Journal of Materials Processing Technology 211 (2011) 1796–1803

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Multiphysical modeling of dissimilar welding via interlayer

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ARTICLE INFO

Article history:
Received 2 March 2011
Received in revised form 30 May 2011
Accepted 2 June 2011
Available online 13 June 2011

Keywords:
Dissimilar welding
Multiphysical modeling
Heat and mass transport
Titanium alloys

ABSTRACT

A multiphysical finite element modeling of dissimilar welding via interlayer material was proposed. A 2D model including heat transfer, fluid flow and level set problems allowed to simulate the morphology and the composition of melted zone in horizontal plane. The calculated thickness of melted interlayer was used as a main criterion for the choice of optimal welding conditions, when the chemical interaction between the joined materials must be avoided. A 1D diffusion model at the limit of melted zone allowed estimating the length and the composition of diffusion layer between one of the materials and the interlayer basing on previously calculated local temperature gradient. The simulations were carried out in finite element software COMSOL Multiphysics.

The application of the models to dissimilar TA6V to stainless steel AISI 316L electron beam joining via copper interlayer allowed to study the effect of different welding conditions (beam offset and welding speed) on the mixing between three involved materials and thus to determine the favorable operational conditions basing on the properties of dissimilar system and to give the first approach of heterogeneous interface description. The comparison of modeling results with an experiment confirmed the presence of very narrow region of optimal conditions, which is in good correspondence with simulation.

1. Introduction

Dissimilar joining of metallic materials often confronts the problem of metallurgical incompatibility: chemical interaction in multicomponent metallic systems may result in formation of brittle phases. One of the ways to improve the quality of such joints consists in modification of melted zone content by introduction of the third material which must be compatible with both base metals. In case of welding methods involving fusion, the local melt composition is highly influenced by melt convection, which means that the choice of welding conditions must take in account the final morphology of melted interlayer. To find the appropriate experimental parameters, long-run preliminary experimental research is needed. A summary of requirements to melted zone geometry and composition can be formulated as:

- the continuity of melted interlayer must be preserved;
- the melting at least of one of the materials, especially if it forms intermetallic phases with an interlayer, must be minimized by the correct choice of heat source offset from the joint line;
- the mass transport between the materials can be minimized by reducing the time of thermal cycle.

The numerical modeling of heat transfer and melt convection in such three-component melted zones may provide an important information on optimal conditions of the welding. The fist attempts to model the three-component welding have been recently made. Mathieu et al. (2006) propose finite element model of heat transfer in laser steel to aluminum welding via zinc filler wire, validated by comparison with thermographic measurements. Dörfler (2008) proposes multiphysical level set based finite element model of thermal, mechanical and morphological evolution of dissimilar friction stir welds of aluminum alloys via copper interlayer. However, the multiphysical modeling of welding process involving fusion and mixing of three different materials has not been developed yet.

The major metallurgical problem for joining of titanium alloys with steels consists in formation of brittle intermetallic compounds, which make the direct joining by conventional welding methods impossible. Therefore, many methods using metal interlayer have been developed. The best results can be been obtained with interlayer materials which do not form the brittle phases with Ti, as, for example, pure vanadium and niobium (Kireev and Zamkov, 2002). The use of more accessible filler materials as copper (Elrefaey and Tillmann, 2009), nickel (Kundu and Chatterjee, 2006), silver (Atasoy and Kahraman, 2008) and their alloys (Noda et al., 1997) also allows obtaining good quality joints whose mechanical resistance is however lower than that of base materials. The mechanical resistance of such joints is determined not only by efficacy of isolation of base materials by the interlayer, but also by

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doi:10.1016/j.jmatprotec.2011.06.004

Nomenclature

c	element concentration (at.%)
C_p	heat capacity (J/(kg K))
d	key-hole offset from copper–steel joint line (μm)
D	key-hole diameter (m)
$D_{Ti(Cu)}$	diffusion coefficient (m^2/s)
I	beam current (mA)
$[I]$	identity matrix
E_a	activation energy of diffusion (J/mol)
k	thermal conductivity (W/(m K))
L	thickness of the interlayer by the end of thermal cycle (m)
R	universal gas constant (J/(mol K))
S	the surface of melted zone cut occupied by one of materials (m^2)
t	time (s)
T	temperature (K)
T_m	melting temperature (K)
T_v	vaporization temperature (K)
U_a	acceleration voltage (kV)
u, v	x and y components of velocity field (m/s)
U	velocity field (m/s)
U_r	relative velocity field (m/s)
v_r	y component of relative velocity field (m/s)
v_w	welding speed (m/s)
x, y	Cartesian coordinates (m)
ΔT	smoothing region of Heaviside function for phase change (K)
ε	width of moving interface (m)
ϕ	level set function
φ	calculated fraction of material in the melted zone (vol.%)
φ^{EDS}	element fraction due to EDS analysis (at.%)
γ	reinitialization parameter (m s/kg)
η	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

phase content and thickness of diffusive interfaces between titanium alloy and the interlayer.

The electron beam welding is widely used for the dissimilar joining of metals due to the local and well controllable application of high thermal gradients allowing the compensation of fusion temperature mismatch and the minimization of the mixing between dissimilar metals, and thus, the limitation of the dimensions of brittle zones (Sun and Karppi, 1996). The specificity of high power electron beam welding process consists in formation of narrow keyhole-like cavity in melted material, which results in nearly uniform vertical temperature distribution. The velocity field determining the internal morphology of dissimilar weld can often be reduced to the horizontal convection, which allows solving the problem in two dimensions (Tomashchuk, 2010). The application of finite element method and level set method to the modeling of dissimilar electron beam welding is described in our previous publication (Tomashchuk et al., 2010) dedicated to copper to stainless steel joining.

