Modeling of laser welding of plates made of dissimilar metals with the use of a composite insert

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Abstract. This paper deals with computer simulations of laser welding of plates made of dissimilar metals using a composite intermediate insert. They are performed with the previously developed 3D numerical model implemented with the collocations and least squares method. The use of the composite insert when welding dissimilar alloys prevents the formation of brittle intermetallic phases that adversely affect the strength of the joint. Based on the proposed mathematical model, the features of butt-welding of titanium and stainless steel plates and aluminum and titanium plates are investigated. The rational thermal conditions of laser welding and the geometric parameters of the welds are determined.

1. Introduction
Laser welding of metals is widely used in modern industries. It has several advantages over other types of welding: high speed, flexibility of control and environmental friendliness of the process, low deformation of the parts, etc. The demand for laser welding necessitates the study of this complex physical process and the possibilities of its application. In industrialized countries, new laboratory and industrial installations, teams for scientific research in the field of laser processing of metals are being created. Representative scientific conferences are devoted to its problems; the accumulated experience is described in numerous publications and reviews [1,2].

Recently, there has been increased interest in the development of laser welding technology for dissimilar metals [4-8]. At that, new methods of researching the process are applied and new technological methods are being developed [9-15]. Welded parts and structures made of dissimilar metals, due to the features of their operational properties, are widely used in the production of space, aviation, and other modern equipment. Parts and structures made with the combined use of various metals demonstrate lightness, strength, and high corrosion resistance. A promising way to connect such parts is laser welding. The development of such a technology is primarily hindered by the specifics of the physical process, which is characterized by high temperature and rate in a very small region of the laser beam action on the metal, the formation of a plasma torch. All this causes technical and methodological difficulties for a purely experimental study and optimization of the laser processing of metals and alloys.

Welding of dissimilar metals has its own difficulties and specifics, which are superimposed on the specifics of the laser welding process itself. Despite numerous studies in the field of dissimilar metals welding, the problem of laser welding of alloys based on aluminum, titanium, and steel still needs further study. The key challenge in the welding of such alloys is related to the formation of brittle intermetallic compounds which reduce the strength of the welded joint significantly. For example, titanium and
aluminum are chemically active metals with very different physicochemical and mechanical properties. When welding with fusion of titanium and aluminum alloys, brittle TiAl$_3$-type intermetallic compounds are formed in the welded joint region. Moreover, when welding titanium with steel, due to the low solubility of iron in α-titanium, brittle intermetallic compounds of TiFe, TiFe$_2$, Ti$_3$Fe types and eutectics of various compositions are formed. To prevent the formation of intermetallic compounds during welding of dissimilar metals, various technological methods are used. One of the effective techniques in the production of critical parts is the use of an intermediate insert. There is a need to optimize the process of laser welding of dissimilar metals. It is necessary to choose the optimal laser radiation power and welding speed, and the optimal parameters of various composite intermediate inserts. In the matter of choosing the optimal welding parameters, an expensive physical experiment can be substantially supplemented and partially replaced by calculations using adequate mathematical models, which make it possible to obtain various quantitative characteristics of the welding process. The combination of field experiments and numerical modeling in the development of the technology under consideration can accelerate the search for its optimization. Therefore, in view of the demand for laser welding in industry, its mathematical modeling is relevant [16–25] in addition to studying it using physical experiment methods. Using a mathematical model that adequately describes the properties of the process under study, it is possible to calculate its parameters that are interesting from the perspective of technology. In this regard, numerical modeling can significantly supplement the often expensive physical experiment, in which it is difficult to measure some important process parameters.

In this paper, we propose numerical 3D models for calculating the process of laser butt welding of plates made of dissimilar metals, using composite inserts obtained by explosion welding of thin layers of dissimilar metals. An essential circumstance of the developed and simulated technology is that explosion welding gives durable compounds of various metals with good quality welds and allows one to obtain sufficiently strong composite inserts. This technology is proposed to be used for welding plates of metals, direct welding of which with each other presents certain technological difficulties.

