INFLUENCE OF CORED WIRE MELTING MODE AT ARC SPRAYING ON COATING PROPERTIES

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ABSTRACT. Jointly analysis of melting model of core wire at arc spraying and forming coating structure properties was done. Influence of physicochemical parameters of initial materials and atomization modes as well was established. Basing on investigation results a row of core wires for wear-resistant application was developed. Coatings from such materials are successfully used with reference to parts to be restored in metallurgy, gas-processing industry and machine building.

Practice showed that steels, cast irons, surfacing alloys containing metastable austenite, alongside with a martensite, carbides etc. phases, are of high stability in different conditions of a mechanical wear. The conducted researches have shown, what is it conditioned by synergetic influence to non-equilibrium system. The dissipation of energy, which is brought to a working surface by external exposure, is most effectively made by microheterogenous structure with metastable austenite, transforming into a dispersed martensite on-stream. Structure self-organizing conditioned by relaxation processes at martensite formation, along with formation of compression stresses of high-level strain hardenings of surface layer provide high stability at surface contact loading [1].

Such materials are profitable to use at activated arc metallization (AAM), which is a mode of Arc Spraying, combining high quality of coatings and productivity [2]. In this case most simple way of obtaining of necessary elemental composition of sprayed material is usage of cored wire (CW). Essential structure and properties of coatings are allowed by variation of charge component's content. However specific features of arc spraying prevent to ensure quality of coatings at usage CW, designed with reference to welding and surfacing. Preliminary study showed possibilities of easy receipt of oxygen into metal, and incomplete fusion of a charge core [3]. It results in lowering of adhesive and cohesive strength of coatings, increase of their porosity, decrease of alloying charge components influence.

For analysis of the indicated processes with reference to CW model of propagation of heat, which is caused by electric arc heating, was offered [4]. Heat propagation in area of electrode end face was considered as axially symmetric problem and it is depicted by differential equation of heat transferring:

\[
\frac{\partial T}{\partial t} = \left( \frac{\lambda}{c \cdot \gamma} \right) \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right),
\]

Where T - temperature, K; t - time, s; \( \lambda \) - thermal conductivity, W / (m \cdot K); c - specific heat, J/(kg \cdot K); \( \gamma \) - density, kg/m\(^3\); x, y - coordinates on cross-section and through CW generating, accordingly, m.

Equation [1] was numerically solved by explicit difference method. The considered area was divided on radius (r) by coordinate lines \( i = \text{const} \) with step \( \Delta r = r/10 \) and on depth (s) by coordinate lines \( j = \text{const} \) with a step \( \Delta s = s/10 \) (fig. 1). Within borders of element temperature is considered as constant and is related to its middle.

As electrical conductivity of shell is by a factor of \( 10^2 \), than charge one; it is accepted that active arc spots are localized at ends faces of shells. So, the surface temperature of a shell at end face is adopted 2500 K. Such overheating is typical for arc
processes. The surface of charge receives heat from arc column by radiation and is heated thus up to 1300 K.

Fig. 1  a) Sketch of electrode end face at Arc Spraying.
        b) Scheme for heat propaganda computation.

At calculation the heat propagation during \(4 \times 10^{-4}\) s is reviewed, according to data of oscillography measurement of drops dwell-time at end face before separation in case of solid wire metallization.

The propagation of heat from end face surface deep into electrode is influenced by thermo exchange "shell-gas" and "shell-charge": shell, heated up by arc, give away heat to transporting gas stream and to charge.

At calculation of thermo exchange "shell-gas" the factor of convective surface heat exchange is determined by equation:

\[
\alpha_t = Nu \cdot \lambda / 2r
\]  

(2)

Nusselt criterion is calculated by equation used for cross-flow of tubes:

\[
Nu = 0.245 \cdot Re^{0.6}
\]  

(3)

The temperature variation on outer surface of electrode shell owing to heat exchange was calculated by equation:

\[
\lambda_1 \cdot \frac{(T_{k,j}^k - T_{i-1,j}^k)}{\Delta r} = \alpha_1 \cdot (T_{i-1,j}^k - T_g)
\]  

(4)

The temperature variation on border "shell - charge core" owing to heat exchange was calculated by equation:

\[
\lambda_1 \cdot \frac{(T_{i-1,j}^k - T_{i,j}^k)}{\Delta r} = \alpha_2 \cdot (T_{i,j}^k - T_{i-1,j}^k)
\]  

(5)

Where "1", "2" - indexes conforming to shell and charge, accordingly; \(k\) - number of step on time.
Low-carbon steel (0.08 % C) is adopted as material of the shell. The thermal characteristics, indispensable for calculation, thermal conductivity ($\lambda$), density ($\rho$), specific heat ($c$), are approximated (table 1) by polynomials like:

$$Y = A_1T^3 + A_2T^2 + A_3T + A_4$$

(6)

The charge thermal properties are adopted in interval of compositions, which are typical for these CW components.