The multiphysical models proposed in the present study are used as predictive tools allowing reducing the quantity of preliminary weldability tests needed to determine optimal welding parameters of electron beam TA6V to stainless steel welding via pure copper interlayer. A 2D multiphysical model based on level set method predicting the morphology and composition of melted zone, and particularly, the state of melted copper interlayer under different operational conditions, is coupled with a 1D diffusion problem at TA6V-melted zone limit, which opens a perspective of further simulation of local phase content. The models have been implemented in finite element software COMSOL Multiphysics 3.5.

2. Models description

In case of continuous welding, the melted zone can be imagined as a constant volume of liquid metal, which has steady temperature and velocity distribution and displaces at a constant speed along the joint line. Such quasi-stationary representation of heat transfer and fluid flow problems allows considerable reducing of calculation time.

2.1. Level-set based model

To represent the development of mixing process in a melted zone formed by dissimilar materials, the position of the interfaces between the interlayer and the base materials represented by level set function has been calculated over a characteristic time, which is given as a relation of the length of quasi-stationary melted zone to the welding speed.

The morphology of melted interlayer is defined by two level-set interfaces which separate it from base materials and whose displacement is governed by convective movements in melted zone. 2D horizontal plane model of butt joint is assumed (Fig. 1a): the different materials are represented by rectangular plates (copper plate is 0.5 mm thick) and the simplified keyhole profile is given as a circle with diameter of electron beam (400 μm).

The initial considerations of the model are follows:

- only horizontal propagation of phenomena is considered (plane symmetry);
- the energy source is presented as an isotherm of vaporization;
- the vaporization zone is geometrically imposed;
- no solubility between dissimilar materials is assumed.

These simplifications restrict the applications of the model to the cases of continuous and full-penetrated high power beam welding, where the keyhole can be considered as a cylinder and the influence of the vertical convection can be neglected, which is the case of electron beam welding. In case of laser welding, the 2D resolution must be considered with care because of important nail head effect.

The input data for the model are the welding speed (v_w) and the position of keyhole with respect to the plane of joint (d). The physical properties of the materials used in calculations are given in Table 1.

Our description of melting is based on quasi-stationary heat equation, which considers only the temperature as a dependent variable (Eq. (1)):

$$\rho \cdot C_p \cdot \vec{U} \cdot \vec{\nabla} T + \vec{\nabla}(-k \cdot \vec{\nabla} T) = 0 \quad (1)$$

The properties of the materials are given as:

$$k = \begin{cases} k_L, T > T_m \\ k_S, T < T_m \end{cases}; \quad \rho = \begin{cases} \rho_L, T > T_m \\ \rho_S, T < T_m \end{cases}; \quad C_p = \begin{cases} C_p, T > T_m \\ C_p, T < T_m \end{cases}. \quad (2)$$

The Heaviside function is used to describe the step-wise change of physical properties during the phase change from solid to liquid state, which happens under $T = T_m$ (for alloys T_m is considered as middle value between solidus and liquidus temperatures). The smoothing is applied to avoid sharp discontinuity in properties, which can harm the convergence of the model. The temperature region dT during which the smoothing takes place, must be sufficiently large to allow the convergence. For each state, the

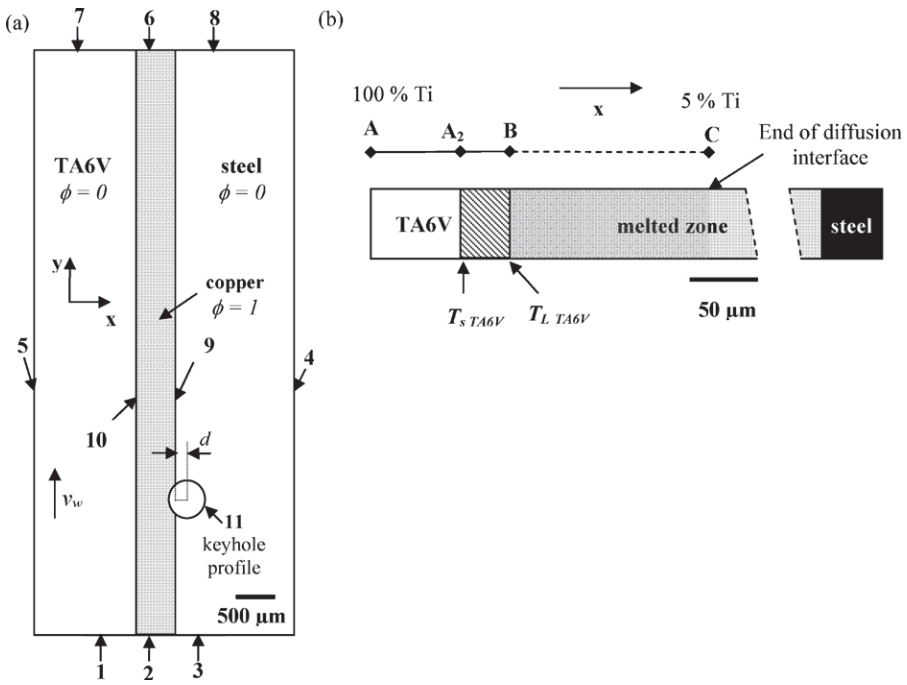

Fig. 1. Geometry and limit conditions: (a) 2D level set based model (maximal mesh size 100 µm); (b) 1D diffusion model (maximal mesh size 2 µm) and schematic representation of TA6V/copper interface.

physical properties are assumed as constants. This simplification is determined, above all, by the insufficient and divergent literature data on evolution of physical properties in melted metals and alloys.

