Kinetics of the melting front movement in process of centrifugal induction surfacing of powder material with nanoscale modifiers

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Abstract. For solving the problem of improving the powder coatings modified by nanostructure components obtained by induction surfacing method tribological characteristics it is necessary to study the kinetics of the powdered layer melting and define the minimum time of melting.

For powdered layer predetermined temperature maintenance at sintering mode stage it is required to determine the temperature difference through blank thickness of the for one hundred-day of the define the warm-up swing on of the stocking up by solving the thermal conductivity stationary problem for quill (hollow) cylinder with internal heat source. Herewith, since in practice thickness of the cylinder wall is much less then its diameter and the temperature difference is comparatively small, the thermal conductivity dependence upon the temperature can be treated as negligible.

As it was shown by our previous studies, in the induction heating process under powdered material centrifugal surfacing (i.e. before achieving the melting temperature) the temperature distribution in powdered layer thickness may be considered even. Hereinafter, considering the blank part induction heating process quasi-stationarity under $F_o$ big values, it is possible to consider its internal surface heating as developing with constant velocity.

As a result of development the melting front movement mathematical model in a powdered material with nanostructure modifiers the minimum surfacing time is defined. It allows to minimize negative impact of thermal influence on formation of applied coating structure, to raise productivity of the process, to lower power inputs and to ensure saving of nonferrous and high alloys by reducing the allowance for machining.

The difference of developed mathematical model of melting front movement from previously known is that the surface temperature from which the heat transfer occurs is a variable and varies with a time after the linear law.

1. Main positions and admissions

The kinetics of the modified by nanostructure components powdered layer melting under centrifugal induction surfacing renders significant influence upon physico-mechanical and working characteristics of protective coatings obtained. This is connected with the fact that most of fused materials are thermally sensitive i.e. increase the surfacing temperature and time of the thermal influence, as a rule, renders the negative influence on powder layer microstructure, including modified
nanostructure components. For solving the problem of improving the powder coatings modified by nanostructure components obtained by induction surfacing method tribological characteristics it is necessary to study the kinetics of the powdered layer melting and define the minimum time of melting. At the point, the studies devoted to decision of this problems are fulfilled by developing the mathematical model of phase transition front (the front of melting) motion process under conditions of the centrifugal induction surfacing.

The decision of the problem with aggregate conditions material change is one of the most complex mathematical physics sections. This is connected with the fact that similar problems must be formulated as problems of conjugation the two temperature fields in presence of specific boundary condition at moving boundary. The Main difficulty of the problem solving is a fact that it belongs to the class of the nonlinear problems, i.e. to problems with nonlinear boundary condition. Such a problems, as a rule, may be solved only by means of approximate methods. One of the the most efficient methods of solving is an approximate method, designed by academician L.S. Leybenzon, and developed also by academician A.V. Lykov. Essence of this method is concluded in approach after which the functions of the temperature distribution in melted and not melted layers are selected so that they satisfy the boundary condition. Matched in such a way functions are to be substituted into condition of conjugation at the boundary of the phases and after that one solve the obtained differential equation for the front of the phase transition coordinate \( \xi \).

As it was shown by our previous studies [1-2], in the induction heating process under powdered material centrifugal surfacing (i.e. before achieving the melting temperature) the temperature distribution in powdered layer thickness may be considered even. Hereinafter, considering the blank part induction heating process quasi-stationarity under \( F_0 \) big values, it is possible to consider its internal surface heating as developing with constant velocity.

On the base of these admissions problem of powdered layer melting is reduced to the following. There is unlimited hollow cylinder at the temperature \( T_0 = T_m \) (\( T_m \) is a powder melting temperature). The cylinder external surface temperature increases linearly. Melted layer with thickness \( R - \eta = \xi \), where \( \eta \) is a distance from axis of the cylinder to the layer boundary, is formed beginning from the cylinder surface.

![Diagram](image)

1 – melted zone; 2 – not melted zone; 3 – blank.

Fig 1 – a boundary conditions under centrifugal induction surfacing.
The temperature of not melted layer is expected uniform in all cylinder and equal to melting temperature.

The known methods of solving the heating problems for induction sintering processes and powdered coatings surfacing processes reveal the following main limitations:

- the blank surface radiant heat exchange is not taken into account and it reduces greatly the calculation accuracy;
- used for solving the problems operational methods and finite-difference method bring about exceedingly bulky mathematical expressions, requiring for calculations the use of calculating machinery, and not suitable to engineering practice;
- there are no based on the known decisions recommendations for the technological processes optimization.

The analysis of the centrifugal induction surfacing technologies main features allows to draw a conclusion that the most important stage of the technological process, defining the physico-mechanical and exploitative characteristics of two-layer products obtained, is isothermal soaking at the powdered material surfacing temperature. The main engineering problem at this stage is a powdered layer average temperature (the surfacing temperature) maintenance during certain time interval (surfacing time). Here the thermal regimes on previous stages of heating do not render essential influence upon the process of powdered layer sintering to substrate kinetics.