Two cases of dissimilar metals welding were simulated using the numerical collocation and least squares (CLS) method developed by the authors [26–27]. For modeling, modifications of the thermophysical model of laser welding, previously proposed by the authors and used for the numerical simulation of welding plates of various homogeneous metals, were formulated. The previous versions of the model were previously described in sufficient detail in [14–15, 19, 21–22, 24]. In particular, they describe in detail the self-consistent model of the vapor channel, which is different from [17]. The depth and shape of the channel in this model are consistent with the amount of heat received from the laser beam by the surface of the channel and heat fluxes from it to the outside of the welding zone. In some of them, the presence of a heat transfer rate increased due to melt convection in the weld pool was modeled, as in [21, 25], simply by an artificially increased heat conductivity coefficient. In others, convection of the melt in the weld pool was described by the Navier – Stokes equations [22]. Here, a simple method was used to simulate the increased rate of heat conductivity in the weld pool. The difference of the modified versions of this model from [19,21,22] is that for each metal and melt in the pool it uses its own thermophysical parameters in all the equations and boundary conditions. For example, this is taken into account when choosing the coefficients of thermal conductivity and heat capacity, melting heat, and other parameters. An essential detail of the model used here is that in the heat transfer from the laser beam to the welding zone, in its heat exchange with other parts of the welded product and with the external environment, heat fluxes were taken into account, which, in comparison with those not taken into account, determine the most significant quantitative characteristics of the temperature distribution in the product during the welding process.

Here, in the first case, the welding of plates made of steel and titanium alloys is simulated, in the second case, the welding of plates made of aluminum and titanium alloys. In the first case, the insert consisted of layers of steel, copper, niobium, and titanium. In the second one, the insert contained aluminum and titanium layers. In both cases, the use of intermediate insert between dissimilar metals to be welded is intended to prevent their mixing in the weld pool and the formation of brittle intermetallic compounds in the weld.
Calculations based on the proposed models make it possible to select the thicknesses of the layers in the intermediate insert, the laser radiation power, and the welding speed at which “dagger” penetration of the welded joints is achieved. In addition, it is important to make sure that with the calculated welding mode in the weld pools there is no mixing of metals, leading to the formation of intermetallic compounds. Finally, it is important to make sure that with the selected mode during the welding process, a temperature distribution established in the product does not damage the explosion welds in the insert.

2. Schemes for welding dissimilar metals with intermediate inserts

To obtain high-quality welds when welding a titanium alloy with stainless steel, it seems promising to use intermediate layers of other alloys. Thus, earlier, various metal inserts (copper, bronze, etc.) were used for this purpose at the Institute of Theoretical and Applied Mechanics SB RAS. The most effective was an insert made of a copper plate, the use of which made it possible to obtain joints with tensile strengths of the order of 350 MPa. A significant increase in the strength of the welded joint of steel plates with titanium was provided by the use of composite inserts obtained by explosion welding of a layered composite made of thin layers of four metals. Plates of copper and niobium were taken as the two middle layers in the insert, and plates of steel and titanium as the outer ones. In the welded joint, the titanium layer of the insert fits tightly with the welded titanium plate, and the steel layer of the insert with the plate of steel (figure 1). During welding, the laser beam passes first along one of the joints, and then along the other. With this method of joining plates, steel is welded to steel, and titanium to titanium. With the given parameters of the welding process, it is possible to choose the thicknesses of the outer layers in the composite insert so that the molten steel does not mix with titanium and thereby do not create conditions for the formation of brittle intermetallic phases in the weld.

For welding a titanium plate of rectangular shape with aluminum, a composite insert was used, cut from a bimetallic plate obtained by explosion welding of titanium and aluminum layers 3 mm thick. The width of the rectangular insert was taken equal to the thickness of the plates being welded. In this case, the welding had two stages as well: the titanium plate was butt welded with titanium layer of the insert, and the aluminum plate with aluminum layer of the insert (figure 9).