Our initial hypothesis is that the temperature of the walls of the keyhole is not far from vaporization temperatures of materials. The keyhole has been introduced as equivalent heat source having vaporization temperature of corresponding material. Comparing to the energy input provided by electron beam (about 10^{12} W/m^2), the energy released by local phase change is considered as negligibly small.

An incompressible, laminar and Newtonian liquid flow is assumed in the weld pool:

$$\rho \cdot (\vec{U} \cdot \vec{\nabla}) \cdot \vec{U} = \vec{\nabla}\{-P \cdot [I] + \eta \cdot [\vec{\nabla}\vec{U} + (\vec{\nabla}\vec{U})^T]\},$$
$$\vec{\nabla}(\rho \cdot \vec{U}) = 0 \quad (3)$$

where $\vec{U} = (u, v)$: the global velocity field, where u and v are x and y velocity components;

$$\eta = \begin{cases} \eta_L, T > T_m \\ \eta_S, T < T_m \end{cases}$$

the dynamic viscosity of liquid metals. The viscosity of solid material is assumed to be big enough to suppress all residual convection movements in the numerical solution.

The resulting velocity field $\vec{U}$ is the superposition of welding speed (the displacement of entire junction) and velocity of liquid metals. The relative velocity field $\vec{U}_R$ that corresponds to the movements of melted metals relatively to the keyhole can be obtained by the subtraction of the welding speed from the general velocity field:

$$\vec{U}_R = (u; v - v_w) = (u; v_r) \quad (4)$$

Table 1
The parameters of materials used in calculations.

Constant	Unit	Name	Materials		
			Copper	AISI 316 L	Ti6Al4V
Liquidus temperature	K	T_s	1356	1720	1993
Solidus temperature	K	T_l		1690	1968
Vaporization temperature	K	T_{vap}	2835	3013	3600
Density (solid)	kg/m^3	ρ_S	8700	7980	4500
Density (liquid)	kg/m^3	ρ_L	7940	7551	4100
Heat capacity (solid)	J/(kg K)	C_{pS}	385	433	610
Heat capacity (liquid)	J/(kg K)	C_{pL}	350	734	720
Thermal conductivity (solid)	W/(m K)	k_S	400	8.116	20
Thermal conductivity (liquid)	W/(m K)	k_L	140	12.29	35
Dynamic viscosity (solid)	Pa s	η_S	1	1	1
Dynamic viscosity (liquid)	Pa s	η_L	0.003	0.005	0.003
Interval of phase change	K	dT	50		
Thickness of moving interface	m	ε	5×10^{-5}		
Interface mobility	m^3 s/kg	γ	0.005		
Diffusion coefficient of Ti in pure Cu	m^2/s	$D_{Ti(Cu)}$	0.693×10^{-4}		
Activation energy of Ti diffusion in pure Cu	kJ/mol	E_a	211		

Table 2
Limit conditions for level set based model.

Limit	Heat transfer	Convection	Level set
1			$\phi = 0$
2			$\phi = 1$
3	$T = 300$ K	Inflow: $v = v_w$	$\phi = 0$
4			$\phi = 0$
5			$\phi = 0$
6			
7	Convective flux $\vec{n} \cdot (-k \cdot \vec{\nabla} T) = 0$	Outflow: $v = v_w$	Outflow: $\vec{n} \cdot (\varepsilon \cdot \vec{\nabla}\phi - \phi \cdot (1-\phi) \cdot \vec{\nabla}\phi / \left\lvert \vec{\nabla}\phi \right\rvert) = 0$
8			
9			
10	Continuity $\vec{n} \cdot (-k_1 \cdot \vec{\nabla} T_1) = \vec{n} \cdot (-k_2 \cdot \vec{\nabla} T_2)$	Continuity[a]	Initial interfaces[b]
11	$T = T_v$	Keyhole: tangential sliding[c] on back side and $v = v_w$ on front side	$\phi = \phi_{\text{domain}}$

[a] $\vec{n} \cdot (\vec{\eta}_1 \cdot (\vec{\nabla}\vec{U}_1 + (\vec{\nabla}\vec{U}_1)^T) - P_1 \cdot [I] - \vec{\eta}_2 \cdot (\vec{\nabla}\vec{U}_2 + (\vec{\nabla}\vec{U}_2)^T) + P_2 \cdot [I]) = 0$.
[b] $\vec{n} \cdot (\vec{N}_1 - \vec{N}_2) = 0$ with $\vec{N} = \varepsilon \cdot \vec{\nabla}\phi - \phi \cdot (1-\phi) \cdot (\vec{\nabla}\phi / \left\lvert \vec{\nabla}\phi \right\rvert) - \phi \cdot \vec{U}$,where 1 and 2 are steel/copper or copper/TA6V couples.
[c] $\vec{n} \cdot \vec{U} = 0$, $\vec{\tau} = (-\vec{n}_y, \vec{n}_x)$ with $\vec{U} \cdot \vec{\tau} = v_w$ on the left side and $\vec{U} \cdot \vec{\tau} = -v_w$ on the right side.

