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INFLUENCE OF PLASTIC DEFORMATION CARBON STEEL ON THE PROCESS OF BURNING ELECTRIC ARC

Summary. During a study of the combustion process of a direct polarity electric arc, a directly proportional dependence of the electric current value on the degree of cold plastic deformation of carbon steel used as an electrode was found. To calculate the value of the electric current during arc burning, in the indicated ratio, it was proposed to replace the surface tension force of the liquid metal with the surface tension of ferrite of plastically deformed carbon steel. Calculation of the ferrite's surface tension value on the deformation degree of the steel under study through the size of the coherent scattering regions was used to explain the observed dependence of the electric current during arc burning. From the analysis of the considered correlation ratios, it was found that with an increase in the cold

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deformation degree, the refinement of the coherent scattering regions results in the ferrite's surface tension increase and consequently, to an increase in the electric current during arc burning. Comparative analysis of the obtained results of calculating the value of electric current during arc burning through the surface tension of ferrite of cold-deformed carbon steel showed a fairly good coincidence with experimental data. The differences did not exceed 9%.

Keywords: substructure, density dislocation, electric current, plastic deformation, cementite, ferrite

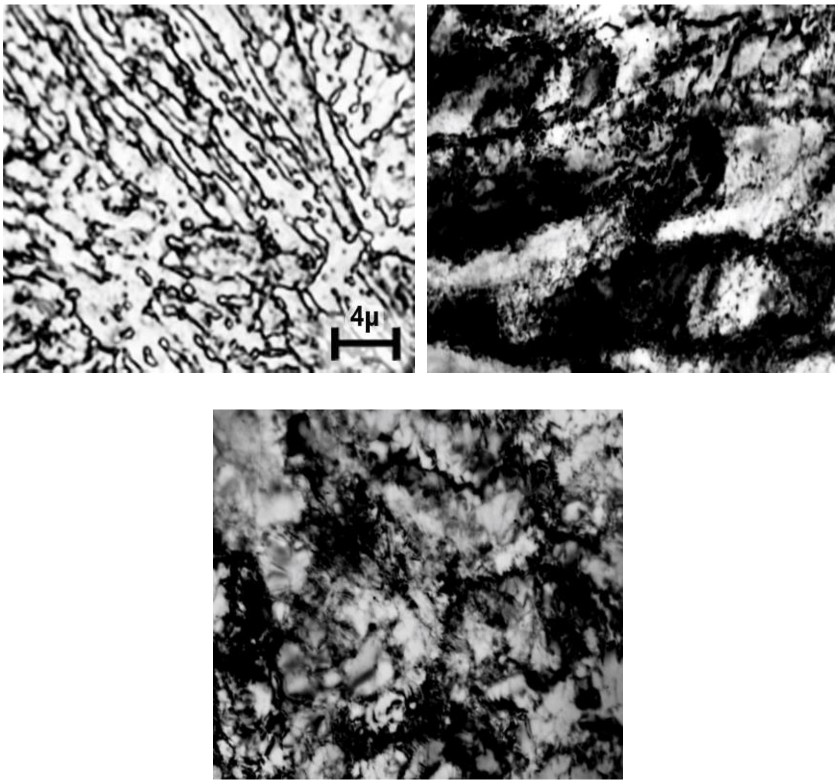
1. INTRODUCTION

When repairing railway transport elements that are subject to significant wear during operation, electric arc surfacing technologies are commonly used [1]. The technologies for the repair of worn-out parts provide not only the restoration of the shape but the achievement properties in the deposited volume of metal, close to the original state. One of the main conditions in achieving high-quality restoration of products is the use of electrodes for surfacing with a chemical composition close to the base metal. Compared to the electrodes for electric arc welding, the repair technology of worn-out surfaces by weld deposition does not provide for restrictions on the carbon and alloying elements concentration for the electrode wire. In general, rather difficult conditions for stabilisation of arc combustion [2-4] can be reduced to two main processes: changing the state of metal aggregation and transferring it to the weld pool [5-9]. When the first portions of liquid metal appear, a static pressure gradient directed towards the electrode axis, which is caused by the pinch effect, arises at the end of the electrode. As the electric current increases, a change in the ratio between the pinch effect and surface tension force of liquid metal takes place. The moment of achieving equality between the said effects corresponds to the stage of completion of the liquid metal's drop formation capable of being transferred to the deposition surface. The electric current value corresponding to the fulfilment specified condition is considered a critical value. The critical value of the electric current is estimated by parabolic dependence on the electrode diameter and surface tension force of the liquid metal. Furthermore, the correct choice of the electric current value during arc burning, in comparison with the critical value, is one of the main factors in the formation of a high-quality layer deposited metal. On this basis, the force of surface tension metal and strength of the electric field in comparison with other factors should prevail when choosing conditions for the combustion of an electric arc [7]. The known dependence surface tension force on the characteristics of crystal structure metal can be considered as evidence of the possible influence of structure parameters on the specified characteristic. Based on this, the choice main structure element of the electrode metal can be used to explain the nature of the change at the magnitude of the electric current during arc burning. For cold-worked metal, such characteristic can be substructure parameters

