency, these electrodes are superior to the standard electrodes with the conical tip of the working section (maximum permissible density of current in the working sections of these electrodes is higher than 150 A/mm^2). The decrease of the wall thickness of the working section and also the increase of the depth of penetration displace the range of working current towards lower values. This is accompanied by a decrease of current I_{pc}, resulting in the burning of the arc with the de-concentrated cathode spot.

At the same time, the electrodes with the cavity in the working section are not used for welding with the alternating sinusoidal current, because the burning of the arc with the de-concentrated cathode spot (in the straight polarity pulses) is not possible. The experimental results show that at K^{τ}_{ac} < 0.35, there is no melting of the electrode with the cavity at the end, and the arc runs with the de-concentrated cathode spot. In this case, the increase of K^{τ}_{ac} from 0.06 to 0.25 result in a decrease of the current I_{pc} from 210 to 150 A (at the electrode diameter of 5 mm, wall thickness 0.35 mm, the depth of the cavity 5 mm). According to the results of pyrometric measurements, this is associated with the increase of the temperature of the working section and, consequently, the increase of the density of thermal emission current.

To examine the effect of the design of the electrode on the energy and technological characteristics of the RAP arc, investigations were carried out to determine the effective efficiency of heating η_h, the force effect of the arc on the weld pool and the penetrating capacity of the arc.

Figure 3 shows the dependence of η_h on K^{τ}_{ac} and the design of the working section. The effective power of the arc in the penetrated sheet produced from AMg6 alloy was determined by calorimetric measurements. The duration of the pulses of straight and reversed polarity τ_s and τ_r, and also the current and voltage in the pulses were measured using the two-beam oscilloscope S8-14 followed by calculations of the actual values of current I_a and voltage U_a, using the standard relationships derived in Ref. 7. The results of the penetration calculations were used to determine the effective efficiency.[8] As indicated

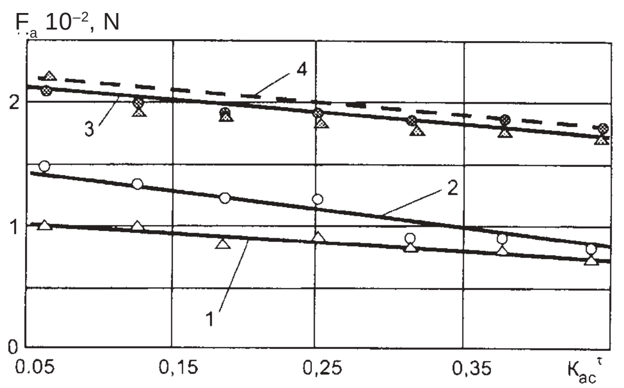


3 *Dependence of η_h on K^{τ}_{ac} and electrode design (I_a = 180 A, f = 20–230 Hz): 1) composite; 2) with a cavity in the working section; 3, 4) with conical grinding to an angle of 30° and a hemispherical tip with a diameter of 3 mm, respectively.*

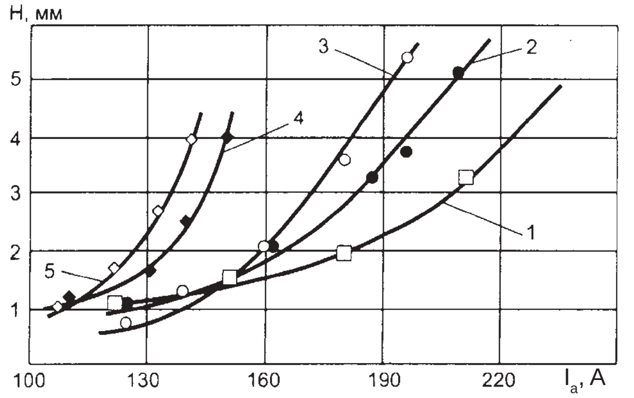
by Fig. 2, the value of η_η in welding with the composite material is considerably higher (0.66 with the minimum K^τ_{ac}), due to the higher current density in the working section of the electrode. It is also important to note the less marked dependence of the effective efficiency on K^τ_{ac} when using the electrodes with the conical tip and the cavity in the working section. For example, in the former case, the electrodes in the range of variation of K^τ_{ac} 0.06–0.3 (when the shape of the working section is unchanged) have the mean value η_h = 0.57–0.8, in the latter case η_h = 0.58–0.61 (with increase of K^τ_{ac} from 0.06 to 0.3).

It is well-known that the penetration capacity of the arc is determined not only by the thermal characteristics but also by the force effect on the weld pool. In examination of the technological characteristics of the arc it is interesting to evaluate the force effect on the pool and determine the dependence of this effect on the parameters of the arc and the design of the nonconsumable electrode. The integral pressure of the arc on the welded metal F_a was determined by the weight method,[9] and the results of the experiments are presented in Fig. 4. It may be seen that the value of F_a in the examined current range changes in the range (0.5–2.3) × 10^{-2} N and depends not only on I_a but also on K^τ_{ac} and the shape of the working section of the electrode. With increase of K^τ_{ac} from 0.06 to 0.38, the value of F_a decreases by a factor of 1.5 which makes it possible to draw a conclusion on the higher integral pressure on the weld pool in the case of the straight polarity arc.

