Plasma-jet hard-facing modeling

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Abstract. The problem of automating the process of parts restoration by means of plasma welding in the environment of ANSYS.

1. Introduction

In order to restore and / or strengthen powder plasma surfacing is applied in mechanical engineering. Advantages of this technology are such as high performance, quality of weld metal, minimal loss of filler material, the possibility of facing relatively thin layers. [1, 6]

The problem is its widespread introduction comprises the difficulty of using traditional design methods, because the solution of such problems requires a large number of field experiments. This is due to large material costs and time-consuming processes when preparing the process of parts restoration. A particularly large number of samples is required in assessing the stability of the welding parameters to random deviations and determining tolerances. Implementation tasks for CAE modeling environment will automate the process of parameters optimization on the stage of technological preparation. [3]

2. Mathematical model r construction

The model considers the propagation of energy along the axis x, wherein the beam axis coincides with the x axis of the cylindrical coordinate system x, R (see fig.1). The surface of the metal substrate is normal to the x-axis at \( x = x_3 \). On the surface \( x_2 \) separating the condensed phase and running over a two-phase medium (fig.1) it follows the law of energy flow conservation, taking into account the energy absorption of the radiation surface, transferring heat energy particle surface, the heat transfer surface by convective heat and radiative cooling and heat sink deeper.

The equation of motion is based on the implementation of the law of mass surfaced particles conservation. At the same time account evaporation and condensation of steam are not taken into account at the condensed phase boundary \( x_2 \). On the boundary \( x_3 \) between weld material and the substrate material the equality of temperature and heat flow continuity are followed. At the boundary \( x_4 \) between the solid and molten materials it provides temperature conservation and the law of heat flow conservation based on energy consumption for melting, when \( x_4 \leftrightarrow x_3 \).
The system of equations, describing the process of dispersed metal particles plasma-jet hard-facing when moving in a stream of inert gas, on the fixed metal substrate contains the following basic equations:

\[ \frac{\partial q_n}{\partial x} + (\alpha_0 + \alpha_{ap} + \alpha_M) = 0, \]

where \( q_n = IU_0 \tilde{\eta}/v_0 \) - heat input, J/cm \( U \) - arc voltage, I- amperage, \( \tilde{\eta} \) - utilization of energy roof for penetration the deposited material; \( v_0 \) - deposition rate, cm/s,

\[ \alpha_0 = \pi N_0 \int_{0}^{r_0} (K_f + K_o) f_0(r_0) dr_0 \]

, attenuation coefficient of particle radiation, teplomasso halos and gas phase , when \( \alpha_{ap}, \alpha_a << \alpha_o \) and they are neglected \( K_p, K_r, K_o \) respectively, the factors of absorption efficiency, scattering and attenuation with the current particle radius \( r_0, f_0, f_0(r_0) \) - a function of the particle size distribution, \( \int_{0}^{r_0} f_0(r_0) dr_0 = 1 \),
The energy balance equation [5]

\[ \rho_0 V_0 c_0 \frac{\partial T_0}{\partial t} + (V x )V T_0 = \frac{1}{4} q_\infty K T_0 - j_m S_0, \]

where \( \rho_0, c_0 \) - density and specific heat of the particles material, \( T_0 \) - temperature of the particles, assumed to be uniform throughout its volume, \( t \) - time, \( V_0 = 4\pi r_0^3 / 3, j_m, j_e \) - respectively, density, mass and energy flows on the surface of the particle because of its heat and mass transfer from the gas, \( Vx \) - velocity of the particle along the axis,

The two-dimensional heat equation of the gaseous medium [4]

\[ \rho_c c_e \left( \frac{\partial T_c}{\partial t} + (U V) T_c \right) = \frac{\partial}{\partial x} \left( k_c \frac{\partial T_c}{\partial x} \right) + \frac{1}{R} \left( k_c R \frac{\partial T_c}{\partial R} \right) + q_T, \]

\( T_c \) - ambient temperature, \( q_T = 4\pi N_0 \int_0^\infty \left( j_m + j_e \varepsilon (T - T_e) \right) r_0^2 f_0 (r_0) dr_0 \)

- power density of heat due to heat conduction from the particles of \( J_T \) and heating with superheated steam, \( c_c, c_e, c_2 \) - accordingly, the heat capacity of the gas-vapor and gas, \( T \) - temperature of the medium directly from the surface of the particle, \( U \) - gas stream velocity, \( j_e = j_{Tm} + j_f + j_m (c_1 (T - T_e) + L_H), L_v \) - latent heat of vaporization of the material particles, \( j_{Tm} = c_2 \sigma (T_0^4 - T_e^4) \) - energy flux density of rejection heat radiation from the particle, where \( \varepsilon \) - the emissivity of the particle surface, \( \sigma \) - Stefan-Boltzmann constant, \( k_e \) - thermal conductivity of the medium,

The equation of state of the gas medium -

\[ p_c = R_c, \rho_c T_c = \rho_0 \]