2. MATERIALS AND METHODS

To study the process of electric arc burning, a cold-drawn wire 1 mm in diameter made of steel with 0.8% *C*, 0.84% *Mn*, 0.51% *Si*, 0.02% *S*, 0.014% *P* was used as an electrode. To achieve various degrees of cold plastic deformation, the diameter of the workpiece was selected in such a way that, after drawing to diameter 1 mm, the required reduction was obtained.

To achieve various degrees of cold plastic deformation and a constant final wire diameter, the blanket diameter was selected in such a way as to obtain the required reduction value after drawing to a diameter of 1 mm. For a uniform arrangement of cementite particles and exclusion of its participation in the plastic deformation, steel blanks were martensite quenched and tempered at a temperature of 650°C for 1 hour (Figure 1a). The workpieces were heated to prevent oxidation in ampoules with the preliminary evacuation of air. Cold drawing of workpieces was carried out on a wire mill at deformation values (ε) of 17, 30, 50, 60, 70 and 80%. The substructure was investigated under the light and electron microscope UEMV-100K at an accelerating voltage of 100 kV. The substructure elements size of the cold-drawn steel was determined by quantitative metallographic methods. The size of coherent scattering regions was estimated by dislocations density using X-ray structural analysis by reflection methods (110) [10]. Investigations of process combustion of electric welding arc were carried out on a special stand (Figure 2). The source of direct electric current for the straight polarity arc was a PSG-500 welding converter. The wire (3) is fixed vertically (2) at a special table as an electrode. On the table (1), there is a removable plate (4) made of low carbon steel. To form an electric arc and stabilise the process of its combustion, the gap between the end of electrode (3) and the plate (4) (no more than 1-1.5 mm) is filled with a powder mixture (6) from the components of electrode coating for manual arc welding. After the electric current is applied to the terminals (7), the electric arc is ignited by introducing a graphite rod (5) into the gap between electrode and plate (4). During the period of arc burning, value of the electric current is determined under conditions of its stable burning.



a *b* *c*

Fig.1. Steel structure after quenching and tempering at 650°C (a) and follow plastic deformation 17% (b,c)

3. RESULTS AND DISCUSSION

Electric arc formation is largely determined by the transition processes of metallic material into a liquid state. In this case, change in surface tension force determines conditions for the liquid phase formation, the shape and dispersion of drops [4]. Moreover, increase in electric current value, through the liquid metal's temperature increase is accompanied by a decrease in surface tension and the dispersion of drops associated with it.

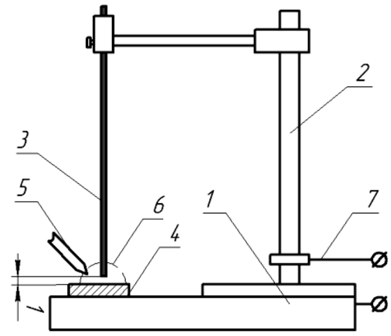


Fig. 2. The schema representation stand for study combustion process of the electric arc

From the ratio of the hydrostatic pressure at pinch effect and the value of metal surface tension, a dependence for estimating the critical value of the electric current (I_c) when the drop is detached from the electrode is proposed [7]:

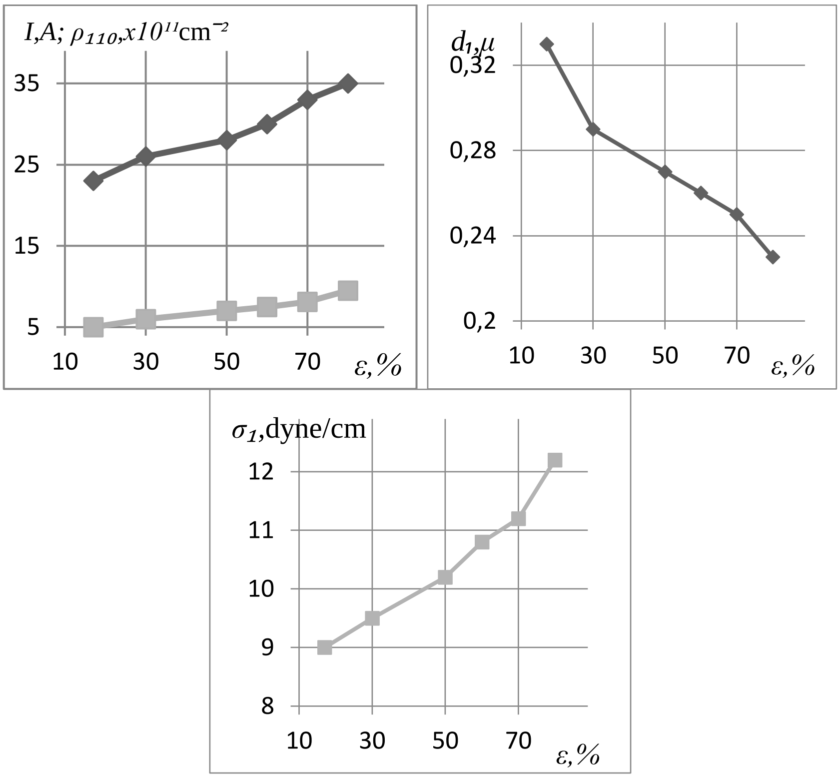
$$I_c = A\sqrt{\sigma_L \cdot d_e}\,, \tag{1}$$