Table 1. Equations of approximating of thermal parameters [10, 11]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Temperature interval, K</th>
<th>Polynomial's coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$, W/(m·K)</td>
<td>300..2500</td>
<td>$-2 \cdot 10^{-8}$</td>
</tr>
<tr>
<td></td>
<td>2500..3500</td>
<td>0</td>
</tr>
<tr>
<td>$\rho$, kg/m$^3$</td>
<td>300..3500</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>323-1073</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1073-1273</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1273-2473</td>
<td>0</td>
</tr>
</tbody>
</table>

In calculation by equation [1] fusion enthalpy was taken into account as follows. On each step temperature of calculation cell was compared with melting point ($T_m$) of shell or charge, accordingly. At achieving ($T_m$) temperature of cell stays constant on time at subsequent points. Here the heat, stored in a cell, is summarized:

$$\sum_{k=1}^{N} c_{ij}^k \cdot (T_{ij}^k - T_{ij}^{k-1})$$

(7)

This heat on each step is compared to specific fusion enthalpy of cell material ($h_{pl}$). At fulfillment of condition $\sum_{k=1}^{N} q_{ij}^k > h_{pl}$ on further steps of calculation the temperature rise of cell is allowed.

The calculation of depth of liquid layer at end face, which is fused by heat of arc spot, is executed according to the solution of problem of unheated body of restricted size melting at continuous removal of generating melted metal. Here fusion enthalpy is allowed [12]. In this case heat balance equation is as follows:

$$q_1 \cdot F \cdot dt = dQ$$

(8)

The left-hand part of an equation ($q_1 \cdot F \cdot dt$) represents input of heat into end face, which one is done at the expense of arc spot heat ($q_1$ - specific heat flow from arc spot, W/m$^2$; F - square of end face, m$^2$). The right member of equation (dQ) introduces heat consumption on fusion of layer at end face and on warm-up of solid part of shell.

Portion of heat capacity of arc, which is passed on each arc spot, is adopted approximately equal. Such value of portion falls in interval of portion values of arc heat power income on anodic and cathode spots, presented by Erohin for a case of welding arc burning of normal polarity in air [5]. After permutation and integrating according to Goldfarb [6] the equation obtains a form, in which depth of liquid layer (s), heated by arc spot is unknown:

$$2 \cdot a \cdot t / h^2 = (\Psi(N) - \Psi(N_{\infty}))/N^2$$

(9)

Where $\Psi$ - function that is looking like:

$$\Psi(u) = 9 \cdot u \cdot \sqrt{(u + 3/2)^2 + 8/9} / 16 + \sqrt{(u + 1/3)^2 + 8/9} / 16 +$$

$$+ 2 \cdot \ln \left( 6 \cdot \sqrt{(u + 1/3)^2 + 8/9 + u + 1/3} \right) / 12 - 3 \cdot u^2 / 16 - u / 4$$

$$N = c \cdot \Delta T / (2 \cdot h_{\infty})$$ - melting criteria,

(10)
\[ \omega = \left( h - s \right)/h, \quad (12) \]
\[ \Delta T = T_n - T_c = q_i \cdot h/(2 \cdot \lambda), \quad (13) \]
\[ a = \lambda/(c \cdot \rho), \quad (14) \]

Where \( t \) - drops dwell-time at end face before separation, s; \( T_c \) - temperature of non-heated metal, K; \( T_n \) - surface temperature of melt at end face, K; \( h \) - extension of heating zone, from a surface of end deep into shell, m; \( h_{\text{пл}} \) - fusion enthalpy of liquid iron, J/kg; \( a \) - thermal diffusivity, \( m^2/s \).

The calculation has shown that a few times increase the depth of separated layer of liquid metal takes place in case of CW comparing with solid wire (fig. 2). Besides increase of the layer depth is inversely proportional to growth of shell thickness in case of CW. Computer algebra system Maple 7 was used at equation [9] solving. The correctness of the obtained data was tested for a solid wire by calculation from a condition of equality of liquid layer volume and separated drop volume according to the EAM oscillography data (the latter one value is marked at fig. 2 as solid, test).

Inverse problem concerning thermal parameters of charge and blowing gas, geometrical sizes of CW cross-section was solved at heat exchange calculations. Favorable conditions for formation of sprayed drops were imposed as constraints at searching intervals of values of these parameters.

