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## MATHEMATICAL FORMULA FOR DETERMINING THE SIZE OF THE TRANSFERRED DROPS OF ELECTRODE METAL DURING MMA

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**Аннотация:** В статье описан способ определения геометрических размеров капель электродного металла в зависимости от продолжительности короткого замыкания. Он обеспечивает количественную оценку переноса электродного металла и энергетического воздействия на свариваемые металлические детали.

**Ключевые слова:** ручная дуговая сварка, фронт плавления, эволюция зоны проплавления, математическая модель, управление формированием шва.

**Abstract:** A method is described to determine geometrical dimensions of electrode metal droplets depending on short circuit duration. It provides a quantitative evaluation of the electrode metal transfer and the energy impact on metal parts being welded. It is proved that using inverter power source decreases the size of droplets transferred to the welding pool by 24% in average if compared with a diode power source. It also reduces overheating of the droplets which improves efficiency of transferring chemical elements from the electrode to the weld metal.

**Keyword:** shielded metal arc welding, melting front, fusion zone evolution, mathematical model, weld formation control.

Research

When studying the transfer of electrode metal droplets, the following assumptions are accepted [1, 2]: the arc column is fixed and coaxial with the electrode, and a molten metal droplet has the shape of a segment or a sphere. Assuming that a molten droplet at the end of the electrode has the shape of a spherical segment with the base equal to the cross section of the electrode, the mass of the transferred droplet can be calculated from the formula [3]:

$$m = \frac{\pi\gamma}{3}\left[2 \cdot R^3 + (2R^2 + r_0^2)\sqrt{R^2 - r_0^2}\right] \cdot 10^{-3}, \quad (1)$$

where m is the droplet mass, g; γ is the liquid metal density, g/mm3; R is the radius of droplet surface curvature, mm; r0 is the electrode rod radius, mm.

On the other hand, the mass of electrode metal droplets transferred with short circuits [4] can be found by a third-order regression equation:

$$m = a \cdot \tau_{k.z.}^3, \quad (2)$$

where τk.z. is the time of the droplet residence at the end of the electrode, s; a is a coefficient of $0.33 \cdot 10^{-4}$ g/s3.
The radius of the electrode droplet surface curvature can be found by formulae (1), (2) and using the Cardano formula [5]:

$$R = \sqrt[3]{\frac{-1}{27}\cdot(\frac{-\pi\cdot\gamma\cdot r_0^2}{4a\cdot\tau_0^3\cdot 10^3})^3 + (\frac{-3a\cdot\tau_{k.z.}^3\cdot 10^3}{8\cdot\pi\cdot\gamma} + \frac{\pi\cdot\gamma\cdot r_0^2}{24\cdot a\cdot\tau_{k.z.}^3\cdot 10^3}) - \sqrt{\frac{2}{27}(\frac{-\pi\cdot\gamma\cdot r_0^3}{4a\cdot\tau_{k.z.}^3\cdot 10^3})^3 + (\frac{-3a\cdot\tau_{k.z.}^3\cdot 10^3}{8\cdot\pi\cdot\gamma} + \frac{\pi\cdot\gamma\cdot r_0^2}{24a\cdot\tau_{k.z.}^3\cdot 10^3})\cdot\frac{1}{4} - \frac{1}{27^2}\cdot(\frac{-\pi\cdot\gamma\cdot r_0^2}{4a\cdot\tau_{k.z.}^3\cdot 10^3})^6}} + \frac{\pi\cdot\gamma\cdot r_0^2}{12a\cdot\tau_{k.z.}^3\cdot 10^3}. \quad (3)$$

A simplified formula:

$$R = \sqrt[3]{-\frac{1}{27}\cdot c^3 + (в - \frac{c}{6}) - \sqrt{\frac{2}{27}\cdot c^3 + \frac{1}{4}(в - \frac{c}{6}) - \frac{1}{729}\cdot c^6}} - \frac{c}{3}, \quad (4)$$

where $c = \frac{-\pi\cdot\gamma\cdot r_0^2}{4a\cdot\tau_{k.z.}^3\cdot 10^3}$; $в = \frac{-3a\cdot\tau_{k.z.}^3\cdot 10^3}{8\cdot\pi\cdot\gamma}$;

τк.з – is the short-circuit dutation when the droplet transfers from the end of the electrode to the welding pool, s; a is the coefficient of 0.33·10–4 g/s3; π – is a mathematical constant equal to the ratio of the circle length to the length of its diameter, the irrational number π ≈ 3.14; γ – is the density of the liquid meta, g/mm3; R is the radius of the droplet surface curvature mm; $r_0$ – is the radius of the electrode rod, mm.

Thus, formula (4) shows that the shorter the short circuits duration, the smaller the radius of the transferred electrode metal droplet, which agrees with conclusions in [1–4]: Dk = 0.2τk.
The volume of a transferred electrode metal droplet which has the shape of a spherical segment with the base equal to the electrode cross section can be determined by the formula [1–4]:

$$V = [2R^3 + (2R^2 + r_0^2)\sqrt{R^2 - r_0^2}]\cdot 10^{-3}, mm^3. \quad (5)$$

The active surface area of the molten electrode metal droplet of can be found by the formula:

$$S = 2\pi R((R - \sqrt{R^2 - r_0^2}) + r_0), mm^2. \quad (6)$$

Using the experimental data (Table 1) of the droplet transfer parameters, we verify the obtained formulas 4-6.

