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Novel algorithm for modeling combined laser and induction welding respecting keyhole effect

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A B S T R A C T

Numerical model of combined laser and induction welding is presented and solved. From the physical viewpoint, the process represents a coupled problem of nonlinear and non-stationary interaction of the magnetic and temperature fields respecting the phase change and evaporation of heated molten metal (keyhole effect). A specific algorithm was developed for manipulation with the space and time variation of interface between solid and molten metal. Selected results are compared with the realized experiment.

1. Introduction

Laser processing of metals belongs nowadays to very prospective technologies applied in many industrial branches. We can mention, for example, welding or cladding [1,2]. But despite of a number of advantages, this technology suffers from one drawback—very fast heating of material at the place of irradiation by the laser beam. Very high gradients of temperature produce in material mechanical strains and stresses of thermal origin that may lead to cracks, bending and other damages. These unfavorable consequences can be, however, reduced or even suppressed by appropriate measures like preheating or postheating of the material by magnetic induction. In their previous papers [3–5] the authors investigated phenomena accompanying this technology, that follow from the nonlinear and nonstationary interaction of magnetic field and temperature fields produced by induction and laser beam. But welding, no matter whether with or without welding rods is a more complicated problem. Regardless the welded parts are preheated or not, the laser beam burns out in the material a hole containing molten metal, whose boundary changes in time (keyhole effect) [6,7]. The molten material may also vaporizes, which leads to creation of a small plasma cloud above the hole that (due to absorption and reflections) reduces the power delivered by the laser head to the material. Another approach can be found in [8] where the authors study welding of immiscible metals using a phase field method.

The authors offer a methodology how to cope with the phenomenon of the hole that changes its shape in time with the aim to map the process of welding with a higher reliability. Some results are compared with experimental data.

2. Formulation of the problem

Two massive steel plates moving at a low velocity $\boldsymbol{v}$ (of several mm/s) are welded one to another by laser beam delivered by an unmovable laser head. The arrangement is depicted in Fig. 1, upper part. The plate may (or may not) be preheated or postheated by induction. The transverse cut through both plates is shown in Fig. 1, bottom part.

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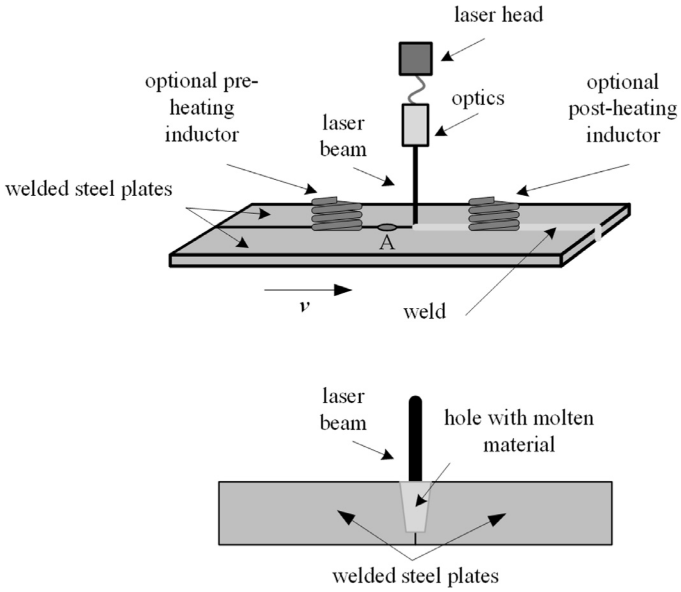

Fig. 1. Arrangement of the welding process—up, transverse view at situation at laser beam trace—bottom.

The task is to map the time evolution of magnetic and temperature fields in the welded material (mainly in the neighborhood of weld) together with the keyhole effect.

3. Continuous mathematical model

The continuous mathematical model of the process generally includes the description of the magnetic field, the temperature field and the shape of the hole containing the molten metal. The problem has to be treated as a hard-coupled one because of intensive changes of various material parameters along with temperature.

3.1. Magnetic field

The field must be solved only in the case when preheating and/or postheating inductors are present in the system. The inductors are then supposed to carry time varying currents of density $\boldsymbol{J}_{\mathrm{ext}}$. The magnetic field generated by the inductors can be now described by magnetic vector potential $\boldsymbol{A}$ that obeys the equation [9,10]

$$\mathrm{curl}\,\left(\frac{1}{\mu}\,\mathrm{curl}\,\boldsymbol{A}\right)+\gamma\left(\frac{\partial\boldsymbol{A}}{\partial t}-\boldsymbol{v}\times\mathrm{curl}\,\boldsymbol{A}\right)=\boldsymbol{J}_{\mathrm{ext}}\,, \tag{1}$$

where μ denotes the permeability that depends (in ferromagnetic parts) on applied magnetic field, γ is the electric conductivity and $\boldsymbol{v}$ represents the velocity of the plates. Although the equation does not seem to be too much complicated, due to nonlinearity and incommensurability of the time constants of the magnetic and temperature fields its numerical solution in 3D is still practically unfeasible.

Fortunately, two simplifications of (1) can be introduced without any substantial distortion of results. First, the magnetic permeability in ferromagnetic elements is assumed to be constant by parts. Its value in every cell of the discretization mesh is supposed to be constant and corresponds to the average value of local magnetic flux density. Based on results of such simplification for 2D, the error should not exceed about 5 % (the authors are not aware, that such an experiment would be performed also for a 3D arrangement). Moreover, for low velocities on the order of mm/s the term in (1) containing this velocity can be neglected with an error not exceeding 1 %. In this way, magnetic field in the system may be described by the phasor $\underline{\boldsymbol{A}}$ and the corresponding equation reads

$$\mathrm{curl}\,\left(\mathrm{curl}\,\underline{\boldsymbol{A}}\right)+\mathrm{j}\cdot\mu\omega\gamma\underline{\boldsymbol{A}}=\mu\underline{\boldsymbol{J}}_{\mathrm{ext}}\,, \tag{2}$$

where $\omega=2\pi f$ denotes the angular frequency.

The principal difference between the solution of (1) and (2) consists in the fact that (1) has to be solved in the time domain, while (2) in the frequency domain, which is much faster and does not require extremely high computational capacities.

The boundary condition along a sufficiently distant boundary are of the Dirichlet type ($\underline{\boldsymbol{A}}=\underline{\boldsymbol{0}}$). When the problem exhibits any space symmetry, also the Neumann condition may be prescribed along the corresponding interface.

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