Simulation model of Al-Ti dissimilar laser welding-brazing and its experimental verification

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Abstract. Formation of dissimilar weld joints of light metals and alloys including Al-Ti joints is interesting mainly due to demands on the weight reduction and corrosion resistance of components and structures in automotive, aircraft, aeronautic and other industries. Joining of Al-Ti alloys represents quite difficult problem. Generally, the fusion welding of these materials can lead to the development of different metastable phases and formation of brittle intermetallic compounds. The paper deals with numerical simulation of the laser welding-brazing process of titanium Grade 2 and EN AW 5083 aluminum alloy sheets using the 5087 aluminum filler wire. Simulation model for welding-brazing of testing samples with the dimensions of 50 × 100 × 2 mm was developed in order to perform numerical experiments applying variable welding parameters and to design proper combination of these parameters for formation of sound Al-Ti welded-brazed joints. Thermal properties of welded materials in the dependence on temperature were computed using JMatPro software. The conical model of the heat source was exploited for description of the heat input to the weld due to the moving laser beam source. The sample cooling by convection and radiation to the surrounding air and shielding argon gas was taken into account. Developed simulation model was verified by comparison of obtained results of numerical simulation with the temperatures measured during real experiments of laser welding-brazing by the TruDisk 4002 disk laser.

1 Introduction

Demands on the weight reduction and effort to achieve constantly better properties of components and complex large structures support the development in the field of joining of dissimilar materials. During last decades, intensive research has been targeted at the formation of joints from Al-Ti alloys [1-3]. The joining of these materials is interesting for automotive, aircraft, aeronautic, shipbuilding and other industries. However, fusion welding of Al-Ti alloys is quite difficult not only due to the large differences in melting temperatures and thermal properties of these materials but mainly owing to formation of brittle intermetallic compounds during weld metal solidification. Many methods have been investigated to join Al-Ti alloys, including arc and laser fusion welding [4-10], brazing [11-13], friction stir welding [14-16], explosion welding [17-19] or diffusion bonding [20-21] with the aim to suppress or minimize the growth of the brittle intermetallic phases.

In this paper, the laser welding-brazing process is applied to join sheets from titanium Grade 2 and EN AW 5083 aluminum alloy using the 5087 aluminum filler wire. The simulation model for numerical analysis of the dissimilar laser welding-brazing of Ti-Al alloys is developed and verified using temperature measurement during experimental joint formation.

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2 Problem description

Laser beam welding-brazing process is intended to exploit for joining of two sheets with the thicknesses of 2 mm from commercially pure titanium Grade 2 and the EN AW 5083-H111 aluminum alloy. The filler wire with the diameter of 1.2 mm from the 5087 aluminum alloy was chosen as a filler material. The chemical composition of welded and filler materials is given in the Table 1 and 2, respectively. Argon with the flow rate of 18 l.min^{-1} is supposed to be used as shielding gas to protect the weld bead and weld root during laser beam welding.

Table 1. Chemical composition of the titanium Grade 2.

Element	Fe	C	O	H	N	Ti
wt. %	0.3	0.1	0.25	0.015	0.03	balance

Table 2. Chemical composition of the EN AW 5083-H111 aluminum alloy and filler material.

Element	Mg	Si	Fe	Mn	Cu	Cr	Zn	Zr	Ti	Be	Al
Al alloy	4.7	0.4	0.31	0.26	0.19	0.13	-	-	-	-	bal.
Filler	4.5 – 5.2	≤ 0.25	≤ 0.4	0.7 – 0.1	≤ 0.05	0.05 – 0.25	≤ 0.25	0.1 – 0.2	≤ 0.15	$\leq 3.10^{-4}$	bal.

The following welding parameters were chosen for initial trials of laser welding-brazing process:

- the laser power from 1.8 kW to 2.0 kW,
- the welding speed from 25 mm.s^{-1} to 30 mm.s^{-1} and
- the laser offset of 300 µm from the weld centerline towards the aluminum sheet.

The influence of these parameters on the quality of dissimilar joints was studied numerically applying computer simulation of welding-brazing process in programme code ANSYS and also experimentally. The welding trials were performed with continuous wave TruDisk 4002 disk laser with the maximum power of 2.0 kW, the wavelength of 1.03 µm and the beam quality (BPP) of 8 mm.mrad. Laser beam was transported to the BEO D70 focusing optics via laser light cable with the core diameter of 400 µm. The disk laser beam was focused at +2 mm above the surface of welded samples. During experiments, the temperatures were measured by two thermocouples of the K-type placed on the top side of titanium plate and bottom side of aluminum plate, respectively, in the distance of 5 mm from the weld centerline. Results of experimental temperature measurements were used for the verification of results of numerical simulations.