The movement of liquid/liquid interfaces between the interlayer and base materials is given by level set equation:

$$\frac{\partial \phi}{\partial t} + \vec{U}_R \cdot \vec{\nabla}\phi = \gamma \cdot \vec{\nabla} \left(\varepsilon \cdot \vec{\nabla}\phi - \phi \cdot (1-\phi) \cdot \frac{\vec{\nabla}\phi}{\left\lvert \vec{\nabla}\phi \right\rvert} \right), \tag{5}$$

where ϕ is the level set function that varies from 0 (steel and TA6V) to 1 (copper) and is equal to 0.5 at the interface between the materials; ε is the parameter that determines the thickness of the transition region where ϕ goes smoothly from 0 to 1 (taken as 50 μm, which corresponds to 1/2 of mesh size); γ is the mobility parameter related to the magnitude of velocity field.

The limit conditions are summarized in Table 2 according to the numeration given at Fig. 1.

The mixing in melted zone is possible under condition that at least one of the base materials remains melted: the displacement of TA6V/copper interface is possible only under $T > T_m^{\text{TA6V}}$, when the displacement of steel/copper interface is limited by the isotherm T_m^{steel}. As $T_m^{\text{steel}} < T_m^{\text{TA6V}}$, the mixing between steel and copper will continue some time after the solidification of TA6V.

For solving the model, a two-steps scheme has been used:

(1) solving of coupled quasi-stationary heat transfer and fluid dynamics problems with direct UMFPACK solver;
(2) solving of level set problem in temporary mode basing on previously calculated relative velocity field $\vec{U}_r$ with direct temporary UMFPACK solver and the time of calculation given as $t = v_w / L^{\text{steel}}$, where L^{steel} is a length of calculated melted steel zone confined by T_s^{steel} isotherm.

2.2. Diffusion model

The present 1D model allows reproducing Ti diffusion from solid TA6V side basing on local thermal history, which is available from 2D model. It illustrates the development of heterogeneous interface along x axis (Fig. 1b): TA6V and copper are represented by AB and BC segments respectively. The length of the segments is chosen to be sufficient for the description of the entire interface (AC = 250 μm). The point B corresponds to the most advanced position of melted zone in TA6V (the position of T_l^{TA6V} isotherm in 2D model: $x_{T_l^{\text{TA6V}}}$).

The interface between solid TA6V and copper can be divided into two main zones (Fig. 1b): partially melted TA6V ($T_s^{\text{TA6V}} < T < T_l^{\text{TA6V}}$), saturated in Cu (95 at.% Ti), and melted copper. The thickness of partially melted TA6V layer corresponds to the distance between solidus ($x_{T_s^{\text{TA6V}}}$) and liquidus ($x_{T_l^{\text{TA6V}}}$) isotherms of TA6V and can be obtained from the results of 2D model. The thermal conditions at the interface determine the length of Ti diffusion in copper, where Ti concentration drops from 95 at.% Ti to 5 at.% Ti (maximal Ti solubility in copper, due to Cu–Ti phase diagram (Smithells, 1967).

The calculation of Ti diffusion is carried out basing on local temperature field at the interface, issued from level set based 2D model: the thermal history ($T = f(t)$) of A and C points is obtained from T variation along y axis ($T = f(y)$) for x_A and x_C. Thus, it can be represented as polynomial function of time: $T = a_1 t^6 + a_2 t^5 + a_3 t^4 + a_4 t^3 + a_5 t^2 + a_6 t + a_6$, where $t = (y - y_0)/v_w$ and y_0 is a coordinate of the melted zone front. The temporary heat equation is used in 1D model:

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} + \frac{\partial}{\partial x} \left(-k \cdot \frac{\partial T}{\partial x} \right) = 0 \tag{6}$$

For simplification, the diffusion of pure Ti in pure Cu is assumed and the convection effects are neglected:

$$\frac{\partial c_{\text{Ti}}}{\partial t} + \frac{\partial}{\partial x} \left(-D_{\text{Ti(Cu)}} \cdot \frac{\partial c_{\text{Ti}}}{\partial x} \right) = 0, \tag{7}$$

where $c_{\text{Ti}} + c_{\text{Cu}} = 100$ at.% and where Ti diffusion coefficient is given as a smoothed Heaviside function of type:

$$D_{\text{Ti(Cu)}} = \begin{cases} D^0 \cdot \exp\left(-\dfrac{E_a}{R \cdot T} \right) & \text{if } T > T_s^{\text{TA6V}} \\ 0 \quad \text{if } T < T_s^{\text{TA6V}} \end{cases} \tag{8}$$

The initial conditions of the model are follows:

- the thermophysical properties of materials are given in the same form as for 2D model;
- in TA6V domain (AB) the initial amount of Ti (at.%) is given by smoothed Heaviside function which separates unmelted TA6V (segment AA2) from the zone saturated in Cu (A2B):

$$c_{\text{Ti}} = \begin{cases} 90 & \text{if } x < x_{T_s^{\text{TA6V}}} \\ 100 & \text{if } x > x_{T_s^{\text{TA6V}}} \end{cases}; \tag{9}$$

- in copper domain: $c_{\text{Ti}} = 5$ at.%;
- the limit conditions:

  - point A: $c_{\text{Ti}} = 100$ at.% (unmelted TA6V), temperature variation $T_A = f(t)$;
  - point B: continuity of diffusion flow $-D_{\text{Ti(Cu)}} \cdot (\partial c_{\text{Ti}}/\partial x)$; continuity of thermal flow $-k_{\text{TA6V}} \cdot (\partial T/\partial x) = -k_{\text{copper}} \cdot (\partial T \partial x)$;
  - point C: $c_{\text{Ti}} = 5$ at.%, temperature variation $T_C = f(t)$.