3. Numerical simulation of the welding process

The described welding process is a complex set of simpler interacting physical processes. It depends on the values of many parameters, first of all, on the power of laser radiation, welding speed, the insert layers thicknesses and their thermophysical parameters. Due to the specifics of laser welding, this process is difficult both for experimental research and numerical simulation. It is necessary to use a sufficiently universal numerical method for solving boundary value problems for partial differential
equations in order to ensure a sufficiently accurate approximation not only of differential equations, but also of nonlinear boundary conditions, including those at curvilinear boundaries.

In view of the presence of discontinuity surfaces of the thermal conductivity coefficient at the boundaries between different metals and their different phases, for the convergence of the numerical solution obtained using this method, it is necessary that it possess conservatism, that is, comply with the conservation laws with some accuracy. Otherwise, as known, the numerical solution obtained by any methods does not converge on any grid – it either has an inevitable finite error, or diverges. There are discontinuities of the thermal conductivity coefficient in the computational domain cased by the different properties of welded metals in liquid and solid states. For adequate handling of this the numerical algorithm must be conservative. I.e., it must represent conservation laws on the computational grid. In this study we use a fairly universal method of collocation and least squared, which is capable to support all the functionality mentioned above as is was demonstrated before when solving various differential and integral equations [26-27].

This paper contains the simulations of welding of an austenitic steel plate with a titanium one (figure 1, figure 3 - figure 8), as well as welding a titanium plate with an aluminum plate (figure 9 - figure 11) using the corresponding inserts.

3.1. Welding of titanium and steel plates

Below are some results of numerical modeling of the butt welding of VT1-0 titanium alloy and 12Kh18N10T steel rectangular plates with thickness of \( t = 3 \) mm with a composite insert in between consisting of layers of copper and niobium with thickness of 0.2 mm. The laser power \( W = 2.5 \) kW, the welding speed in steel \( V_w = 1 \) m/min and in titanium \( V_w = 1.8 \) m/min. In numerical experiments, the temperature fields, the position of the internal boundaries in the welded joint, the shape and depth of the vapor channel were determined. The figures show rectangular coordinate system associated with the laser beam and one of the welded joints: the origin is at the intersection of the upper surface of the plates with the axis of the laser beam, the \( z \) axis is directed along the beam, the \( x \) axis is along the joint.

Figures 3–7 show the calculated positions of the isotherms corresponding to the melting points: 1 – titanium, 1941 K; 2 – steel, 1775 K; 3 – copper, 1356 K. Isotherm 4 corresponds to temperature of 650 K. For clarity, only a part of the computational domain containing the isotherms under consideration is shown. The straight lines show the boundaries of the copper and niobium inserts before welding, denoted by symbols Cu and Nb, respectively. Parts of the computational domain occupied by titanium and steel before the welding are denoted by Ti and Steel, respectively. The focus position of the laser beam in all calculations \( z_F = 4 \) mm.

The black region containing point \((0, 0, 0)\) in figure 4 corresponds to the steam channel. The values of the thermophysical parameters with which the calculations were carried out were taken from well-known sources [28, 29] and others.

Figure 7 shows the calculated position of the welds boundaries in steel and titanium. For comparison, figure 8 presents the morphology of the cross section of the weld obtained in the experiment. Note that from the position of the melting isotherms of the metals being welded, it is easy to determine the cross-sectional area of the molten part of each metal and to calculate their quantitative ratio in the mixture in the weld pool and weld. The calculation provides these parameters with sufficient accuracy. A certain morphological difference between the calculated shape of the weld boundaries and the experimental one is obviously due to the lack of consideration in the model version used here of melt flows in the weld pool, which affect the conditions of local heat transfer in the melt zone and the shape of the pool walls. Quantitatively, the volume and, qualitatively, the picture of the melted region of the joint are in a satisfactory agreement with the experiment.

Here we omit the discussion of the various details that are obtained from the calculation, including the melt cooling rate, which affects the crystal structure of the weld. However, we note that in the calculated welding mode, such a temperature distribution is obtained in the plates and in the insert that the weld between copper and niobium does not melt and retains strength. Moreover, in the weld pool there is no mixing of the molten steel and titanium.
Figure 3. Calculated temperature distribution in the cross section $x=0$, the beam moves in steel. Isotherms: 1 – 1941 K (Ti for titanium), 2 – 1775 K (Ti for steel), 3 – 1356 K (Ti for copper), 4 – 650 K.