3 Simulation model for the analysis of temperature fields during laser welding-brazing

Transient temperature fields developed during laser welding-brazing process can be described by the heat diffusion partial differential equation in the form [22]

$$\rho c_{\mathrm{p}} \frac{\partial T}{\partial t} = \left[\frac{\partial T}{\partial x}\left(\lambda_{\mathrm{x}} \frac{\partial T}{\partial x} \right) + \frac{\partial T}{\partial y}\left(\lambda_{\mathrm{y}} \frac{\partial T}{\partial y} \right) + \frac{\partial T}{\partial z}\left(\lambda_{\mathrm{z}} \frac{\partial T}{\partial z} \right) \right] + q_{\mathrm{v}} . \quad (1)$$

where $T(x, y, z, t)$ is the temperature [°C, K], t is the time [s], ρ is the density [kg.m^{-3}], c_{p} is the specific heat [J.kg^{-1}.K^{-1}], λ_{x}, λ_{y}, λ_{z} are the thermal conductivities [W.m^{-1}.K^{-1}] in the x, y, z directions of Cartesian coordinate system and q_{v} is the volumetric density of internal heat sources [W.m^{-3}], i. e. the heat generated in the unit volume of material per unit time. To solve the Fourier-Kirchhoff´s partial differential equation (1), it is necessary to define geometrical, physical, initial and boundary conditions, i. e. geometrical shapes and dimensions of welded components, thermo-physical properties of welded materials, intensity of internal heat sources, initial temperature distribution at the beginning of the welding process and also the conditions and thermal effects at the interface of welded structures and environment.

Geometrical model consists of two plates with the dimensions of 50 mm × 100 mm × 2.0 mm. The geometry of a weld joint including the filler material (figure 1a) was proposed on the base of previous similar experiments [23]. The 3D finite element mesh (figure 1b) was generated using the element type of SOLID 70 in the ANSYS software [24].The mesh density was higher in the region of the weld pool and the heat affected zone where the largest temperature gradients are supposed. The finest mesh density perpendicular to the weld line was 0.005 mm. The length of elements in welding direction was constant with the value of 0.2 mm.

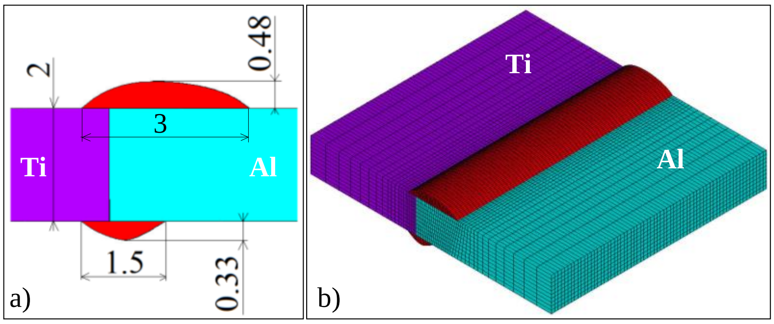

Figure 1. Geometry of the weld joint (a) and a detail from the generated FE mesh (b).

Thermo-physical properties of the Ti Grade 2, Al base material and filler wire in the dependence on temperature (figure 2) were computed using the JMatPro software [25]. Titanium Grade 2 represents commercially pure titanium (99.2 wt. %) with the solidus temperature of T_S = 1665 °C and the liquidus temperature of T_L = 1713 °C. The equilibrium solidus and liquidus temperatures for the AW 5083 alloy were computed to be 575 °C and 635 °C, respectively. The transformation temperatures for filler material are similar with the values of T_S = 573 °C and T_L = 635 °C. The enthalpy of fusion was modeled applying the method of modified specific heat [24].