The diffusion model has been solved with direct temporary UMFPACK solver. The time of calculation is chosen in order to finish when local temperature approaches to 300 K.

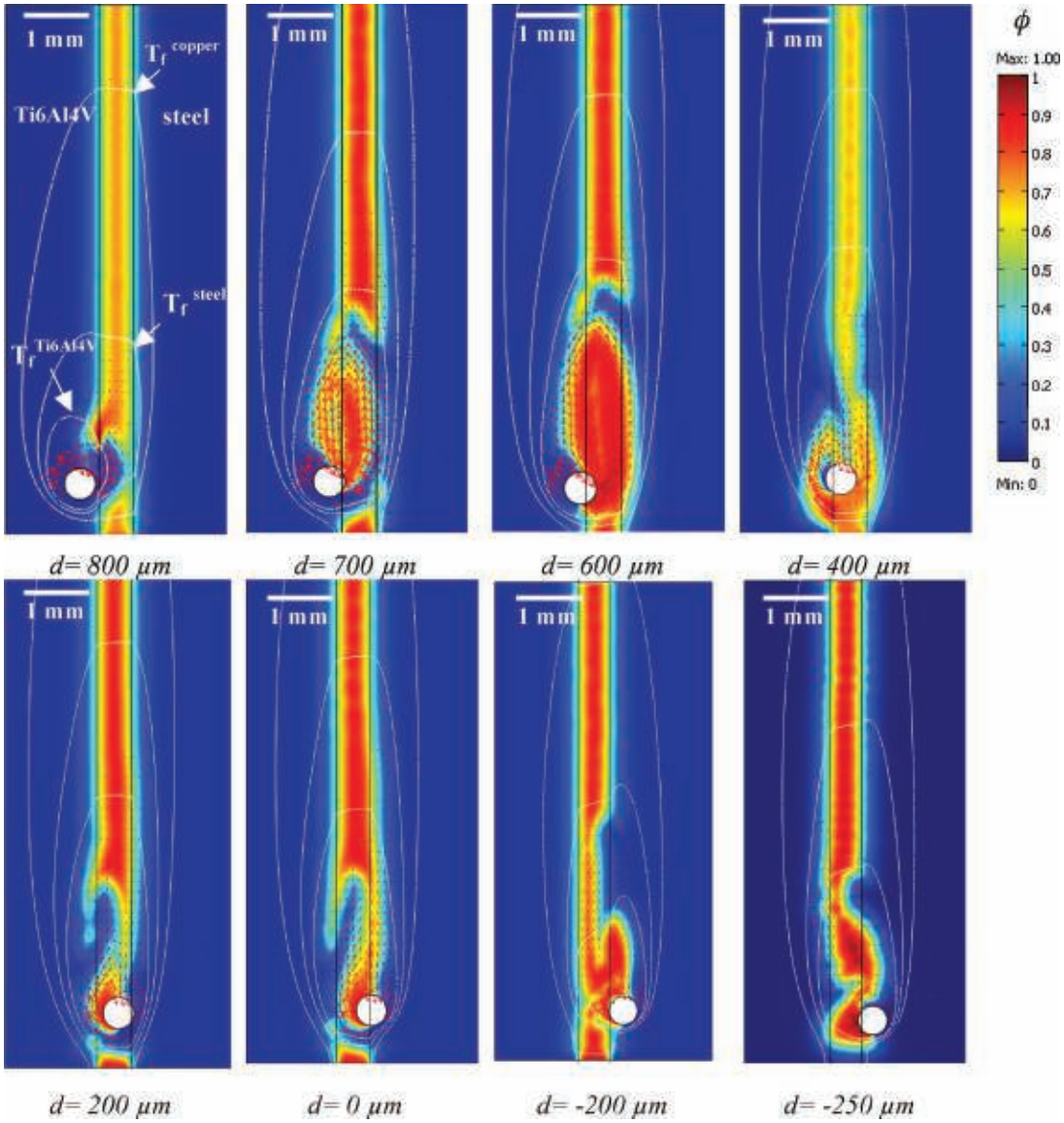

Fig. 2. The variation of weld morphology in function of keyhole position (v_w = 1.8 m/min).

3. Results and discussion

The study is organized in the following manner. Firstly, the influence of keyhole position at the thickness of interlayer and at the weld composition is studied. The initial position of copper/steel interface is chosen as a reference point: the displacement of the keyhole at steel side is chosen as a negative direction ($-d$) and at copper as a positive ($+d$). Secondly, the influence of welding speed on weld morphology and composition has been studied for optimal keyhole position. Resulting optimal condition has been applied to obtain TA6V/copper/steel weld, which morphology and composition have been compared with calculation results issued from level set based and diffusion models.

The main feature of studied system consists in sharp difference in melting temperature between base materials and soft interlayer (Figs. 2, 4 and 6). The melted zone can be divided in two regions:

(1) front part, where at least one of the base materials is melted, and thus convection movements may reduce the thickness of the interlayer;

(2) back part, where base materials are already solidified, but copper interlayer remains liquid, so the diffusive transport at TA6V/copper and steel/copper interfaces continues.