The form of the working section of the non-consumable electrode has a strong effect on the force effect of the RAP arc in the range of the conditions, at which the thermal load on the electrode is not high and the electrode operates in the favourable conditions (low current, a low coefficient K^τ_{ac}). For example, at I_a = 150 A and K^τ_{ac} = 0.06, of the integral pressure of the arc at the electrode with the conical tip is 1.5 times higher in comparison with the electrode with the hemispherical end. Evidently, in the range of low currents in which the depth of penetration of the metal is not high, the application of the electrodes with the conical tip does not have any significant effect. With increase of current and the volume



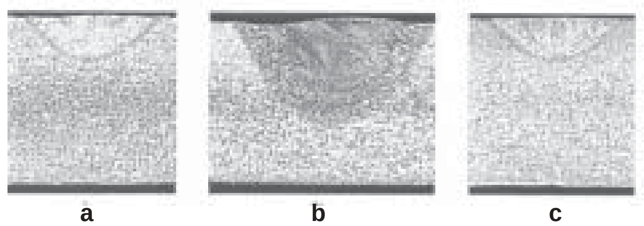
4 *Dependence of the force effect of the RAP arc on K^τ_{ac} and the shape of the working section of the electrode with the hemispherical (1, 4) tip with a diameter of 4 mm, and a conical tip with an angle of 60° (2, 3):1, 2) I_a = 150 A; 3, 4) 200 A.*



5 *The dependence of the depth of penetration of arc current: 1) the arc produced with alternating sinusoidal current; 2–5) the RAP arc, K^τ_{ac} = 0.19; 1–2) electrode with the hemispherical tip of, diameter of 3 mm; 3–2) conical electrode (30°); 1–3 δ_{Al} = 6 mm; 4, 2) 4 mm.*

of the weld pool the effect of the thickness of the liquid layer of the metal on weld formation becomes very strong. When using the electrodes with the conical tip, the depth of penetration increases more rapidly with increasing current of and in the case of the electrodes ground to the hemisphere. This is explained by the higher degree of constriction of the arc in the former case and by the higher peak value of arc pressure. The displacement of the liquid layer, clearly detected in visual examination, improves the efficiency of heat transfer from the arc to the welded metal and this is reflected in an almost 50% increase of the penetration depth.

The arc generated by the alternating sinusoidal current has a lower penetration capacity in comparison with the RAP arc, and with increase of current this difference becomes more appreciable (Figs. 5, 6). This is explained evidently by two factors. Firstly, the higher peak value of the arc pressure of the RAP arc on the weld pool results in displacement of the liquid metal interlayer of the weld pool. This is supported by the fact that the application of the electrodes with the cavity in the working and, ensuring burning of the arc with the de-concentrated cathode spot and, consequently, more uniform distribution of arc pressure on the weld pool, greatly decreases the depth of penetration (Fig. 6). In the case of the RAP arc with the electrode with the spherical end, 1 mm of penetration requires approximately 41 A (in the current range of 240–250 A), whereas in the case of the arc with the electrode with the cavity in the working section, it is



6 *The macrosections of the penetration achieved with the RAP arc (**a**, **b**) and alternating sinusoidal current (**c**) (δ_{Al} = 10 mm): a) the electrode with the cavity in the working end; **b**, **c**) with the hemispherical end, diameter of 4 mm; **a**, **b**) K^τ_{ac} = 0.19, I_a = 250 A.*

approximately 100 A. Evidently, the application of these electrodes with the RAP arc is sufficient in cases in which welding must be carried out with a relatively powerful arc with the minimum the penetration capacity: in surfacing, filling of gaps in multipass welding. Secondly, it is also necessary to consider the effect, on the penetrating capacity of the RAP, of the variation of the pressure of the arc on the weld pool during the process of polarity change. The sharp pressure gradient resulting from the difference of the force effect of the arcs with straight and reversed polarity results in more intensive mixing of the metal, improvement of the heat exchange conditions, and increase of the penetration capacity and mechanical properties of the welded joints.

According to the data presented in Table 1, the strength of the produced welded joints in AMg6 alloy is in the range 0.9–0.95 σ_B of the parent metal. Comparing these data with the strength characteristics of the welded joints, obtained in welding with the alternating sinusoidal current (σ_B = 300–350 MPa)[10, 11] it may be concluded that regardless of the decrease of K^τ_{ac}, they are on the same level. The ductility properties of the welded joints, produced with the RAP arc, are superior to the parameters for the arc produced using alternating sinusoidal current, by 40–50%.

Table 1

Thickness of metal, mm	Conditions		Mechanical properties	
	I_a, A	K_{ac}^{τ}	σ_B, MPa	α, degree
5	165	0.19	315–320	120–126
		0.3	323–328	121–124
		0.38	320–324	125–128
8	240	0.19	310–313	118–120
		0.3	322–325	119–125
		0.38	322–324	117–122

Comment. Filler wire Sv–AMg–63 was used in all cases.

Conclusions

1 In welding aluminium and its alloys using alternating current with right-angled pulses with specific values of the asymmetry coefficient in relation to the pulse duration K^τ_{ac}, the durability of the composite nonconsumable electrode with the cavity in the working section and the conical tip is not inferior to the durability in welding with the direct current with the straight polarity.

2 The penetration capacity of the arc produced with alternating current with the right angled pulses depends strongly on the design of the working section of the non-consumable electrode. Therefore, at K^τ_{ac} = 0.06–0.35, using the electrodes with different design of the working section, it is possible to ensure burning of the arc with both the concentrated and de-concentrated cathode spot. This increases the efficiency of the process and makes it possible to control the penetration capacity of the arc in welding and surfacing.

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