Vacuum-arc hardening of metals surface

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Abstract. The possibility of using cathode spots of vacuum-arc discharge for surface hardening of metals is estimated. Based on the analysis of literature data, theoretical and experimental studies, the main parameters of cathode spots affecting to the hardening process are determined. Experimental data on changes in the microhardness of the surface layers of steel exposed to cathode spots of the vacuum arc are presented.

Technological processes, which are based on the heating of the processed material by a locally concentrated energy source, are one of the most promising methods of processing, which is confirmed by numerous studies in this area. Thermal hardening occurs due to local heating of the surface area and its cooling at a high rate due to heat removal into the inner layers of the metal. A promising method of surface treatment is hardening of the surface by vacuum arc discharge, in which local heating of the surface is carried out by rapidly moving high-temperature cathode spots on the surface.

The essence of hardening is the transformation during rapid cooling of the face-centered cubic lattice of austenite into a distorted volume-centered cubic lattice of martensite. The final properties of the hardened zone depend from the rate and temperature of heating, from the holding time in the heated state, from the cooling law, as well as from the initial structure. Knowledge of the thermal cycles of heating and cooling allows to predicting the structural and phase transformations in the substance and the final result of vacuum arc hardening. At the heart of this consideration, together with the metallophysical laws of phase transformations, it is necessary to solve the equation of thermal conductivity. In this regard, it is necessary to evaluate the main parameters of the cathode spot.

Photographing the vacuum arc and analysis of erosion traces (figure 1) showed that the movement of cathode spots is intermittent: for some time the spot remains in one place, and then jumps to a new area of the surface, separated from the initial on one or two radius of the spot (figure 1a).

Figure 1. Effect of cathode spot on the surface: (a) – photo of the trace of the cathode spot; (b) – conditional image of the cathode spot.
The vacuum arc is characterized by large voltage fluctuations. The lower voltage level fluctuates slightly, while the upper one changes more strongly [1]. Probe measurements and observations of cathode radiation show that these oscillations are associated with the cathode processes. Moving of the cathode spot (jump) occurs at the time of voltage rise, when for the spot it becomes unprofitable to remain in the old place. The cause of cathode spot displacement has been discussed in a number of papers [2–5]. During his life on one place spot is continuously deepens into the cathode body on a depth of \( h \) (figure 1b). Deepening leads to elongation of the compressed part of the arc, that at a very high current density in the plasma near the cathode requires of a significant additional a voltage, so much the greater, then is longer the compressed part of the arc. This additional voltage increases the potential difference between the electrode and the plasma on the Langmuir shell behind the deepening (figure 1b). Therefore, than longer the spot is remains in one place, moreover greater the voltage becomes between the plasma and the cathode outside the spot. When the increasing near-electrode voltage drop becomes sufficient for the emergence of a new emission center, the cathode spot jumps to a new location.

Calculations show that the deepening of the crater is mainly not due to evaporation, but due to the melting of the metal under the spot and the extrusion of the molten film under high pressure \( p \) (figure 1b), existing in the plasma at the base of the cathode jet. On the surface of the cathode there is a film of molten metal, the thickness of which increases due to the melting of new layers of the cathode under the spot and decreases due to the extrusion of the molten metal (figure 1b), leaving the crater with a speed of \( v \) (figure 1b).

The study of erosion traces of moving cathode spots showed that the current density \( (j) \) in such spots is of the order of \( 10^7--10^8 \) A/cm\(^2\). To ensure such high current densities, the electric field strength on the cathode surface should be at \( E \sim 10^8 \) V/cm. In the cathode spot of the vacuum arc this field is created by ions formed from evaporated atoms, so the cathode temperature in the spot should be high enough. Thus, at a current density of \( j \sim 10^8 \) A/cm\(^2\), the ion current density (should be at \( j_i \sim 10^7 \) A/cm\(^2\)).

Assuming that the plasma temperature near the cathode is about 1 eV, from the condition \( j=env_i \) we obtain an ion concentration \( (n_i) \) near the cathode of the order \( \sim 3\cdot10^{30} \) cm\(^{-3}\), which corresponds to a pressure \( p \sim 300 \) atmospheres. In order to create such a pressure, the temperature in the cathode spot must be at the level of \( T \sim 5000 \) K.

The existence of a strong electric field \( E \sim 10^8 \) V/cm at the cathode is ensured by the high concentration of ions in the Langmuir shell \( n_i \).

\[
E = 4\pi n_i Z e d, \tag{1}
\]

where \( d \) – shell thickness, \( Z \) – average charge of ions, \( e \) – electron charge. The total arc voltage consists of the cathode jump \( V_k \) and the ohmic voltage drop (without deepening) on the plasma \( U \approx 1/2\pi n_dR \), where \( \sigma \) – is the conductivity of the plasma, \( R \) – is the radius of the spot, \( I \) – is the arc current. Due to the essential role of the diffusion current, the voltage drop in the case of a non-deepening cathode spot is significantly reduced. The fact of voltage reduction can be taken into account by multiplying the conductivity of the plasma by a factor \( \gamma_\sigma \), greater than one.