Table 1

*Surfacing parameters*

| Power source - rectifier | Electrode type | Average parameters values (oscillograph) AKIP-4122/1V | Number of short circuits during surfacing | Short circuit duration τk.z., ms |
|---|---|---|---|---|
| diode | LB-52U | Current 89+2.7 A<br>Voltage 20.8+0.6 B<br>Estimated rate of welding 0.25 m/min | 17 | 6.7 ± 1.85 |
| inverter | | | 22 | 5.36 ± 1.34 |
| diode | LEP UONI 13/55 | Current 88+2.7 A<br>Voltage 21.5+0.6 B<br>Estimated rate of welding 0.29 m/min | 17 | 6.5±2.1 |
| inverter | | | 22 | 6 ± 1.9 |
| diode | CL-11 | Current 86 A<br>Voltagee 24.5+0.6 B<br>Estimated rate of welding 0.27 m/min | 12 | 12 ± 3.8 |
| inverter | | | 24 | 8.1 ± 2.3 |

Data in Table 1 show that the droplet transfer time decreases and the number of short-circuits increases when using an inverter rectifier which means that the transferred electrode metal droplets are smaller. This assumption can be either proved or refuted by calculations based on the developed method (formulas 4-6) for determining geometric dimensions of the transferred electrode metal droplets (Table 2).

Table 2

*Average estimated data on the mass and radius of transferred electrode metal droplets*

| Power source - rectifier | Electrode type | τk.z., 10–3 s | Droplet mass m, g | Droplet radiusли, R, mm | Droplet volume V, mm3 |
|---|---|---|---|---|---|
| diode | LB-52U | 6.7 ± 1.85 | 0.099 ± 0.002 | 1.39 ± 0.026 | 6.89 ± 1.9 |
| inverter | | 5.36 ± 1.34 | 0.052 ± 0/015 | 1.05 ± 0.01 | 4.36 ± 1.38 |
| diode | UONI 13/55 | 6.5±2.1 | 0.091 ± 0.004 | 1.3 ± 0.03 | 6.5 ± 1.99 |
| inverter | | 6 ± 1.9 | 0.071 ± 0.002 | 1.23 ± 0.02 | 5.66 ± 1.8 |
| diode | CL-11 | 12 ± 3.8 | 0.57 ± 0.04 | 2.5 ± 0.05 | 15.48 ± 4.9 |
| inverter | | 8.1 ± 2.3 | 0.175 ± 0.05 | 1.8 ± 0.04 | 10.28 ± 2.9 |

Analysis of the data in Table 2 shows that the use of an inverter rectifier makes it possible to reduce the volume of a transferred electrode metal droplet by 9-37% which provides a more stable fine-droplet transfer, especially when using high-alloy electrodes.

To prove the calculation results presented in Table 2 we have analyzed images of high-speed filming (KOMPAS and VEGAS programs) (Figure 1) which certify the calculated data presented in Table 2.

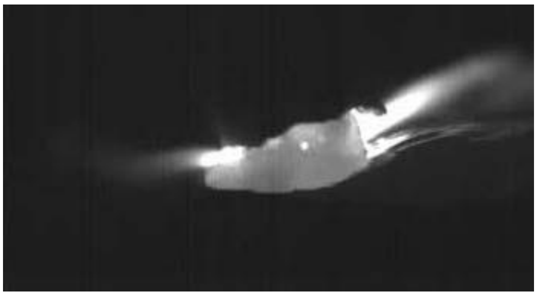

*Fig. 1. Kinogram frame of electrode metal transfer in MMA (inverter rectifier, CL-11 electrodes)*

Decrease in time of the droplet at the end of the electrode (Table 1) and reduction of the geometric dimensions of the transferred droplets (Table 2) reduces heat content of the electrode metal droplets. Droplets of different sizes have different active surfaces interacting with the slag and the atmosphere and accordingly different completeness of metallurgical reactions [6].

Our findings agree with the research results obtained in [7] in which authors proved that the smaller the size of the transferred droplets and the greater the transfer frequency, the lower the heat content of the weld pool. It should be accompanied by a higher melt crystallization rate and as a result lead to a smaller influence on thermal deformation changes in the permanent joint. This fact will be vital for reducing residual stresses and will substantially limit the growth of structural components in the permanent joint.

Conclusion

A valid method has been developed for determining geometric dimensions of the transferred electrode droplets depending on short circuit duration. It provides quantifying electrode metal transfer characteristics and energy impact on the metal of the welded products. It is shown that the use of an inverter power supply for MMA welding, reduces the size of the transferred drops in the weld pool by an average of 24% in comparison with a diode rectifier and reduces their overheating, which increases efficiency of transferring chemical elements from the electrode to the weld metal.

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