The mixing between copper interlayer and base materials is determined by recirculation movements of liquid metal past the keyhole. Consequently, the main criterion of weld quality will be the minimal interlayer thickness (W) in region 1, which traduces as the distance between two ϕ = 0.5 isolines (equal to 500 μm before melting).

The local properties of TA6V/copper/steel weld can be characterized by Cu–Fe–Ti phase diagram (van Beek et al., 1995). As Ti forms intermetallic phases with Cu and Fe, it is advantageous to minimize the content of TA6V in melted zone. In the same time, Fe does not form intermetallic phases with Cu, which allows varying the proportion between these two materials over a wide range. Consequently, the second criterion of weld quality will be the quantity of melted TA6V φ_{TA6V} (volume fraction, %), which can be determined as:

$$\varphi_{TA6V} = \frac{S^l_{TA6V}}{S^l_{TA6V} + S^l_{copper} + S^l_{steel}} \cdot 100, \quad (10)$$

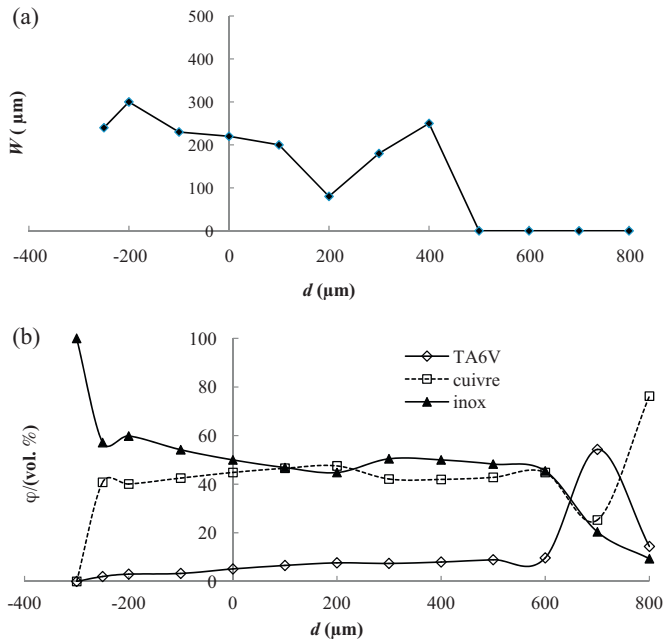

Fig. 3. The variation of the minimal thickness of melted interlayer (a) and of the average proportion between the materials in the melted zone (b) in function of keyhole position (v_w = 1.8 m/min).

where S^i is the melted area of each of materials obtained from the isotherm positions in 2D model.

3.1. The effect of keyhole position

Due to the model, the simultaneous melting of all three materials is possible in the range of keyhole offsets of d = [−250; 800] μm (Fig. 2). The thickness of melted interlayer W depends non-linearly of keyhole position (Fig. 3a) and is determined by existing recirculation flows. In function of beam offset, two flow modes can be defined: (1) d = [500; 800] μm, where counterclockwise flow situated in copper and TA6V domains leads to their important mixing which makes joining impossible; (2) d = [−250; 400] μm, where two concurrent flows past the keyhole are observed. A minimal interlayer thickness in this second region corresponds to case when the keyhole is situated in the middle of the interlayer: the liquid base materials get close one to another as the recirculation flows collide after the keyhole. Two W maxima correspond to: (1) d = −200 μm, where the fusion of TA6V is minimized and the morphology of recirculation steel flux allows to maintain constant thickness of the interlayer; (2) d = 400 μm, where steel-rich flux does not create important recirculation movement, but TA6V mixes intensively with copper.

The variation of melted zone composition in function of keyhole offset (Fig. 3b) shows the domination of copper and steel, which the proportion does not vary much in the range of d = [−200; 600] μm. The content of TA6V remains low under d = [−300; 600] μm and increases rapidly under higher offsets. From the point of view of melted zone composition, the offset of d = −200 μm is more advantageous as it provides less TA6V melting comparing to d = 400 μm: the content of melted TA6V is only 3 vol.%, when for d = 400 μm it is of 8 vol.%.

3.2. The effect of welding speed

The variation of welding speed influences the development of recirculation movements through the change of weld composition and melted zone lifetime (Fig. 4). Under low welding speed (v_w = 0.6 m/min) the quantity of melted TA6V is important enough to develop the flux entering in copper interlayer, when copper/steel interface moves not much. The middle welding speed (v_w = 0.9 m/min) results on more or less constant interface thickness: the recirculation fluxes compensate each other. High welding speed (v_w > 1 m/min) induces more important development of steel recirculation flux, but the continuity of the interlayer is steel preserved. The maximal thickness of the interlayer is observed for v_w = 1 m/min (Fig. 5a).

In function of welding speed, the composition of the melted zone changes mostly because of the elongation of melted zone in the interlayer part (Fig. 5b): the amount of copper rises from 27 to 50 vol.% over the range of v_w of 0.3–2 m/min. The quantity of melted TA6V varies over several %, so it is more judicious to compare the welds by measuring the thickness of melted TA6V layer, which can be defined as a distance between initial TA6V/copper joint line and the isotherm T_m^{TA6V} ($x_{TA6V/copper} - x_{T_l^{TA6V}}$). For v_w < 1.2 m/min the