The powdered layer thickness, as a rule, has far less substrate thickness and its surface curvature radius. Powdered layer free internal surface and two-layer cylinder butt ends can be considered as heat-insulated. Consequently, powdered layer thermal resistance can be considered as negligible, and temperature distribution in its thickness can be treated as uniform and equal to the substrate inner surface temperature. Herewith, beginning from certain Fourier criterion value \( (F_o=0.305) \) quasisteady thermal conduction mode occurs, when the temperature distribution shape through the substrate changes not, but the temperature in each point grows with time retaining constant relative velocity. Upon achieving the powdered material melting temperature by internal surface of the cylindrical blank the temperature of this surfaces is support to be constant by heating source (the high frequency current generator) power management. Here the temperature distribution through blank thickness is stationary, but power, released by internal sources, is equal to heat flux from the blank external surface due to convective and radiant heat exchange with ambient medium.

For powdered layer predetermined temperature maintenance at sintering mode stage it is required to determine the temperature difference through blank thickness of the for one hundred-day of the define the warm-up swing on of the stocking up by solving the thermal conductivity stationary problem for quill (hollow) cylinder with internal heat source. Herewith, since in practice thickness of the cylinder wall is much less then its diameter and the temperature difference is comparatively small (less then 1 K), the thermal conductivity dependence upon the temperature can be treated as negligible.

2. Mathematical model development

On the grounds of mentioned above considerations the mathematical problem is formulated according to following expressions:

\[
\frac{\partial T(r, \tau)}{\partial \tau} = a \left( \frac{\partial^2 T(r, \tau)}{\partial r^2} + \frac{1}{r} \frac{\partial T(r, \tau)}{\partial r} \right) \quad (\tau > 0; r > \eta; \eta = f(\tau));
\]

\[
T_{\eta}(r, \tau) = T_0 = T_{w} = \text{const} ;
\]

\[
T(\eta, \tau) = T_w = \text{const} ;
\]

\[
T(R, \tau) = T_w - b\tau ;
\]

\[
\lambda_1 \frac{\partial T(\eta, \tau)}{\partial r} = \rho \gamma_2 \frac{d\eta}{d\tau},
\]
Here:

- $T_1$ – temperature of the liquid phase (melt), K;
- $T_2$ – temperature of not melted powder layer, K;
- $\lambda_1$ – liquid phase thermal conductivity factor;
- $\lambda_2$ – powdered ambience thermal conductivity factor;
- $R$ – blank internal surface radius, m;
- $\rho$ – filler material density, kg/m$^3$;
- $b$ – rate of heating, K/s;
- $\gamma$ – filler material specific heat of melting, J/kg;
- $\eta$ – a distance from axis of the rotation to the melting boundary, m;
- $\tau$ – time, s.

In accordance with method of L.S. Leybenzon take distribution of temperature in melted zone under the law of temperature distribution in hollow cylinder in stationary state, i.e.

$$ T_1(r, \tau) = -\frac{b\tau \ln r + (T_m + b\tau)\ln \eta - T_m \ln R}{\ln \frac{R}{\eta}}. \quad (6) $$

The solution (6) satisfies the boundary conditions and differential equation (1). Substituting decision (6) into boundary condition (5), obtain

$$ -\lambda_1 \frac{b\tau}{\eta \ln \frac{R}{\eta}} = \rho \gamma_2 \frac{d\eta}{d\tau}. \quad (7) $$

After this equations integration we have expression:

$$ \eta^2 \ln \frac{R}{\eta} - \frac{1}{2} \left(R^2 - \eta^2\right) = -\frac{\lambda_1 b}{\rho \gamma_2} \tau^2. \quad (8) $$

The transcendental algebraic equation (8) defines relationship between the melting front coordinate $\eta$ and time $\tau$. Its decision with respect to $\eta$ can be enough simply realized by means of the applied mathematical program packages "Matlab", "Math-CAD", "Mathematics" and others.

On the base of the relationships obtained it is possible to define the powdered layer full melting time $\tau_m$. Under conditions $\tau = \tau_m$, $\eta = R_0$ it will be equal:

$$ \tau_m = \frac{\rho \gamma_2}{b \lambda_1} \left[\frac{1}{2} \left(R^2 - R_0^2\right) - R_0^2 \ln \frac{R}{R_0}\right]. \quad (9) $$

Thereby, as a result of analysis of the technological scheme and features of powdered coating centrifugal induction surfacing, modified by nanostructure components, mathematical model of the phase transition front moving in surfacing material is designed. This has allowed, in turn, to define the minimal time, providing melting the powdered layer during deposited coating formation.

**References**

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