\( \rho_0, \rho_1, \rho_2, \rho_3 \) - in accordance with it, the density of the gas-vapor medium, particles gas and inert gas, \( p_c \) — pressure, \( R \) - gas constant, \( r_0, r_2, f, T_r, \rho_0 \) - the initial values of the relevant parameters

The heat equation for the condensed phase of the deposited material and the substrate material

\[ \rho_1 c_1 \frac{\partial T_1}{\partial t} = \frac{\partial}{\partial x} \left( k_1 \frac{\partial T_1}{\partial x} \right) + \frac{1}{R} \left( k_1 R \frac{\partial T_1}{\partial R} \right), \]

\( \rho, c_1, k_1 \) — respectively, density, specific heat and thermal conductivity of the condensed phase at \( x \geq x_2 (x_3) \), taking into account the differences of these values to the deposited material and the raw material substrate - \( T_1 \) - temperature condensed phase

with the initial conditions

\[ T_0 (x, R, t = 0) = T_{in}, \quad T_1 (x, R, t = 0) = T_{in}, \quad T_f (x, R, t = 0) = T_{in}, \]
\[ r_0 (x, R, t = 0) = r_{in}, \quad \rho_1 (x, R, t = 0) = 0, \quad \rho_2 (x, R, t = 0) = \rho_{2in}, \]
\[ f_0 (x, R, t = 0) = f_{in} (r_{in}) \]

\( r_0, \rho_2, f_{in}, T_{in}, \rho_{2in} \) - the initial values of the relevant parameters

and boundary conditions

\[ T_0 (x = x_1, R, t) = T_c (x = x_1, R, t = 0) = T_f (x = x_{max}, R, t) = T_{in} \]
\[ k_c \frac{\partial T_c}{\partial R} \big|_{R=0} = 0 \]

\[ k_f \frac{\partial T_f}{\partial R} \big|_{R=0} = 0 \]

\[ \rho_c D_c \frac{\partial (\rho_1 / \rho_2)}{\partial R} \big|_{R=0} = 0 \]

\[ q_n(x = x_i, R \leq R_{max}, t) = 0 \]

\[ T(x < x_2, R = R_{max}, t) = T_{\rho} \quad (x = x_{max}, R, t) = t_{fr}, \]

where radius \( R_{max} \) and length \( x_{max} \) for the calculated volume are selected so that unperturbed initial parameter values remain at the boundaries in the time interval under consideration, \( \rho_C = \rho_1 + \rho_2, \rho_1, \rho_2 - \) respectively, gas-steam density, particulate material steam and inert gas, \( k_c, D_c - \) thermal conductivity of the medium, and medium vapor diffusion, \( T_C - \) ambient temperature

\[ \rho_j (x, R = R_{max}, t) = 0 \]

\[ \left[ A_{nl} I + N_0 \rho_0 V_x \right] 0 \int_0^\infty c_i(T_0 - T_{Hi}) + L_{al} \left\{ 4 \pi r_0^3 f_0(r_0) dr_0 - \right. \]

\[ + \left. \alpha_T (T_{\rho} - T_{Hi}) - \varepsilon \sigma (T_{\rho} - T_{\rho}) \right|_{T_{i+0}} = -k_{Hi} \frac{\partial T_{Hi}}{\partial x} \big|_{T_{i+0}} - \]

\[ -k_{Hi} \frac{\partial T_{Hi}}{\partial x} \big|_{T_{i+0}} - k_{Hi} \frac{\partial T_{Hi}}{\partial x} \big|_{T_{i+0}} - \]

\[ L_{Hi} \rho_{Hi} \frac{dx_i}{dt}, \]

where \( An - \) absorbance of the condensed phase surface; \( Vx - \) velocity of the particle along the \( x \) axis, \( \rho_0, c_0 - \) density and specific heat of the material particles, \( Tn - \) condensed phase temperature, \( L_{al} - \) melting heat, \( \alpha_T - \) the coefficient of convective heat transfer, \( \rho, c_n, \kappa_n - \) respectively, density, specific heat and thermal conductivity of the condensed phase at \( x \geq x^2 \) (x3), taking into account the differences of these values differences for deposited material and initial support material

\[ T_{Hi} \big|_{T_{i+0}} = T_{Hi} \big|_{T_{i+0}}, T_{Hi} \big|_{T_{i+0}} = T_{Hi} \big|_{T_{i+0}} - T_{\rho}, \]

\[ 0 \leq t < t_{fr}, t_{fr} = x_2 + x_3, t \geq t_{fr}, t_{fr} = x_2(t) = x_3 - \frac{w_0 V_x(t-t_{fr})}{\rho_0}, \]

\[ w_0 = \frac{4 \pi N_0 \rho_0}{3} \int_0^\infty r_0^3 f_0(r_0) dr_0 - \text{particulate material bulk, contained in a medium volume unit, } t_{Hi} \]

- time of beginning deposition of powder initial time deposition onto the substrate

The melt surface shape (\( r - \) meniscus radius) can be determined from the equations of equilibrium pressures:

\[ p_\sigma + p_{vac} + p_g + p_{an} = 0 \quad (8) \]

\( p_\sigma - \) capillary pressure, which depends on the melt surface curvature \( p_\sigma = (2 \sigma)/r, \sigma - \) interfacial tension, \( p_{vac} - \) the pressure of the powder particles, depending on the speed and flow, \( p_g - \) hydrostatic pressure \( p_{an} - \) internal pressure, which is determined by appropriate amounts of deposited metal and powder entering the molten bath.