where σ_L – surface tension of the liquid metal, d_e – electrode diameter, A – constant value. For a wide variety of steels, A is 32.7 A/dyne^{0,5} [6]. Evaluation I_c according to (1) for low carbon steel at σ_L = 1220 dyne/cm, A = 32.7 A/dyne^{0,5} and d_e = 1 mm, showed a value about 1140 A, although the value from experiment was 480 A.

Similar differences between calculated and experimental values were obtained for steel with 0.12% *C*, 18% *Cr*, 9% *Ni*, 1% *Ti* (190 A) [7], and the steel with 0.06% *C* of the same alloying, additionally 40% less than the calculated ones. The results obtained indicate insufficient accuracy of the I_c estimate by the ratio (1). On the other hand, during the deposit welding of the metal, the value of electric current under conditions of stable arc burning is a more important technological characteristic in comparison with I_c. In addition to this, the observed differences between experimental and calculated values I_c according to (1) indicate the need to search for other characteristics that will make it possible to predict the electric current value during deposit welding. The analysis of the experimental data [2, 4, 8, 9] shows that the electric current value under conditions of stable arc burning (I) is approximately an order magnitude less than those calculated according to (1). Furthermore, observed similar nature of change in I and density of accumulated dislocations (ρ) from ε (Figure 3a) indicate possible use of substructure parameters of cold-deformed steel to describe I. To explain the given ratios, dependence of metal surface tension on dislocation density was used [11]. Considering that the volume fraction of cementite in the steel under study is about 12%, the particles are uniformly distributed in the ferrite matrix, and ferrite is a structurally continuous phase, an attempt was made to replace σ_L in (1) by the surface tension of carbon steel ferrite (σ_f). Consequently, the main effect on ferrite surface tension at solid state should be exerted by its structural state. Calculation σ_f was carried out according to the ratio [11]:

$$\sigma_f = \frac{G \cdot b^2}{2l}, \qquad (2)$$

where G – is the shear modulus of ferrite ($0.82 \cdot 10^{12} dyne/cm^2$), b – is the Burgers vector ($2.3 \cdot 10^{-8}\, cm$), l – is the distance between dislocations, *cm*. The relation (2) was obtained for ferrite of low carbon steel after small plastic deformations, with an almost uniform distribution of dislocations. However, already after 7-10% of plastic deformation, the decomposition of uniform distribution of dislocations into the periodic structures begins [12] (Figure 1b), and after 20-30% dislocation cells are being formed (Figure 1c).



a b c

Fig. 3. Influence degree of reduction during drawing (ε) steel with 0.8% C after improvement on the density of dislocations at reflection (110) (■) and magnitude electric current of the arc by straight polarity (♦) – (a); d_1 (b) and σ_1 (c)

The size of dislocation cells in cold-deformed high-carbon steel is limited by the distance between cementite particles. To estimate the distance between particles (λ) for the steel under study, the relation is used [13]:

$$\lambda = (0{,}6\sqrt{\pi/f} - 1{,}22)D, \qquad (3)$$

where D – is the diameter of particles, f – their volume fraction.

For the particles with average diameter of 0.32μ, λ in steel was about 0.6 μ. After beginning of dislocation cells formation, increase in total dislocations density in metal is accompanied by their redistribution into those located inside the cells and presented in the form of sub-boundaries. Based on such recombination of dislocations, the size of dislocation cells should be only a certain fraction of λ, which will decrease in proportion to ε. In this case, the width of individual sub-boundaries can reach up to half the diameter of the dislocation cell itself (Figure 1c), which significantly complicates the assessment of its effective size. Based on this, estimation of the dislocation cell size according to the results of electron microscopy for calculating I will inevitably lead to significant errors. As an alternative to estimating the dislocation cell size by electron microscopic studies, to calculate the surface tension of the steel under study (σ_1), ratio (2) with the replacement of l by the size of coherent scattering regions (d_1) should be used. The value of d_1 was calculated using the dependence:

$$d_1 = \sqrt{3/\rho}, \tag{4}$$

where ρ – the dislocation density (Figure 3a). In turn, ρ was determined by the ratio [10]:

$$\rho = \frac{m \cdot \beta^2 \cdot (ctg\theta)^2}{b^2}, \tag{5}$$

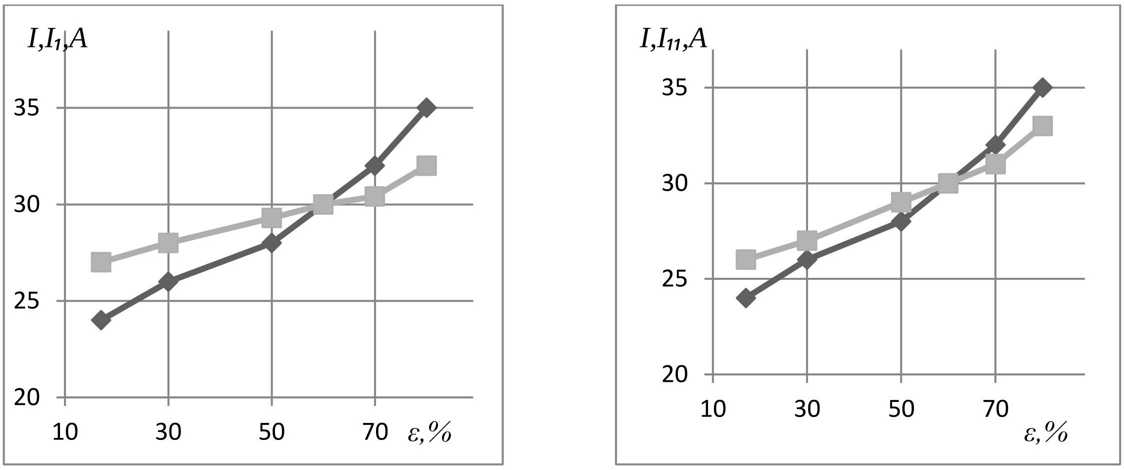
where m = 0.8, β – the broadening of X-ray interference (rad) at reflection (110) – (ρ_{110}), θ – is the interference angle, b – is the Burgers vector.

The given nature of change d_1 from ε (Figure 3b) corresponds to the accumulated dislocation density during steel drawing (Figure 3a) and qualitatively coincides with the results of evaluating the dislocation cellular structure of similar steels. As a result of replacing l by d_1 in (2), the calculated values of σ_1 are shown in Figure 3c. The monotonous nature of increase in σ_1 with increasing ε fully justifies the expected change of I. After replacing σ_L by σ_1 in (1), the calculation of electric current during arc burning (I_1) from ε, at A = 32.7 $A/dyne^{0,5}$ was carried out according to the ratio:

$$I_1 = A\sqrt{\sigma_1 \cdot d_e} \tag{6}$$

Comparative analysis of I_1 with I (Figures 3a and 4a) testifies only to qualitative coincidence according to the dependences. The differences by absolute values between I and I_1 are approximately 10-20%, which may be due to the lack of accounting influence volume fraction of cementite on I_1. Indeed, the use of a carbon equivalent during the development of most welding technologies indicates the need to consider carbon concentration in steel when calculating I. According to [13], dependence (3) is obtained from the ratio $\lambda \sim (1-f)N^{-1}$, where N – is the total number of particles per unit length of the random secant. Based on this, it was proposed to change ratio (6) to the form:

$$I_{11} = A(1-f)\sqrt{\sigma_1 \cdot d_e} \tag{7}$$



a b

Fig. 4. Influence of ε on *I* (♦) and calculation (I_1), according to (6) (■) – (a) and (I_{11}), according to (6a) (■) – (b)

The calculation results I_{11} according to (7) are shown in Figure 4b. Comparative analysis of absolute values of electric current showed a decrease difference between I_{11} according to (7) and *I* to 8-9%. Thus, additional consideration of cementite volume fraction in steel made it possible to increase the estimation accuracy of the electric current during deposit welding using a cold-drawn high-carbon steel wire as an electrode.

5. CONCLUSIONS

1. The electric current value during the arc burning of straight polarity for carbon steel electrode is a proportional degree of cold plastic deformation.
2. To estimate the value of electric current during arc burning, the dependence of ferrite surface tension from substructure parameters cold-deformed steel was used.
3. The size of coherent scattering regions was chosen as a main substructural element of cold-worked steel for calculating the surface tension of ferrite.
4. Estimation of the value of electric current during arc burning based on the dependence from the size of coherent scattering regions and volume fraction of cementite in cold-drawn carbon steel, showed a satisfactory coincidence with the experimental data.

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