Shape Optimization of Deposited Layer Produced by Combined Cladding Process

V. Kotlan, *Member, IEEE*, D. Panek, *Member, IEEE*, R. Hamar, and I. Dolezel, *Member, IEEE*

Faculty of Electrical Engineering, University of West Bohemia, 306 14 Plzen, Czech Republic, vkotlan@kte.zcu.cz

***Abstract*---A methodology of optimizing the process of combined laser cladding with induction preheating is proposed and verified. The resultant shape of deposited layer consisting of a series of parallel tracks should be as uniform as possible and resistant with respect to cracks of any origin. The main aim is to develop a technique (based on a simple experiment) of calibrating geometrically more complex 3D arrangements. The task consists of solution of a strongly nonlinear coupled electromagnetic-thermal problem (forward part) and multi-parametric optimization (backward part). Solution of the forward part uses a specific *h*-adaptive technique developed by authors that allows working with continuously varying geometry of the system due to added powder material.**

***Index Terms*—Laser cladding, induction preheating, electromagnetic field, temperature field, numerical solution, *h*-adaptive technique, numerical analysis.**

I. Introduction

LASER CLADDING belongs to the best techniques of depositing material on a substrate [1] with the aim to improve the surface properties (hardness, corrosion and/or wear resistance) or renovation of the damaged areas. Laser beam heats metal powder added by a nozzle and the powder melts together with the surface layer of the substrate, thus producing a melt pool. After its solidification, a track is created, containing mixture of the substrate and added powder metals. A series of parallel tracks then forms the deposited layer. The basic scheme is shown in Fig. 1. Here, the substrate is supposed to move at a velocity $\boldsymbol{v}$ while the laser head with the nozzle are unmovable.

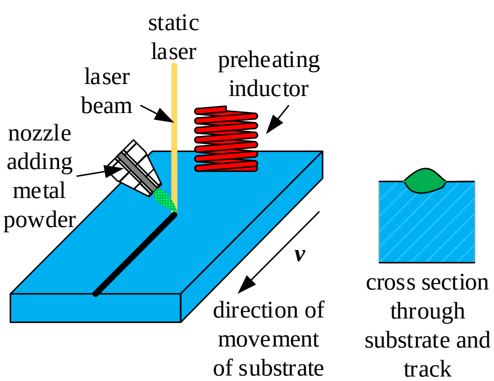

Fig. 1. Process of combined cladding (using laser heating and induction preheating)

The process of laser heating is characterized by extremely high temperature gradients commonly exceeding 1000 °C/s. This leads, however, to subsequent mechanical stresses in the processed material whose presence is highly undesirable [2]. One of suitable methods for their suppressing is induction preheating of the substrate, indicated in the above figure (but its induction postheating is also possible).

II. Formulation of Technical Problem

The resultant shape of the deposited layer consisting of many parallel tracks depends on more parameters. We can mainly mention the distance between two neighbor tracks, velocity $\boldsymbol{v}$ of motion of the substrate, power delivered by laser beam, powder injection rate. The transverse cut through the substrate with several parallel tracks may look like those in Fig. 2. Its left part shows the case characterized by higher velocity $\boldsymbol{v}$ leading to production of separate tracks (unacceptable result), middle part shows the acceptable shape of the deposited layer, while the right part depicts higher (and also unacceptable) interferences of the tracks caused by either very low velocity $\boldsymbol{v}$ of the substrate or excessive powder injection rate.

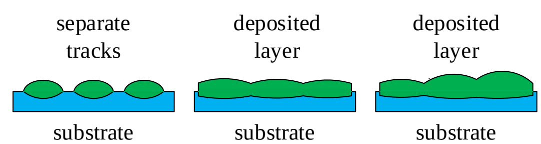

Fig. 2. Possible results of process of cladding (transverse cross section)

It is practically impossible to reach a perfectly flat surface. Thus, the aim is to reach a slightly wavy surface with non-uniformities as low as possible in order to avoid any additional massive surfacing. For prediction of mechanical stresses in material it is necessary to know the resultant deformation of the surface. But any change of the above parameters affects coefficients for prescription of changes in particular directions. That is why it is a must to calibrate them using a known solution provided by an experiment. The process of optimization allows full recalculating these coefficients.

According to Fig. 3, two objective functions can be considered and minimized

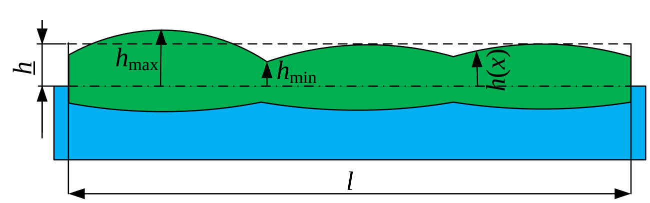

Fig. 3. Definition of objective functions

$$Q_1 = \int_0^l \left(h(x) - \underline{h}\right)^2 \mathrm{d}x, \quad Q_2 = \max\left\{\left|h - h_{\min}\right|, \left|h - h_{\max}\right|\right\},$$

where $\underline{h} = \int_0^l h(x)\,\mathrm{d}x / l$ is the average value of $h(x)$.

The result of the methodology is a procedure based on properties of simple experimental samples that in a short time allows calibrating the model for preset input parameters. This procedure will be used for prediction of behavior of cladded layers in more complicated 3D arrangements.