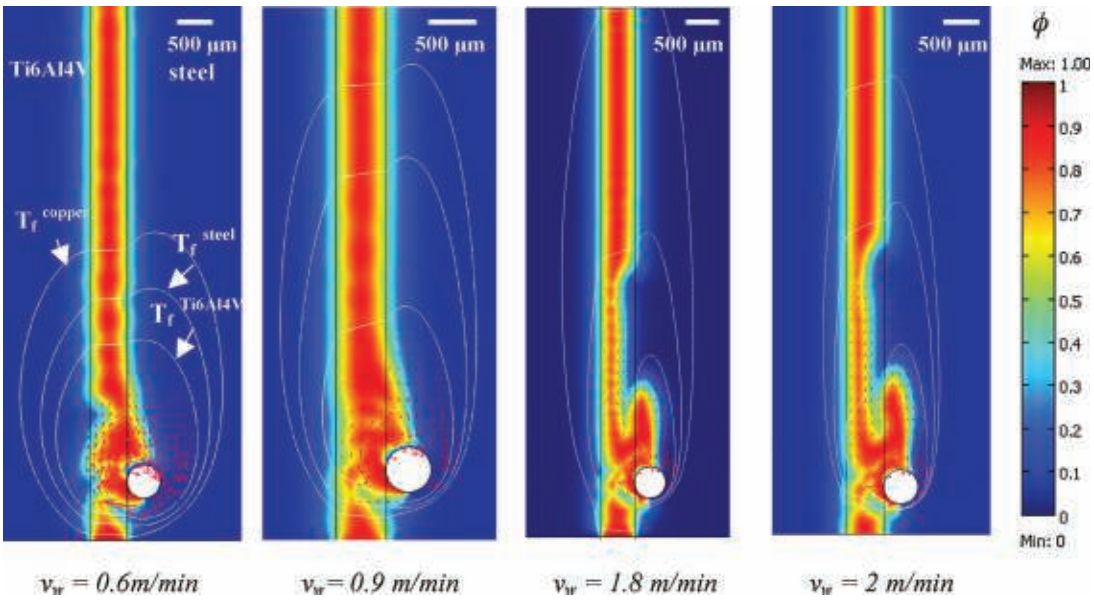

Fig. 4. The variation of weld morphology in function of welding speed (d = −200 μm).

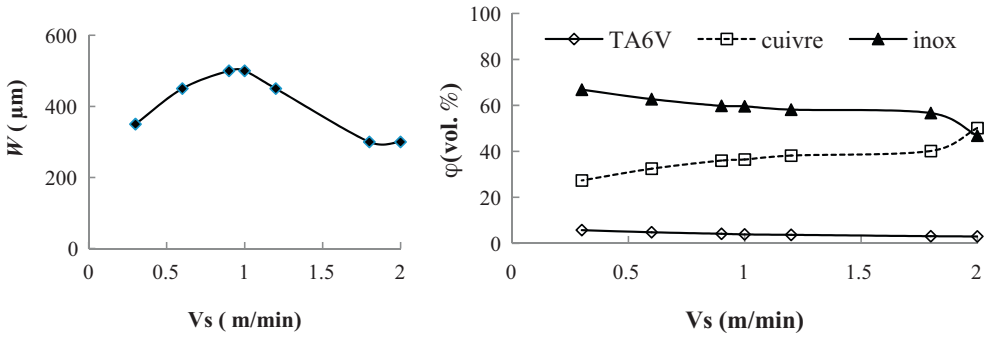

Fig. 5. The variation of minimal thickness of melted interlayer (a) and average composition of melted zone (b) in function of welding speed ($d = -200$ μm).

layer has 200–300 μm, which signifies the formation of relatively thick and compact zone of Ti_xCu_y crack-susceptible intermetallics. High speed of welding results on <100 μm layers, and is limited by 2 m/min (only 10 μm thick layer of melted TA6V). For $v_w = 1.5–1.8$ m/min TA6V layer has a thickness big enough to make joining possible (Tomashchuk, 2010): 30–50 μm. The thickness of copper interlayer over this range of v_w (≈300 μm) remains constant and sufficient for isolation of base materials.

3.3. The validation of the models

It can be concluded that the optimal condition for TA6V/copper/steel joining is situated in the region of $d = -200$ μm and $v_w = 1.5–1.8$ m/min. The experimental application of this condition has resulted in successful joining (ultimate tensile strength: 356 MPa), when the other tested keyhole positions of $d = 0$ μm, 200 μm, 500 μm do not allow to obtain the weld because of formation of brittle intermetallics. The parameters of electron beam have been adjusted in order to have a full penetration of 2 mm thick plates ($I = 40$ mA, $U_a = 25$ kV, focus point on top surface).

The morphology of calculated melted zone has been found to be in good correspondence with experiment (Fig. 6): the steel flux (1) entering in copper interlayer (2) reduces its length to 300 μm, when TA6V is only slightly melted. This difference between experimental (270–310 μm) and calculated interlayer thickness can be explained by influence of vertical convection effects induced by the contact of two liquid metals with different density. The calculated weld composition (40 vol.% copper, 3 vol.% TA6V) is in good correspondence with results of EDS analysis (37 vol.% copper, 5 vol.% TA6V).

