International Journal of Heat and Mass Transfer 95 (2016) 902–912

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Numerical simulation of transport phenomena, formation the bead and thermal behavior in application to industrial DMD technology

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ARTICLE INFO

Article history:
Received 19 August 2015
Received in revised form 14 December 2015
Accepted 21 December 2015
Available online 12 January 2016

Keywords:
Coaxial laser cladding
Heat-affected zone
Melt pool
Bead formation
Gas-disperse jet flow
Mathematical simulation
Experimental investigation

ABSTRACT

The paper presents the results of theoretical and experimental investigations of the laser cladding with TRUMPF DMD 505, which enables to implement the industrial-level coating technology. The physical–mathematical model is proposed to describe and numerically simulate the processes; the model combine powder transportation and heating and formation of bed-like cladding in the conjugate statement. Special attention is paid on the simulation of gas dynamics of a triple coaxial nozzle, peculiarities of gas-disperse jet formation and optimal powder supply into the melt pool. Thermal processes in the bead and substrate are considered on the base of the conductive heat transfer with movable boundaries, phase changes, and condition of kinematic consistency of clad surface points (melt thermal convection is beyond our consideration). The influence of the governing cladding parameters on the linear sizes of individual beds from Stellite 6 alloy on a steel substrate is studied. Comparison of calculated bead profiles and full-scale experiment data showed good qualitative and quantitative agreement. The proposed model is self-consistent and can be applied to optimize the regime parameters of the laser cladding of materials.

1. Introduction

The laser assisted direct metal deposition belongs to the category of laser cladding methods. It is an effective method of production of various coatings including functional-gradient, multi-layer ones, plus it is a flexible way to produce the articles of complicated geometry [1]. The coatings feature high strength, low porosity, and thickness changeability within a wide range, from tenths millimeter to several centimeters. Metals and alloys of various physical and chemical properties are used as clad materials, so the modes of deposition require special analysis.

The laser cladding models for this task have been initiated several decades ago [2,3]. These models, however, are highly restricted by the fact that the processes are considered in two-dimensional stationary or quasi-stationary statement. Moreover, under study were only those processes which occurred in the bead and substrate, whereas the powder particle transportation, focusing, and heating during its supply into the cladding area were not simulated. There are analytical models mainly purposed for the prediction of the bead sizes and derivation of simple formulas for them at different cladding modes [4,5]. Detailed analysis of the process physics is however problematic in such approaches.

In a number of subsequent works [6–18], the processes occurring during the laser cladding are considered in 3D statement; as a rule, they come under two groups – the works devoted to the powder transportation toward the substrate together with the powder heating [6–8], or to the bead cladding [9–16]. In the latter case, attention is paid on the problems of mixing of the clad layer and base, definition of the bead surface shape, velocity fields in the melt pool, and temperature. Simplified models without gas-dynamic calculations are often used to evaluate the level of falling particles heating in order to determine the energy share contributed by them (for example, [15,16]). On the one hand, this approach permits performing detailed investigations of the processes in the bead; on the other hand, inaccuracies may appear as a result of lack of physical agreed quantitative information on the distributions of the mass flow of the particles falling onto the substrate and their temperature.

In our opinion, the laser cladding process should be considered in an integrated manner, grouping together simulation of the powder transportation, heating, and cladding in the form of the bead on the substrate. It is reasonable to do it consequently: to determine the spatial distribution of the particles in the gas using the calculation of the gas-dynamic flows in relation to a certain nozzle geometry, then to calculate the particle heating in the laser beam, and then to use the resulting dependencies to calculate the clad bead.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.12.046
0017-9310/

Note that the authors of [17,18] demonstrate understanding of the necessity to simulate the laser cladding in such a way. However they do not present any particle mass-flow nor temperature distributions over the substrate and bead surface, and hence the importance of the calculations of the powder particle gas dynamics and heating is not shown.

The software developed by the authors of this paper to simulate the coaxial laser cladding [19–21] in used here; interrelated models of gas flow calculation and powder transportation are combined on the base of joint solution of the tasks in the conjugate 3D statement [19,20], as well as the problems of coating growth and variation of its thermal state during the laser beaming [21].

In [19] presents the results of the study of powder particles transportation (powder Metco 42C) toward a flat substrate; the results were obtained from the numerical simulation and experimental visualization made by a CCD camera. To simulate the flows of gas of a triple coaxial nozzle, Navier–Stokes equations were applied for an axisymmetric flow. Powder particles transport are calculated from a discrete-trajectory model with due regard to particle collision with solid walls of the transport nozzle. The effect of the reciprocal of the particle form factor on the particle velocity and flight trajectory was studied numerically, as well as the temperature variation during heating and melting during the passage of the laser beam light field. Similar investigations were carried out in [20] for the alloy TiAl6V4, plus the measurements of brightness temperature of the melt pool in the clad area. In [21], the authors focus their attention on the simulation of the clad surface profile and heat and mass-exchange processes in the beam and substrate, whereas the powder particle flow was assigned analytically. Calculation data of [21] and results of full-scale experiment have not been compared.

The present paper contains an attempt to combine previously developed models of [19] and [21] in the conjugated statement, and the analysis of the calculation result compared with the specially arranged experimental investigations in TRUMPF DMD 505.