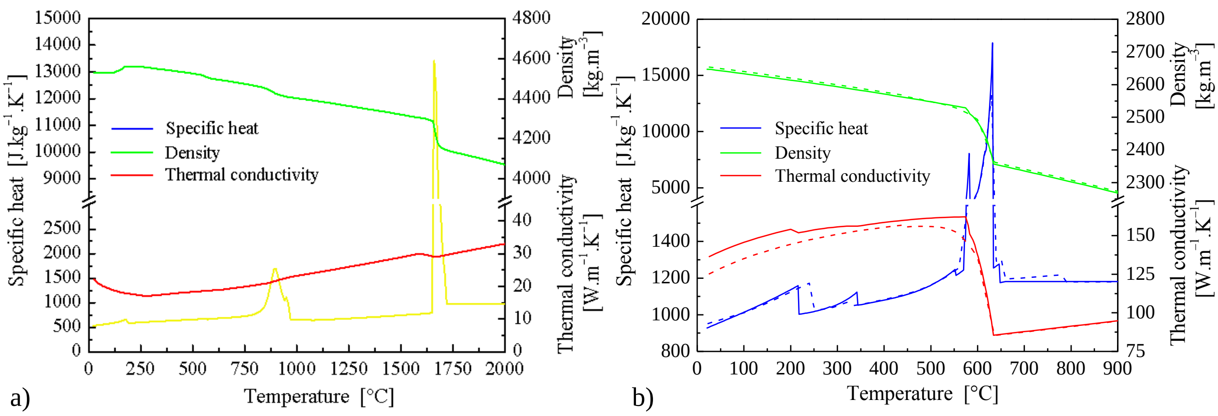

Figure 2. Thermal properties of the a) Ti Grade 2 and b) AW 5083-H111 alloy and filler material. in the dependence on the temperature

The initial condition can be written in the form

$$T(x, y, z, t = 0) = T_0(x, y, z) \tag{2}$$

where T_0 is the initial temperature of welded components. The initial temperature of plates was supposed to be 20 °C.

The boundary condition of the 3rd kind [22] was exploited for the definition of welded plates cooling by convection and radiation to the argon shielding gas and surrounding air

$$-\lambda \frac{\partial T}{\partial \mathbf{n}} = h(T_w - T_f) \tag{3}$$

where T_w [°C, K] is the sample surface temperature, T_f [°C, K] is the surrounding fluid temperature and h [W.m^{-2}.K^{-1}] represents the combine heat transfer coefficient given by the sum of convection heat transfer coefficient h_C and radiation heat transfer coefficient h_R

$$h = h_C + h_R = h_C + \frac{\varepsilon \sigma_0 \left(T_w^4 - T_f^4\right)}{T_w - T_f} \tag{4}$$

where ε [-] is the emissivity and σ_0 is the Stefan-Boltzmann´s constant. The values of the combine heat transfer coefficient for the top and bottom surfaces of welded plates were computed using classical criterial equations [22] and entered to the ANSYS software in the dependence on the surface temperature.

The heat input in fusion welding can be modeled by different methods including moving point or line heat sources, surface or volumetric heat sources. For presented numerical simulation of laser welding-brazing of Ti-Al plates, the 3D conical volumetric heat source model (figure 3) was applied. The volumetric density of internal heat source q_v [W.m^{-3}] is given by the function [26]:

$$q_v(x,y,z) = \frac{9\eta Q_0 e^3}{\pi(e^3-1)} \frac{1}{(z_e - z_i)(r_e^2 + r_e r_i + r_i^2)} \exp \frac{3(x^2+y^2)}{r_0^2(z)} \tag{5}$$

where Q_0 [W] is the maximum heat source intensity, η is the efficiency, r_e [m] and r_i [m] are the surface radii in planes, $z = z_e$ and $z = z_i$, respectively and x, y, z are the coordinates of the instant position of the heat source.

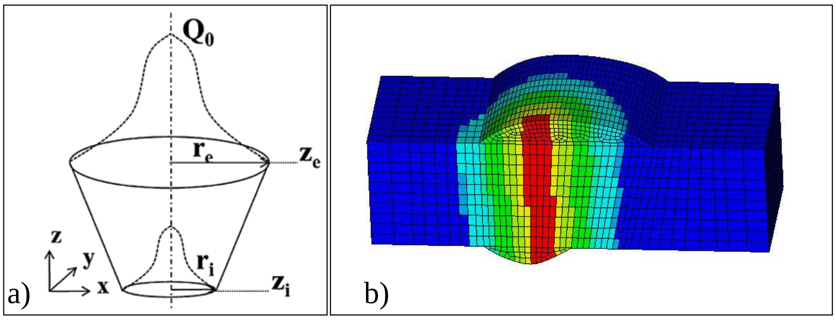

Figure 3. 3D conical heat source [27] and the scheme of its application to the FE model.