2.1. Border conditions
Plasma energy values $q_0$ are approved for heating and melting of the powder particles and the surface layer of the substrate, but without evaporation. As metal evaporation intensively occurs at temperature $T \approx T_{\text{КИП}}$, where $T_{\text{КИП}}$ is a metal boiling point at atmospheric pressure, then at a considerable range of temperatures $T_{\text{пл}} \approx T < T_{\text{кип}}$ modes without evaporating particles and the substrate can always be realized. In this case $\overline{T} = 0$ that means particles and the surface of the substrate only exchange heat with the environment.

The motion of particles in the gas stream is not considered as the particle velocity $V_x$ is taken to be the gas velocity $U$.

Equations (1), (2), (3) and (5) can be regarded as one-dimensional along the coordinate $x$ as values gradients along $x$ are much greater than the corresponding gradients along $R$ and growth examination of the deposited layer along the $x$ flow axis is of the greatest practical interest.

### 3. Modeling tasks decision

С точки зрения проектирования технологического процесса плазменной наплавки обычно решаются следующие физико-математические задачи: In terms of plasma deposition design process the following physics-mathematical problems are usually resolved:

- the ratio plasma energy parameters, gas flow and sprayed powder rate, deposition rate
- plasma distribution in gaseous atmosphere (the ratio of temperature and particle size)
- the motion trajectory of the powder particles formation
- plasma thermal effect on a work piece (warming depth)
- powder and parts interaction (mixing)
- surface shape of the melt formation

Thus, model (1) - (8) describes the phenomena discussed in various physical disciplines. This shows that the development and debugging of software for design automation is a hard-working and long-length task. Development of computer design methods has led to the creation of interconnected systems CAD for designing technologies and tests.

Currently, there are a large number of Russian and foreign aided CADs (Computer-Aided Design) systems. They are usually used in conjunction with engineering calculations automation and analysis systems (CAE), which allow to carry out the tasks of a process modeling in different combined environments. The most common CAE-systems include ANSYS, LS-DYNA, Nastran, Abaqus, T-FLEX CAE, Deform, QForm and so on. It should be noted that CAE systems are divided into highly specialized (e.g. Deform and Qform) and a wide range of applications motivated, such as ANSYS (ANSYS, Inc.), Nastran (MSC.Software Corporation), Abaqus (Abaqus, Inc.). The most popular software packages, focused on a wide range of tasks are products of MSC.Software Corporation (Marc, Nastran, Patran), ANSYS, Inc. (ANSYS, LS-DYNA, and so on).

A distinctive feature of ANSYS software is the ability to take mono and multidisciplinary calculations. In addition, the problem range of this package is much wider than with its counterparts. Therefore, despite the relatively high cost, the preference for the objectives of the study of plasma-powder surfacing has been given to ANSYS.

However, ANSYS, as well as the above-listed CAE system cannot satisfactorily issue and calculate the parameters of welding process with the given accuracy. Settlements in CAE systems are manufactured by highly simplified patterns and the needs of engineers are sometimes neglected because of their diversity. This has led CAE developers to create sophisticated subsystems setting calculation formulas and software environment for interdisciplinary association of calculations.

Therefore, to adjust the analyzing system you need to create an algorithm for determining the optimal conditions for quality powder surfacing parts of engineering production. Then, develop a methodology to assess the stability of the surfacing, the probability of obtaining the desired quality, and to develop a method for determining the tolerances for the process parameters.

A feature of the solution is a representation of a physical space as consisting of two phases, with the free surface - metal and gas. This makes it possible to take into account the effects of surface tension, to simulate the adhesion. It is based on the solution of conventional and radiation heat transfer
problems. Multicomponent metal phases are considered (solid-liquid) as well as gas flows effects (argon gas and metal vapor) and diffusion and melting are emitted.

Electric arc electromagnetism problem solution allows to control the temperature, taking into account gas properties in the local thermodynamic equilibrium, and to describe the thermal and mechanical collision [2].

![Figure 2. The result of plasma jet with deposited particles simulation](image)

The joint solution of electromagnetism and melting problems accounting surface tension makes it possible to obtain the geometry of a weld pool, to analyze structural changes in a detail surface and molten droplets spraying.

![Figure 3. Model Weld pool model](image)

Flow rate modelling allows to show gas flow rate in full detail, as well as the heat transfer, diffusion, mixing the shielding gas and molten filler powder, to take into account the effect of the electric arc on the transport of the material point and the spread of smoke.
References

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