2. Physical model and basic assumptions and restrictions

Comprehensive investigation of various interactions such as the laser beam and powder jet, the laser beam and substrate surface, the powder jet and melt pool, should be done for the correct description of the laser cladding process and understanding of the mechanisms accompanied by fast physical phenomena i.e. heat and mass exchange, phase transformations, etc.

The applied laser energy is consumed for the heating and melting of powder particles and base, the melt pool and heat-affected zone are forming in the base material. The cladding process includes the gas-flow powder transportation into the melt pool which is supported by the laser beam moving with the constant speed V_c over the base surface. The powder jet is focused into the melt region on the substrate wherein the laser radiation is supplied. The cladding process itself is provided by the deposition mechanism which in turn results from the powder mass flux into the melt pool or from liquid particles adhere on the substrate surface leading to the bead formation.

Complicated analysis of the whole set of phenomena taking place during the laser cladding presumes introduction of a number of simplifying assumptions in order to preserve the influence of the governing process factors. Some evaluations are considered below. Let us have the average size of particles 70 μm ($\tilde{r}_p = 35 \cdot 10^{-6}$ m), and average velocity of the powder particle $\tilde{V}_p = 10$ m/s. The amount of the particles falling on the substrate surface can be estimated as follows: $\tilde{m}_p = \left(\frac{F_p}{4/3\pi r_p^3 \rho_p}\right)(\pi\omega_{ls}^2)^{-1} \approx 1.2 \cdot 10^{10}\ 1/(\mathrm{m}^2 \cdot \mathrm{s})$ (where $F_p = 15$ g/min is the powder flow rate, $\rho_p = 8000$ kg/m^3 is the material density, $\omega_{ls} = 2$ mm is the beam spot radius on the substrate). Then the average amount of the particles in the volume unit between the nozzle and substrate is $\tilde{n}_p = \tilde{m}_p/\tilde{V}_p = 1.2 \cdot 10^9\ 1/\mathrm{m}^3 \approx 1.0\ 1/\mathrm{mm}^3$, whereas the average distance between the particles is $L_p = 1/\sqrt[3]{\tilde{n}_p} \approx 1.0$ mm.

Major assumptions are the following:

1. The internal (in the nozzle channels) and external gas jet flows between the nozzle and substrate are described in the Cartesian system of coordinates with full Navier–Stokes equations.
2. Powder transportation is provided by the carrier gas flow through the coaxial nozzle channel, the particle motion in the channel results from the aerodynamic force action; particle collision is ignored since the distance between particles in the gas flow is much bigger than the particle diameter $\frac{L_p}{2\tilde{r}_p} >> 1$.
3. The back reaction of the powder particles on the gas is ignored. Since the particle acceleration takes place inside the nozzle, it is suggested that the particle deceleration of the gas is completely balanced by occurring excessive pressure in the transport channel of the nozzle.
4. The effects of attenuation laser radiation are ignored due to the absorption and dissipation by the powder particles moving in a gas-disperse flow. The evaluation follows from the Mie theory [22,23]. The extinction efficiency factor $K_{att}(x, N_\lambda)$ depends on two parameters: size parameter $x = \frac{2\pi}{\lambda} r_p$, where λ is the radiation wave length, and complex refraction coefficient N_λ. For conductive particles in the IR area, at big x and N_λ, the extinction efficiency factor $K_{att}(x, N_\lambda)$ roughly equals to 2 [22]. Note that in our case $x \sim 12$, and N_λ is greater or much greater than unity. Then, taking only the single dissipation, the attenuation coefficient is evaluated as: $\alpha \approx \tilde{n}_p K_{att} \pi r_p^2 = 3.8465$ 1/m ≈ 0.004 1/mm. Within the characteristic distances of about $\sim$10 mm, the dissipated and absorbed radiation is about 4% from the falling radiation. The spectrum of the thermal radiation of the particles and substrate lies mostly in the IR area ($300 < T < 2500$ K), i.e. the extinction efficiency factor $K_{att} \approx 2$, similarly as for the laser radiation [22]. Then the share of the thermal radiation refracted and absorbed by the particles is of the same order, 4%.
5. Thermal processes in the bead and substrate are analyzed on the base of the heat equation with movable boundaries, phase changes and condition of kinematic consistency of clad surface points.
6. The liquid metal motion in the melt pool is not considered. In practice, the temperature regimes promoting active mixing of the melt pool occurring due to the laser-induced thermocapillary convection, is avoided when possible. The regimes with the minimal substrate melting are the most technological, since the intensive mixing of the deposited and basic materials is a negative factor.
7. The task of powder particles wetting when they come into the melt is beyond consideration. It is assumed that the wetting time is much shorter than the characteristic time of the bead surface growth (about 0.1–0.5 s).
8. Thermal volume expansion of the particle and substrate materials is ignored, despite the fact that the densities of the solid and liquid materials may seriously differ.

From the viewpoint of simulation, the coaxial laser cladding is the task which can conventionally be divided by two sub-tasks to be solved consistently. The first one deal with the powder particles transportation and heating in the laser radiation field, the second considers the formation of the clad bed, heat and mass transfer