Analysis of calculation showed the following:

- Shell at all depth of liquid layer is strongly overheated above melting point.
- Thinning-down of shell, alongside with increase of liquid layer depth, results in decrease of its temperature.
- Temperature of shell surface does not exceed melting point owing to thermal exchange with colder gas. It promotes deceleration of drop separation.
- Temperature of shell surface is strongly depended on conditions of heat transfer in "gas - shell" system.
- Incomplete fusion of charge can be caused by decrease of charge heat conduction and shell depth thinning-down.

Fig. 2 Output computation of depth of separated layer of liquid metal at EAM for solid wire and CW with various shell thickness (\( \delta \), mm)
Model resulted data were used as initial ones at CW developing. Here carbonaceous metastable austenite is contained as structure component.

AAM-sprayed coating of 1,0…1,3 mm thk of 150X8T2 type composition [7] was investigated. Results of study of microstructure and phase analysis are shown. The etching of longitudinal and transversal microsections was made by nitrohydrochloric acid, microhardness was measured at device PMT-3 at loads 50 and 100 g.

Metallographic analysis of transversal microsections of coatings has shown that structure coating has wave-like nature of structural components arrangement (fig. 3). Etching reveals some representative colors and tints of structural components: the white strips alternate with dark-grey, grey-blue, yellow-grey and black ones. Good enough connection at 'coating-substrata' border was revealed; oxide layers are thin with rare thickenings and pores.

Fragment pieces of coating microstructure on surface are multicolored and 10...50 microns by size. They have incorrect or rectangular shape in common.

Similar character of CW and solid wire structures (fig. 4) is found out at comparison. It means that developing of CW for arc spraying is turned out well.

The X-ray analysis showed that phase structure of sprayed coating represents combination of a metallic base, primary carbides and also oxide phases. Structure of metallic base consists of martensite and retained austenite, in equal parts. Microhardness of coating range from 6,2 to 8,2 GPa, but for all that microhardness of white components is 7,2…8,6 GPa, and yellow-grey and grey-blue components is 4,5…5,6 GPa. Apparently, white components, having typical dark points and strips, represent the unoxidized metallic pieces, which have arisen at fast crystallization of carbide eutectic and metallic austenitic-martensite matrix. Good etchable yellow-grey components are, apparently, a dispersed mixture of metallic and oxide components, and grey ones - structure of oxides. Black spots on microsections could arise from deep etching of oxides fragments and small-sized pores.
Thus, structure of AAM coating from CW of 150X8T2 type, represents a heterogeneous dispersed mixture of austenitic-martensite metallic matrix with inclusions of primary and eutectic carbides, and also oxides with high initial microhardness.

At following stage with reference to coatings the influence of metastable austenite upon surface hardening was studied. Coatings were 40 times subjected to running up by roll from bearing steel, 62 HRe, of 10 mm dia, at running speed 0,158 m/s. Specific load was 0,1 MPa. After running up no cracks initiation or spallings on working surface were revealed. Quantity of a retained austenite has decreased from 50 % up to 20 %, and martensite accordingly has increased. It indicates austenite metastability and its capacity to martensite ($\gamma \rightarrow \alpha$) transformation at working loading. Measuring has shown 18 % increase on average of microhardness of surface layer in comparison with initial state (fig. 5).

![Fig. 5 Microhardness of a surface of AAM 150X8T2 type coating before and after roll running up](image)

Fig. 5 Microhardness of a surface of AAM 150X8T2 type coating before and after roll running up

We suppose that under contact load influence at running up the metastable retained austenite in coating is transformed into martensite. It leads to increase of relaxation capacity of structure, which in turn increases its capacity to deformation hardening.

Wear tests confirm it. They have shown that wear resistance of AAM coating from developed wire is 3…5 times as large than that one from 20X13 solid wire.

During four years developed CW are successfully used at AAM restoring of heavy duty parts of more than 80 titles in metallurgy, gas-processing industry, machine-building:

- Vehicle repair enterprise – engine parts;
- Metallurgical works – units of continuous casting machines (fig. 6), hydro-press plungers, and shaft journals;
- Gas-processing works – bearing caps and rotors of electric motors;
- Aircraft building enterprise – parts of tool workshop and machining facilities.
REFERENCES


2. Korobov Yu. S. 'Efficiency of using activated arc metallization for the deposition of protective coatings' Welding international 2005 19 (7) 580-582.


Fig. 6. Restored bush of continuous casting machine reduction gear. 4 mm thk AAM coating is sprayed and machined on worn-out cylindrical surface of Ø 320 mm