III. Mathematical Model

The problem represents a strongly nonlinear and non-stationary electro-thermal task, characterized by continuous addition of powder material and changing geometry that is unknown in advance.

3D electromagnetic field generated by the inductor takes into account eddy currents induced by time variations of its magnetic field [3]. Currents induced by movement of the substrate are neglected, as its velocity is very low. Eddy currents produce in material the Joule losses

While the contribution to the temperature field from the Joule losses is solved by the heat transfer equation supplemented with correct boundary conditions respecting convection and radiation [4], the contribution due to power of the laser beam is determined using a similar equation, but without internal sources. The delivered power of the laser beam is implemented in the boundary condition.

The solution requires a specific algorithm that allows working with added powder material. The authors developed two algorithms of this kind [5].

The first algorithm is based on in space and time localized adaptive refinement of the discretization mesh at the exposed spot that is driven by the time evolution of the local distribution of temperature. The second one is based on the technique of changing the boundary.

The complete model is solved by code COMSOL Multiphysics 5.2 supplemented with a number of own scripts and procedures.

IV. Illustrative Example

The methodology is illustrated with an example of cladding several tracks on a steel substrate (a plate of dimensions $1000 \times 60 \times 20$ mm). The steel is of make S355 and its physical properties are known. The powder is of make Metco 41C prepared from stainless steel alloy.

The inductor is wound by one hollow massive copper turn cooled by water, placed in a composite shell made of Fluxtrol. It carries current of amplitude 2260 A whose frequency is 12 kHz. The power of the laser beam of diameter 3 mm (on the surface of substrate) is 800 W and power density is supposed to obey the Gaussian distribution. The distance between the laser and inductor $b = 40$ mm. Velocity of motion of the substrate is 2, 4 and 8 mm/s and the height of the inductor above it is 2 mm. The distance between the centers of individual tracks is 2 or 5 mm.

Fig. 4 shows the cross section through the substrate with four tracks for the distance between tracks 2 mm and velocity $v = 4$ mm/s, while Fig. 5 shows an analogous cross section again for four tracks and the same velocity, but now the distance between tracks is 5 mm.

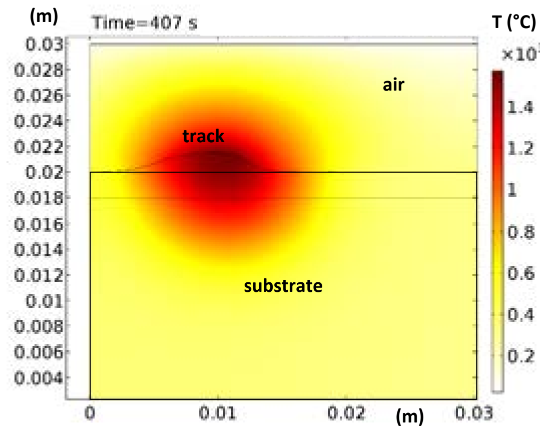

Fig. 4. Distribution of temperature in material and surrounding medium for $v = 4$ mm/s, distance of tracks 2 mm and time $t = 407$ s

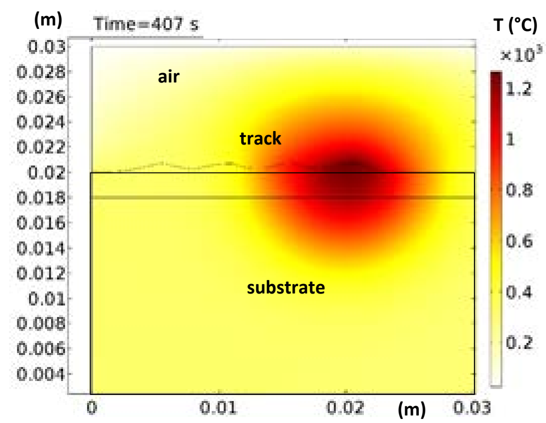

Fig. 5. Distribution of temperature in material and surrounding medium for $v = 4$ mm/s, distance of tracks 5 mm and time $t = 407$ s

After evaluation of many simulations of this kind, it is evident that the distance between tracks and velocity of motion are the parameters most influencing the flatness of the surface. In the full version of the paper, for a given power of the laser and injection rate of the powder just these two parameters will be used for optimization of the surface.

Acknowledgment

This research has been supported by the Ministry of Education, Youth and Sports of the Czech Republic under the RICE New Technologies and Concepts for Smart Industrial Systems, project LO1607.

References

[1] J.T. Hofman, D.F. de Lange, B. Pathiraj, and J. Meijer, "FEM modeling and experimental verification for dilution control in laser cladding," *J. Material Processing Technology*, Vol. 211, No. 2, pp. 187–196, 2011.

[2] F. Brückner, S. Nowotny, Ch. Leyens, "Innovations in laser cladding and direct metal deposition," *Proc. SPIE 8239, High Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications*, January 21, 2012, California, USA.

[3] M. Kuczmann and A. Iványi, "The finite element method in magnetics," *Akadémiai Kiadó*, Budapest, 2008.

[4] J. P. Holman, "Heat transfer," McGraw-Hill, New York, 2002.

[5] V. Kotlan, I. Dolezel, R. Hamar, and D. Panek, "*Modeling of selected 3D electroheat coupled problems with time varying geometries," Proc. 17th Biennial Conference on Electromagnetic Field Computation CEFC 2016*, Nov. 13—16, Miami, FL, USA, CD-ROM.