4 Results of numerical simulation and their comparison with experiments

Numerical simulations of laser beam welding-brazing of plates from dissimilar Ti-Al alloys were performed using the ANSYS software with the laser power of 1.8 kW and the welding speed of 25 mm.s^{-1} in the experiment 1 and the laser power of 2.0 kW and the welding speed of 30 mm.s^{-1} in the experiment 2. In both cases the laser offset was set to 300 µm from the weld centerline towards the aluminum sheet. Adjusting of parameters defining the conical heat source model led to setting the values of r_e and r_i to 1.3 mm and 1.1 mm, respectively. According to the previous experience, the efficiency of laser heat source was supposed to be 63 %.

For illustration, the details of computed temperature fields in the time of 0.6 seconds are shown in figure 4. The top views depict the asymmetric temperature distribution in the in the Al and Ti plates developed during the laser welding-brazing process. The asymmetry of temperature fields results mainly from the differences in thermal properties of welded materials. Some influence can be assigned also to the laser beam offset towards the Al plate. For both considered welding speeds, the laser power seems to be too high as the maximum temperatures exceed the liquidus temperature of both joint materials. The width of molten zone is comparable for both experiments as it can be seen from the temperature fields in the cross-sectional area in figure 4.

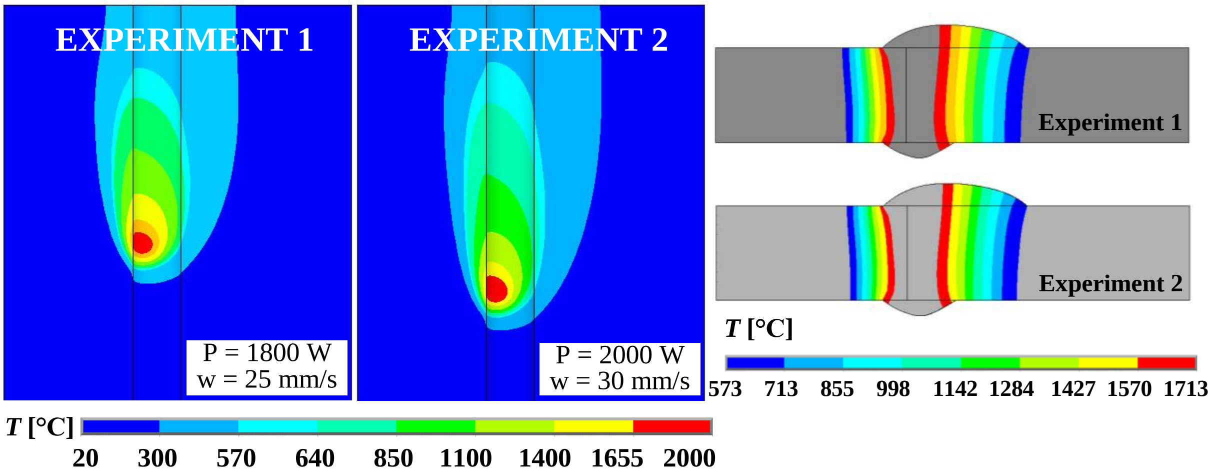

Figure 4. Details from the temperature fields in the time of 0.6 seconds – top view and the weld cross-sections perpendicular to the weld line.

Figure 5 illustrating the macrostructures of welded-brazed joints prepared in experiment 1 and 2 confirms the melting-down both joint materials. It is necessary to note that the weld joint during successful welding-brazing of Ti Grade 2 and AW 5083-H111 aluminum alloy should be formed by molten filler material and Al-alloy and molten filler and solid titanium. By this way it is possible to avoid the development of brittle intermetallic compounds during rapid solidification of molten and mixed Ti and Al alloys. In this reason, the decrease in laser power is recommended for following computations and also experimental joining if the welding speed remains in the interval from 25 mm.s^{-1} to 30 mm.s^{-1}. Another possibility is to increase the welding speed. This alternative can lead to the positive consequences concerning reduction of molten and heat affected zones. Moreover, the laser beam offset from the weld centerline towards the aluminum sheet which was 300 μm can be increased to avoid melting of the Ti Grade 2 sheet.