Basing on optimal condition determined from level set based model, the calculation of Ti diffusion in copper has been carried

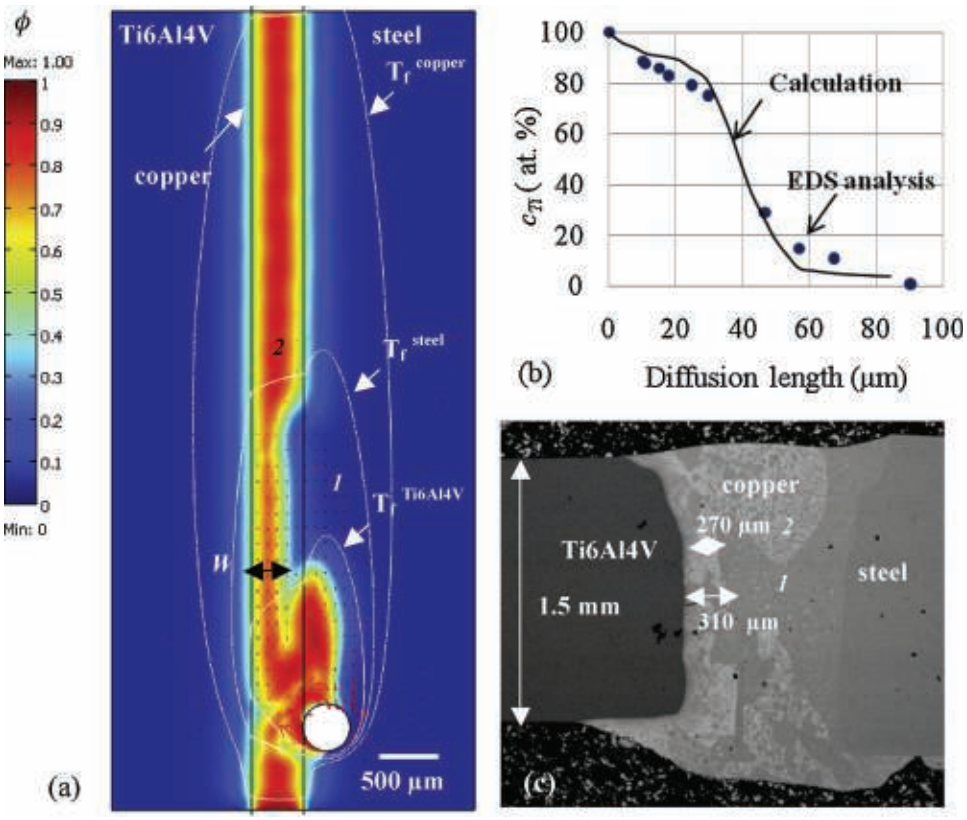

Fig. 6. The comparison of calculation results with an experiment (weld carried out under optimal conditions: $d = -200$ μm, $v_w = 1.8$ m/min): (a) melted zone morphology issued from level set based model, (b) a comparison between calculated and experimental Ti concentrations at TA6V-melted zone interface, and (c) SEM image of the weld.

out. In order to compare the results of the elemental EDS analysis with the model, local Ti amount (at.%) has been given as:

$$c_{\mathrm{Ti}}^{\mathrm{exp}} = \frac{c_{\mathrm{Ti}}^{\mathrm{EDS}}}{c_{\mathrm{Ti}}^{\mathrm{EDS}} + c_{\mathrm{Cu}}^{\mathrm{EDS}}} \cdot 100. \quad (11)$$

A comparison between calculated and experimental Ti diffusion profiles (Fig. 6b) shows a good concordance, which signifies sufficiently realistic representation of local temperature conditions and weak influence of local melt convection. The small length of the interface is determined by rapid cooling (10^3 K/s) and is close to the optimal Ti/Cu interlayer thickness obtained by diffusion bonding by Elrefaey and Tillmann (2009).

The Ti diffusion curve can be divided into three zones:

- x = 0–20 μm: 100–80 at.% Ti, which corresponds, due to Cu–Ti phase diagram, to the formation of the mixture $TiCu_2$ + α-β-Ti; due to experimental study (Tomashchuk, 2010), this is the most brittle zone of TA6V/copper/AISI 316L weld;
- x = 20–55 μm: rapid decrease of Ti concentration is observed; this region can contain numerous intermetallic phases as CuTi, Cu_4Ti_3, Cu_3Ti_2, Cu_2Ti;
- x = 55–85 μm: 7–4 at.% Ti, which corresponds to the formation of $TiCu_4$ and solid solution of Ti in Cu.

Basing only on Ti diffusion equation, which neglects possible presence of steel elements, it is difficult to preview the exact phase content across the interface. However, this 1D model may be interesting for studying the relation between intermetallics layer thickness and mechanical properties of the weld and presents a very first step to the model of local phase content.

4. Conclusions

A multiphysical finite element modeling of dissimilar welding via interlayer material is proposed. A 2D model including heat transfer, fluid flow and level set problems allows simulating the morphology and the composition of melted zone in horizontal plane. The deformation of melted interlayer is represented by level set function governed by previously calculated temperature and velocity fields. The level set field shows the tendency of liquid metals mixing and indicates the final state of copper interlayer. The present model can serve as a prediction tool for choice of operational conditions of keyhole welding via dissimilar interlayer, but neglects vertical convection, which slightly limits its precision.

The optimal condition for TA6V/copper/steel electron beam welding has been determined basing on such criteria: (1) the preservation of melted interlayer continuity; (2) the reduction of TA6V melting in order to minimize the quantity of intermetallic phases in the melt. The study of heat source position and welding speed influence on the morphology and the composition of melted zone indicates the presence of very narrow region of optimal conditions. The results of the modeling have been shown to be in good correspondence with experimental data.

The model of Ti diffusion at TA6V-melted zone interface allows the simple approach to description of dissimilar interface formation basing on known operational parameters and opens the perspective of local phase content prediction.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jmatprotec.2011.06.004.

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