Numerical simulation of laser welding of thin metallic plates taking into account convection in the welding pool*

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A new quasi-three-dimensional model of the laser welding of thin metal plates and a numerical algorithm of its implementation are proposed. Computations of thermophysical processes at a laser joining of titanium plates are carried out. It is shown that the new model adequately describes thermophysical and hydrodynamic processes occurring in the welding region.

Key words: mathematical modelling, numerical methods, Navier — Stokes equations, heat and mass transfer, laser welding of metals, Stefan problem.

INTRODUCTION

The process of laser welding is characterized by a variety of physical, chemical, and hydrodynamic processes in the welding zone, whose complete mathematical model to account for mutual influence of at least its basic components is still far from completion. If the laser power is above some critical one, then the metal boils in the welding zone. A vapor channel of microscopic size is formed. The gas of the ions of metal and different components and inclusions available in the melt escapes from the channel. The region of the interaction of laser beam with the metal is unstable. It is surrounded by a dense cloud of metal vapors and has a high temperature. These circumstances complicate significantly the measurements of the physical parameters of the process and the welding zone visualization. The inhomogeneities in the material of the product and the instability of the laser radiation absorption give rise to the disturbances in the liquid metal motion, which are enhanced at the vertical walls of the channel, grow and become commensurable with its transverse sizes. There is here also a hydrodynamic instability [1]. The arising pulsations of the velocity and pressure in the liquid metal propagate over the entire pool. Under the constant intensity of the laser radiation absorption and the welding velocity, small pulsations of the parameters of the flow of gas and

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liquid metal, however, occur near their certain mean values. In this case, the mean values of the process parameters in the welding zone and on the periphery may be assumed constant in some approximation.

In the earlier models of ray welding (electron-ray and laser welding), the liquid metal motion in the welding pool was not taken into account [2, 3]. The thermophysical model without using the equations of viscous fluid dynamics enables a satisfactory computation of some parameters of the welding process: the welding pool sizes, the regions with the two-phase state of the metal, the welded joint width and the prediction of the sizes of grains in the crystal structure of the solidified metal [4–6]. The modelling of processes in the pool based on the dynamics of a viscous heat-conducting liquid, however, shows that the melt motion in it depends on the physical parameters of the process and, in turn, affects the shape of the pool and, to some extent, its size [7, 8]. The known estimates of the flow velocity of the liquid metal, which arises because of the effect of the surface tension forces and friction of the metal vapors in the channel show that the flow in the pool for the welding regimes used in practice may be turbulent [9, 10].

In the present work, a three-dimensional quasi-steady mathematical model of the butt laser welding process of two metallic plates is proposed. The heat conduction equation with convective terms is used to describe the heat transfer and the Navier—Stokes equations are used to model the liquid metal motion in the welding pool. The model takes into account the presence of a vapor channel in the zone of the laser beam effect on the plates as well as the friction of metal vapors escaping from the channel on its surface.

As a result of the averaging of the equations of the three-dimensional model over one of the spatial variables (the \( y \) variable), a quasi-three-dimensional model has been derived. The term in the heat conduction equation, which describes the heat diffusion in the direction of the \( y \) axis, has been approximated in two ways: with regard for the mean half-width of the pool and by using the length scale in the heat wave [11, 12]. In the case when the value of the pool half-width is known due to some estimations or from experimental data, then it is more preferable to use the first approximation technique because it is more accurate. A new algorithm for numerical simulation of the laser welding process with regard for convection in the welding pool has been developed. It is based on the quasi-three-dimensional model and the variants of the collocations and the least squares method. The algorithm allows one to estimate the influence of the liquid metal convection on temperature distribution in the welding plates and the welding pool shape.

1. THREE-DIMENSIONAL MATHEMATICAL MODEL OF THE LASER WELDING PROCESS

A steady process of the butt laser welding of two metal plates is considered here. The plates have a rectangular shape and the same thickness. The laser beam axis in the process of welding lies in the plane of the junction of plates and is directed along a normal to their upper surface. We introduce a Cartesian coordinate system in the region under consideration, in which the laser beam is at rest, and the plates move at the welding velocity \( \mathbf{V}_w = (V_w, 0, 0) \). The \( z \) axis is directed downwards along the beam axis, the \( x \) axis is directed along the junction in the direction of the plate motion, and the \( y \) axis is directed perpendicularly to the junction. The coordinate origin lies on the beam axis at the upper boundaries of the plates (Fig. 1).

The surfaces of plates are blown by an inert gas to protect the liquid metal from oxidation processes. In view of the complexity and scarce knowledge of the thermo- and hydrodynamic processes in the welding zone we will carry out the investigation of the welding process under certain simplifying assumptions. Assuming the phase transition