International Journal of Heat and Mass Transfer 99 (2016) 711–720

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Numerical study of Heat Modes of laser welding of dissimilar metals with an intermediate insert

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ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form 29 March 2016
Accepted 8 April 2016
Available online 26 April 2016

Keywords:
Laser welding
Heat transfer
Mathematical modeling
Dissimilar metals
Intermetallic phase
Intermediate insert

ABSTRACT

A 3D model of heat transfer in inhomogeneous materials taking into account phase transitions for analysis of laser welding of dissimilar metals using intermediate insert is developed. Based on the proposed model, an algorithm is constructed and numerical studies are carried out of the distribution of temperature fields in the weld joint of titanium and stainless steel with an intermediate copper insert. The processes of melting, evaporation, and solidification of the materials depending on the beam power, its speed, and position of the focal spot in the system are studied. The welding modes reducing interaction of elements of the materials welded and, thus, preventing formation of brittle intermetallic phases in the weld joint are found.

1. Introduction

Welding of titanium-based alloys and iron, including bimetallic ones (titanium alloy – stainless steel), is an important technological process in the manufacturing of parts and mechanisms that have wide application in aerospace, aviation engineering, power engineering, and shipbuilding. The problem of joining titanium and steel, particularly of austenitic class, by melting using a laser beam is yet to be solved in practice, despite the numerous studies on joining dissimilar metals by rolling, friction, explosion, etc. [1–11].

The direct welding of titanium and steel does not give positive results [6]. According to the state diagram of titanium–iron, the solubility of iron in α-titanium is extremely small and is within 0.05–0.1% at the normal temperature. At concentrations of Fe higher than 0.1%, brittle intermetallic compounds of types TiFe, $TiFe_2$, Ti_2Fe, and eutectics of various compositions are formed in the alloy, which drastically reduce the plastic properties of the material. Therefore, one of the main problems in obtaining a durable welded steel and titanium joint is the selection of the welding materials, methods and modes of the welding, in which the probability of creation of the brittle phases would be prevented or significantly decreased. To obtain good quality welds when welding titanium alloy with stainless steel, a promising solution is the use of intermediate layers of other alloys. For example, in [6], for this purpose, various metal inserts (copper, bronze, etc.) were used. The most effective was the insertion of a copper plate, which allowed us to obtain joints with the tensile strength of about 350 MPa.

The laser welding takes place in a small area exposed to laser radiation, causing high temperature with large gradients and forming a weld pool. If the laser power is above a critical value, the liquid metal in the vicinity of the beam axis boils to form vapor-gas channel (keyhole or pore) of small dimensions, from which the metal vapors escape at high speed. Because of the presence of metal inhomogeneity, laser instability, hydrodynamic instability of the keyhole surface, the neighborhood of the contact between the beam and metal is dynamically unstable and surrounded by dense, bright metal vapor cloud (vapor plume). These and other circumstances in the laser welding make it very difficult to measure the physical parameters of the process and the visual observation of the welding zone. However, the processes taking place in this small-sized area determine properties and quality of the weld joint obtained. The difficulties associated with the measurements of some parameters and certain instability of the complex laser welding process complicate the creation of a flexible technology and its application. Therefore, in view of the demand for laser welding in various areas of the industry and some of its advantages over other types of welding, its numerical simulation

