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Multivortex convection of metal in molten pool with dispersed impurity induced by laser radiation

O.B. Kovalev, A.M. Gurin *

Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch of Russian Academy of Sciences, Institutskaya Str., 4/1, Novosibirsk 630090, Russia

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ABSTRACT

Results of the numerical solution of an adjoint problem of thermocapillary microconvection induced by laser radiation in a molten pool on a metal substrate are presented. Problems of modeling various processes of laser-induced surface modification of materials (laser-induced hardening, alloying and cladding) are discussed. Distributions of temperature, velocity, and streamlines in the liquid dimple are presented, which demonstrate specific features of existence of three-dimensional multivortex flows responsible for thermohydrodynamics of the melt, formation of the bottom relief of the liquid dimple, and mixing of refractory alloying disperse components. Alloying additives are inserted into the molten pool by means of gas-jet transportation through a coaxial nozzle or by preliminary (before laser beam passage) application of these additives onto the surface of the processed material. A physicomathematical model for calculating the convection of the fine-grain impurity is proposed, and the calculated dynamics of tungsten and titanium carbide particles in a molten pool on a steel substrate is described. Distributions of their number concentrations in the melted zone after crystallization are obtained.

1. Introduction

One of the methods of improving the performance of materials used in industry is the modification of the material surface. Laser-induced modification of metals (thermal hardening, alloying, and cladding) is used to increase their wear resistance, thermal resistance, hardness, corrosion resistance, etc. Thermal hardening through the liquid phase is performed with laser radiation used to heat the main metal surface up to the melting point. Laser processing is based on scanning the material surface by a laser beam.

Laser-induced alloying differs from conventional laser hardening by the fact that the hardness and other performance indicators are increased not only due to structural and phase transformations in the zone affected by the laser beam, but also by means of generating a new alloy with a different chemical composition, as compared with that of the original material. The alloying elements (titanium, niobium, tungsten, carbon, etc.) are included into the disperse admixture inserted into the molten pool. Addition of such an impurity changes the surface structure.

In contrast to alloying, the matrix material during laser-induced cladding can be located only in a thin layer between the matrix (substrate) and the directed layer, which serves as a binding medium. The clad layer differs appreciably from the matrix material. The thickness of the processed layer ranges from hundreds of nanometers to several millimeters.

These forms of laser-induced surface processing are very promising because of the increasing deficit of pure metals, such as W, Mo, NiCr, Co, and V. The processes of local alloying and cladding are realized with the use of both pulsed and continuous laser radiation, based on the principles of conventional laser-induced hardening. The technological features of the process depend on the method of supplying the alloying composition into the processing zone, the type of the alloying components, and the properties of the processed material.

Fig. 1(a–c) shows the schemes of laser modification of the surface that are used for cladding with additive buildup and reconstruction of parts (a), and also for hardening and alloying (b and c). Two methods of supplying the alloying elements to the zone affected by the laser beam are usually used [1–3]: application of the alloying composition in the powder form onto the processed surface by means of gas-jet transportation, Fig. 1(a) and coating of the surface by a special composition in the suspension form containing the alloying elements, Fig. 1(b), or electroplated.

The processes that occur in the surface layer of metals under the action of laser radiation have been studied for a rather long time [1–10]. Nevertheless, many questions of principal importance are still open. They include manifestations of thermocapillary microconvection and the associated mechanisms of the distribution of

* Corresponding author. Tel.: +7 960 7894636.
E-mail address: guralisk@mail.ru (A.M. Gurin).

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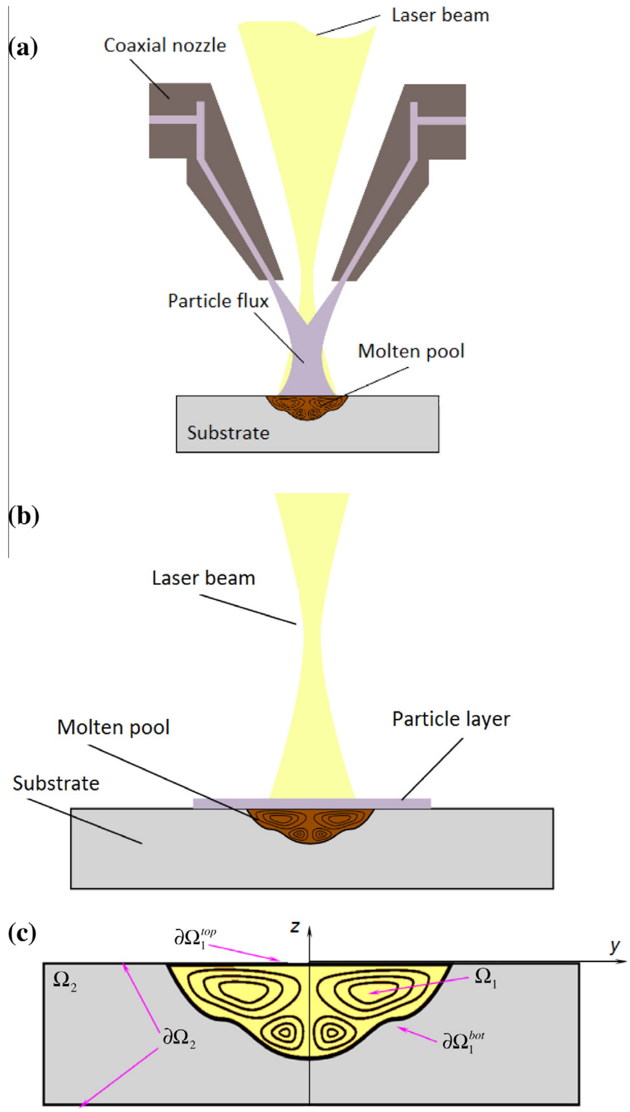