During the life of the spot, the metal warms to a depth much less than the radius, and the task is near-flat. Then:

\[
\frac{d\Delta}{dt} = \frac{\chi}{\rho (CT_k + \lambda)} \frac{T_k - T_{mt}}{\Delta} \frac{dh}{dt} \approx \frac{a}{\Delta} \frac{dh}{dt}, \tag{2}
\]

where \( \rho \) – the material density, \( C \) – the heat capacity, \( \lambda \) – the heat of fusion, \( T_{mt} \) – the melting temperature of the cathode, \( \chi \) – the thermal conductivity, \( a \) – thermal diffusivity, \( h \) – the depth of the crater (figure 1b). In the derivation of the formula (2) it was believed that on the surface of cathode spot is maintained the temperature \( T_k \), much larger \( T_{mt} \).

From the continuity equation we have

\[
\frac{dh}{dt} = 2/R \cdot \sqrt{\Delta}, \tag{3}
\]
where \( v \) is the rate at which the fluid leaves the crater (figure 1b).

The power of the pressure forces \( \pi R^2 \rho (dh/dt) \) is equal to the flow of kinetic energy carried away by the extruded liquid metal \( 2\pi R \rho v \left( \frac{v^2}{2} \right) \Delta \), where \( v = \left( \frac{2p}{\rho} \right)^{1/2} \).

Substituting (3) into (2), we have

\[
\frac{d\Delta}{dt} = \frac{a}{\Delta} - \frac{2}{R} v \Delta
\]  

(4)

Integrating this equation, we obtain

\[
\Delta = \left[ \frac{aR}{2v} \left( 1 - e^{-4vt/R} \right) \right]^{1/2}.
\]  

(5)

Substituting (5) into (3), we obtain an expression for the rate of deepening of the crater of the cathode spot:

\[
h(t) = \frac{Ra}{2v} \left[ \frac{1}{2} \ln \frac{1 + \sqrt{1 - \exp(-4vt/R)}}{1 - \sqrt{1 - \exp(-4vt/R)}} - \sqrt{1 - \exp(-4vt/R)} \right].
\]  

(6)

Additional voltage, associated with the passing of the current of the deepening crater,

\[
\Delta V_k \approx jh/\sigma.
\]  

(7)

Equating \( \Delta V_k \) to the voltage amplitude of fluctuations, the spot lifetime \( \tau \) can be determined from (6) and (7).

Now we have the opportunity to estimate the lifetime of the spot. Let \( I = 10 \, \text{A} \). Using the results of the previous estimates (\( j = 1.6 \cdot 10^7 \, \text{A/cm}^2 \)) and assuming \( \Delta V_k = 25 \, \text{V} \), we obtain \( \tau = 4 \cdot 10^{-8} \, \text{s} \) and \( h = 2.5 \cdot 10^{-4} \, \text{cm} \). The obtained lifetime is consistent with the frequency spectrum of the arc voltage fluctuation – white noise is observed in the frequency band \( \sim 15 \, \text{MHz} \).

The results of the wire tensile tests are presented in table 2.

### Table 1. Change of microhardness of a wire from a surface to a deep into metal.

| Material of sample, dimensions, mm | Status of samples | Average microhardness (MPa) at a distance from the surface, microns |
|-----------------------------------|-------------------|---------------------------------------------------------------|
|                                   |                   | 5          10         20         50         Center |
| Wire – steel, diameter 6.5 mm     | Before hardening  | 2820       2820       2810       2800       2770 |
|                                   | After hardening, at 0.2 m/s | 3360       3150       2970       2920       2770 |
|                                   | After hardening, at 0.1 m/s  | 3680       3420       3130       3060       2770 |

The results of the wire tensile tests are presented in table 2.
Table 2. The results of tensile tests

| Material of sample, dimensions, mm | Status of samples | Indicators of mechanical properties |
|-----------------------------------|-------------------|-------------------------------------|
| Wire – steel, diameter 6.5 mm    | Initial           | $\sigma_b$, МПа | $\sigma_{0.2}$, МПа | $\delta$, % | $\Psi$, % |
|                                  | After hardening   | 845                    | 750                    | 11 | 52.1 |

$\sigma_b$ – ultimate strength, $\sigma_{0.2}$ – conditional yield strength, $\delta$ – relative elongation, $\Psi$ – relative contraction of the cross section.

The obtained results of theoretical calculations and experimental results indicate about the possibility of not only hardening the metal surface by treating it with cathode spots of vacuum arc discharge, but also about the improving of the mechanical properties of the entire material. Of course, the surface treatment should be carried out not by single cathode spots, but by a group of single spots at currents of vacuum arc discharge from tens to hundreds of Amperes. Unlike single cathode spots, a group cathode spot is a stable system whose existence is maintained by the equilibrium between the rate of formation and the rate of death of its components. The properties of group cathode spots are characterized by average values of diameter, current and surface velocity with relatively small dispersions of the normal distribution.

In our case, by the processing of a wire with a diameter of 6.5 mm in vacuum by the cathode spots with an arc current of 100 A, the wire broaching speed of 0.2 m/s was selected from the condition of complete processing of the entire surface while preventing of the repeated movement of cathode spots on the already treated surface. At a wire broaching speed of 0.1 m/s, the group cathode spot repeatedly moved over the already treated surface, which led to an increase of its microhardness (table 1).

References
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