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.04.019
0017-9310/

Nomenclature

A, A_e	absorption factor, equivalent absorption factor
c_i^j	specific heat capacity of *i*th phase of *j*th metal
$\mathbf{e}_z$	ort of *z*-axis
g	acceleration of gravity
H	depth of the keyhole
h_m	maximal linear size of the mesh cell
h_z	coordinate of symmetry point of the keyhole wall generatrix
K_c	curvature of the keyhole surface
l	characteristic length of the cooling zone
L_V	latent heat of the metal vaporization
$\dot{m}$	mass rate of the metal evaporation
$\mathbf{n}$	(n_x, n_y, n_z) weld pool surface unit normal vector
q	heat flux;
q_l, q_r, q_v, q_c, q_b	heat fluxes on the keyhole wall: absorbed, re-reflected, lost on metal evaporation, convective, the model correction, respectively
P	pressure
Pr, Re	Prandtl and Reynolds numbers
R	gas constant
R_c	radius of spherical part of the keyhole bottom surface
r_F	radius of the beam in the focal plane
S_b	area of side surface of the keyhole
S_c	sum of areas of the keyhole outlet and side surface
T	temperature
T_{av}	the average temperature on the keyhole wall in the laser spot
T_m	melting temperature
T_{sat}	boiling temperature of the alloy
t	metal plate thickness
U_g	flow rate of the inert gas
(u,v,w)	vector of a particle velocity in the melt with components u, v, w
V_k	is the volume of molten metal number k in the weld pool
$Vtot$	is the total volume of all molten metals in the weld pool
$\mathbf{V_w}$	velocity of the beam progress (welding rate)
W	laser beam power
x, y, z,	Cartesian coordinates
$x(z)$	keyhole generatrix
$Z(x,y)$	surface of the keyhole in x, y, z coordinates
Z_c	coordinate z of a point on the keyhole surface
Z_F	coordinate z of the beam focus
α_{k1}	coefficient of convective heat transfer as a result of gas blowing
$\alpha_{r_i}^j$	coefficient of radiation heat transfer for metal j in phase i
ε_i^j	reduced degree of metal j blackness in phase i
θ	tangent of inclination angle of the keyhole wall generatrix $x(z)$ to z-axis
κ^j	melting heat of *j*th metal
λ_0	wavelength of the laser radiation
λ_g	the gas heat conductivity
λ_i^j	heat conductivity of *i*th phase of *j*th metal
ν_g	kinematic viscosity of the gas
ρ_3	the average density of melt in the pool
ρ_i^j	density of *i*th phase of *j*th metal
σ	coefficient of surface tension of the liquid metal
σ_0	Stefan–Boltzmann constant
Ω, Ω_{ct}	computation domain and domain of the keyhole

Subscripts

c	vapor-gas channel (keyhole)
g	gas
i	index of *i*th phase
r	recoil reaction
s	static
sat	boiling
m	liquid phase
v	vapor

Superscripts

av	averaged
j	index of *j*th metal

is of current interest. According to the mathematical model that adequately describes the properties of the process under study, it is possible to calculate the parameters of interest from the technological perspective. In this context, the numerical simulation can significantly complement the physical experiment, which is often much more expensive than computer calculations [12–18].

In this paper we consider the process of butt welding of plates made of two different metals with a thin intermediate insert between them of a third metal (see. Fig. 1). Our goal is to construct an adequate mathematical model for the calculation of temperature fields, location of the phase boundaries of melting and solidification in the welded metals depending on the thickness and material of the insert, position of the focal spot of the laser beam, the radiation power and welding speed. This model can be further used for determining the optimal welding conditions excluding (or reducing) the formation of undesirable intermetallic compounds.

In this paper, the 3D quasistationary thermophysical model proposed earlier and described in detail in [12–13] is generalized to the case of welding of two dissimilar plates with an insert of a third metal.

Difference of this model from the one in [12–13] is that for each metal, melt in the weld pool, and solidified welding joint it has different thermal parameters in all the equations and boundary conditions. For example, the coefficients of thermal conductivity and heat capacity, heat of fusion, and other parameters. Due to the convective mixing, the weld pool contains the mixture of molten metals. Therefore, averaged values of the parameters are used in this subdomain. The averaging procedure is described in Section 2.2 in detail.

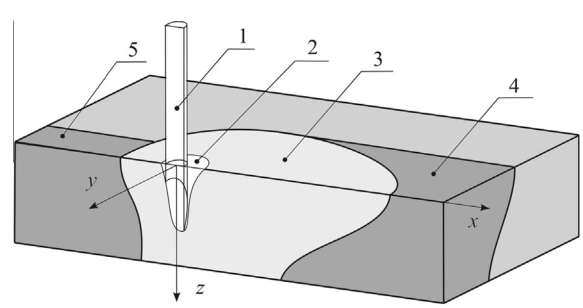

Fig. 1. Welding scheme. 1 – laser beam, 2 – vapor-gas channel (keyhole), 3 – melt pool, 4 – solid phase, 5 – intermediate insert.