Fig. 1. Methods of laser-induced modification of the material surface: (a) laser-induced cladding; (b) laser-induced surface alloying; (c) zoomed-in molten pool together with the adjacent portion of the solid substrate during laser-induced thermal hardening.

the admixture of disperse components added to the melt during laser-induced modification of the material surface [7–10].

Interaction of laser radiation with metals on the interface enhances the role of surface effects. Particles of refractory metals, alloys, or ceramics, whose melting point is higher than that of the processed material, fall onto the melt surface, become wetted, and penetrate into the melt under the action of thermocapillary microflows. An important aspect difficult to predict is the dynamics of the liquid metal and powder particles ranging from one micrometer to several tens of micrometers and also the specific features of the distribution of the added impurity in the surface layer after cooling. These phenomena have been little addressed in the literature.

The development of additive laser technologies appreciably increased the interest in three-dimensional modeling of the processes of convective mixing of disperse components added to the molten pool.

Fig. 2 shows the frames of laser-induced cladding of a cylindrical surface of a certain part with the use of a coaxial nozzle. The experiments were performed in the ENISE DIPI Lab [11]. The power of radiation of the CO_2-laser is up to 5 kW, the scanning rate is 0.5 m/min, the molten pool diameter is 5 mm, the diameter of stainless steel particles is 45–125 μm, the distance between the nozzle and the substrate is 20 mm, and the flow rate of particles is 5–8 g/min. It should be noted that such a comparatively small flow rate of the powder ensures a moderate thickness of the clad layer (smaller than 1–2 mm). The surface of the molten pool has a circular shape (Fig. 2).

The complexity and variety of the processes proceeding at a high temperature in a local area affected by laser radiation does not allow full-scale experimental investigations and diagnostics. Methods of visualization and registration of vortex formation, mixing, and redistribution of added impurities are insufficiently developed. Available information is insufficient for understanding interrelated mechanisms inherent in laser processing of the material surface. For this reason, mathematical and numerical simulations become more and more important because they can supplement and partly replace physical experiments.

In this work, based on available concepts of modeling of thermocapillary convection [7–10], we propose a physicomathematical model of two-phase thermohydrodynamic flows in the melt of a steel substrate, which are induced by laser radiation. Particular attention is paid to the description of the behavior of refractory particles added to the molten pool.

2. Physicomathematical model and formulation of the problem

We consider radiation of a CO_2 laser with a wavelength of 10.6 μm and a power up to 1400 W, which is typical for laser-induced surface processing. The laser beam moves over the material surface and heats the latter to the melting temperature. The temperature gradient arising on the surface of the liquid metal generates thermocapillary forces. Under the action of these forces, vortex flows arise in the liquid, which affect heat and mass transfer. After cooling and crystallization of the melt, the molten zone has a definite distribution of impurity particles. The calculation of this distribution is one of the goals of this work.

2.1. Basic assumptions

It is assumed that the examined regimes of laser heating of the metal have moderate convection velocities, so that the melt flow is assumed to be laminar, and, for this reason, the free surface of the liquid is flat. The following assumptions are used for constructing the mathematical model:

- the melt motion induced by laser radiation is described by the model of the flow of a viscous incompressible heat-conducting fluid in the Boussinesq approximation in a three-dimensional Cartesian coordinate system;
- the substrate and particle materials are continuous and homogeneous;
- the thermophysical properties of the materials in the solid and liquid state are constant and temperature-independent;
- the changes in the liquid surface shape due to evaporation are neglected;
- the free surface of the liquid is assumed to be flat;
- the volume thermal expansion of the particle and substrate materials is neglected;
- the fraction of particles in the melt is rather small, so that the influence of particles on the melt flow and particle collisions with each other are ignored;
- the interaction of particles with the solid boundary is reduced to collisions, which are assumed to be elastic;
- the surface tension of the melt depends only on temperature;