Figure 4. Calculated temperature distribution in the cross section $z = 0$. The beam moves in steel. Isotherms: 1 – 1941 K (Ti for titanium), 2 – 1775 K (Ti for steel), 3 – 1356 K (Ti for copper), 4 – 650 K.

Figure 5. Calculated temperature distribution in the cross section $y=0$. The beam moves in titanium. Isotherms: 1 – 1941 K (Ti for titanium), 2 – 1775 K (Ti for steel), 3 – 1356 K (Ti for copper), 4 – 650 K.

Figure 6. The temperature distribution in the cross-section $z=0$. The beam moves in titanium. Isotherms: 1 – 1941 K (Ti for titanium), 2 – 1775 K (Ti for steel), 3 – 1356 K (Ti for copper), 4 – 650 K.

Figure 7. The calculated position of the boundaries of the welds in steel and titanium.

Figure 8. Photograph of a section of the welded joint after welding using a composite insert.

Figure 9. Laser welding scheme for aluminum and titanium plates with an intermediate insert.
3.2. Welding of plates made of titanium and aluminum

In the scheme (figure 9), the aluminum plate is located in the region \( y < 0 \). Aluminum layer of insert 3 mm wide is joined to it in the region \( y > 0 \) along the \( x \) axis, which, in turn, is explosion-welded to layer of titanium 3 mm wide, and the insert fits tightly with the titanium plate. All layers have width of 3 mm, so their upper and lower surfaces coincide. The surfaces of the plates are blown with an inert gas to protect the liquid metal from oxidative processes.

Below are some results of the numerical simulation of butt welding of VT1-0 titanium alloy and AD1 aluminum plates with thickness \( t = 3 \) mm with a composite insert in between consisting of aluminum and titanium layers with thickness of 3 mm and 2 mm, respectively. Laser power \( W = 3.1 \) kW, speed \( V_w = 3.5 \) m/min for welding of aluminum; and \( W = 1.9 \) kW, \( V_w = 1.8 \) m/min for welding of titanium. In the numerical experiments, the temperature fields, the position of the internal boundaries in the welded joint, the shape and depth of the vapor channel were determined.

![Diagram](image1)

**Figure 10.** The calculated isotherms for butt welding of aluminum plate with layer of aluminum in the insert in cross-sections \( z = 0 \) mm (a), \( x = 0.1 \) mm (b) \( y = 0 \) mm (c); the welding speed 3.5 m/min, laser power \( W = 3.1 \) kW; 1 – aluminum melting temperature 873 K, 2 – 700 K, 3 – 500 K.

![Diagram](image2)

**Figure 11.** The calculated isotherms for butt welding of titanium plate with titanium layer in the insert in cross-sections \( z = 0 \) mm (a), \( x = 0 \) mm (b), \( y = 1.2 \) mm (c); the welding speed 1.8 m/min, laser power \( W = 1.9 \) kW.
The figures show the calculated positions of the isotherms corresponding to the melting points of: aluminum (figure 10) and titanium (figure 11). The black region containing point (0, 0, 0) corresponds to the vapor channel. The values of the thermophysical parameters with which the calculations were carried out were taken from well-known sources [28, 29] and others.

Note that according to the position of the melting isotherms of the welded metals, it is easy to determine the time of the melt cooling and some parameters of the welds. In this case, as in the previous one, the main conclusion from the temperature distribution pattern is that in the calculated welding mode, the welding seam obtained by the explosion in the insert between the layers of aluminum and titanium does not melt.

4. Conclusion
The models of laser welding of dissimilar metals plates with an intermediate composite insert in between used in the work allow us to predict various parameters of the welded joint that are important for the technology. Intermediate composite inserts obtained by explosion welding of thin layers of metals can be used for laser welding of critical parts and structures of dissimilar metals.

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7
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