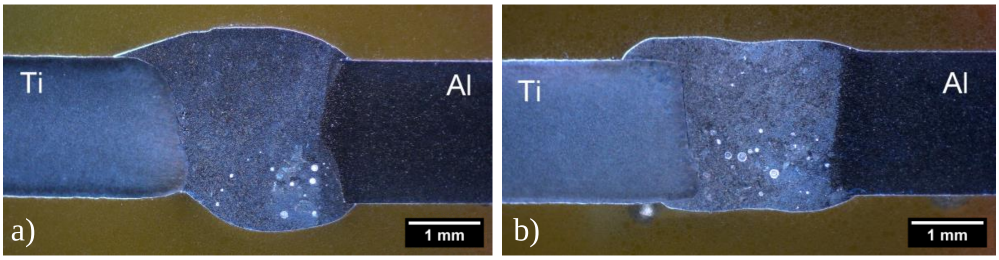

Figure 5. Macrostructures of welded-brazed joints prepared with different welding parameters in a) experiment 1 and b) experiment 2.

In figure 6, the time dependences of computed and measured temperatures for the experiment 1 and experiment 2 are plotted. Comparison of computed and experimental results indicates a good agreement between the numerically and experimentally obtained temperatures on both, Al and Ti sides. However, the computed temperatures are slightly lower than the measured ones. The temperature differences result mainly from the accuracy of the thermocouples location. The next cause for higher measured temperatures is the higher initial and surrounding temperature during the experiments realized in hot summer-time.
In spite of good compliance of computed and experimentally measured temperatures, application of additional thermocouples placed at the distances closer to the weld centerline is advised for the following experiments in order to record the more accurate temperature profile during laser welding-brazing process.

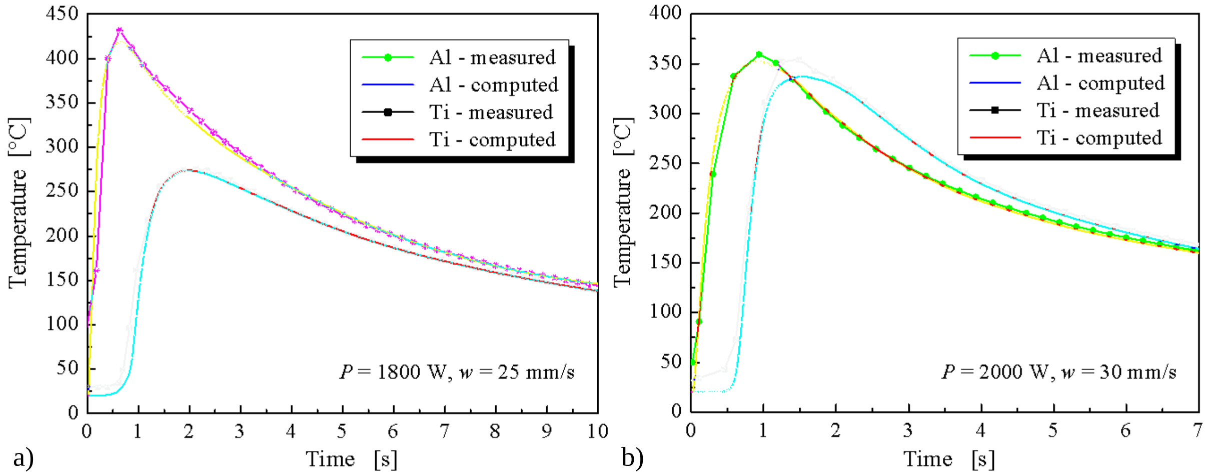

Figure 6. Comparison of computed and measured temperatures during the welding-brazing Ti-Al alloys a) experiment 1 and b) experiment 2.

5 Conclusions

The simulation model for the numerical analysis of the laser welding-brazing of sheets from titanium Grade 2 and EN AW 5083 aluminum alloy using the 5087 aluminum filler wire was developed and verified by the temperature measurements during the laser welding-brazing of experimental samples by the TruDisk 4002 disk laser using the values of laser power from 1800 W to 2000 W and welding speeds of 25 mm.s^{-1} and 30 mm.s^{-1}, respectively. For both compared cases, a good agreement between computed and measured temperatures was achieved.

In the next work, the described simulation model will be used for the investigation of the influence of welding parameters on the temperature fields developed during the laser welding-brazing of dissimilar Ti Grade 2 and EN AW 5083 aluminum alloy plates in order to design optimal parameters for formation of sound dissimilar weld joints.

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