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Modelling of temperature-controlled laser joining of aluminum and galvanized steel

Daniel Weller[a,*], Florian Fetzer[a], Rudolf Weber[a], Thomas Graf[a]

[a]*Institut fuer Strahlwerkzeuge, University of Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany*

Abstract

Numerical modelling of a temperature-controlled laser joining process of aluminum to galvanized steel is presented. First, the temporal evolution of the interface temperature is calculated by the use of an integrated virtual proportional-integral-derivative (PID) controller. The obtained interface temperature is then used to predict the thickness of the intermetallic layer by solving Fick's second law assuming one-dimensional diffusion and considering the temperature dependence of the diffusion coefficient. The results show good agreement with experimentally obtained values of the thickness of the intermetallic layer.

Keywords: Laser joining; dissimilar materials; temperature control; intermetallic phase; process modelling

1. Introduction

Reliable laser joining of 6000 series aluminum alloys to galvanized steel is a challenge for current manufacturing technologies due to the formation of brittle intermetallic phases. The extent of these phases depends on the thermal cycle during the joining process. Weller et al., 2016 showed a temperature-controlled laser joining process which allows stable and reliable process conditions. Key feature of this process was a pyrometer device, which was controlling the applied laser power by measuring the temperature on the surface of the processed material. This enabled a defined thermal cycle of the joining process which leads to reliable mechanical properties. This approach was following previous work e.g. by Peyre et al., 2007. Thereby liquid aluminum, molten in a heat-conduction laser-weld process, spread and wetted a solid steel surface, to generate a sound intermetallic phase spatially limited to the contact zone. In

* Corresponding author. Tel.: +49 711 685 64146.
E-mail address: daniel.weller@ifsw.uni.stuttgart.de.

this process the growth of the intermetallic phases is mainly driven by diffusion which is dependent from the diffusion time and the process temperature.

In this proceeding modelling of this temperature-controlled laser joining process is presented which allows to calculate the thickness of the intermetallic layer as a function of the process parameters.

2. Modelling of the laser joining process

2.1. Interaction time

The thermal modelling of the laser joining process is based on a Volume-of-Fluids model within the OpenFOAM environment. The thermal modelling uses several assumptions. For solving the heat conduction equation, only conductive heat flow was taken into account. The three-dimensional simulation uses constant values for the heat conductivity, heat capacity, and density. Fig. 1 (a) shows a typical temperature

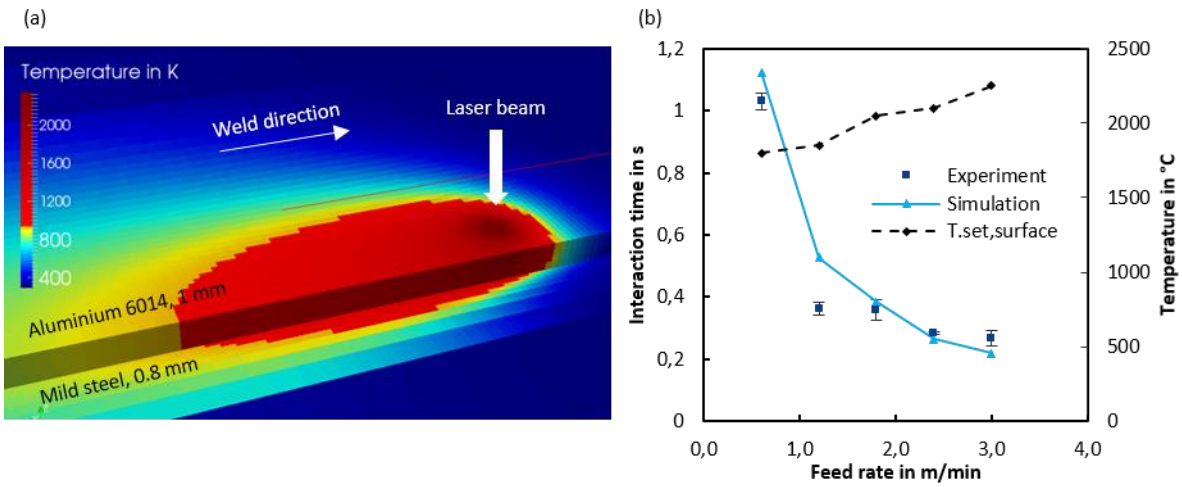

Fig. 1. (a) Typical temperature distribution resulting from Volume-of-Fluids modelling of the temperature-controlled joining process of aluminium to steel; (b) Comparison of interaction time from experiment and simulation related to the feed rate. Second y-axis shows applied set temperature on surface of the aluminium sheet. (d_f = 2250 µm, edge distance to centre of beam a = 1.5 mm).

distribution resulting from finite volume modelling and the investigated joining geometry. The top sheet of the joint was a 6014 aluminum sheet with a thickness of 1 mm and the bottom sheet was a 1.0322 mild steel with a thickness of 0.8 mm. The heat input was applied on the surface of the aluminum sheet with a Gaussian intensity distribution corresponding to the intensity profile of the incident laser beam. Analogous to the temperature-controlled process shown by Weller et al., 2016 a virtual proportional-integral-derivative (PID) controller was implemented to control the heat input on the surface in dependence on the simulated temperature. In Fig. 1 (b) the results of the thermal modelling are compared with the experimental results. The light blue triangles connected with a solid line (simulation) and the dark blue squares (experiment) show the interaction time (left y-axis) during which diffusion takes place as a function of the feed rate. The interaction time was defined as the length of the melt bath divided by the feed rate. For the experimental values the length of the melt bath was evaluated from high speed videos. For the simulation values, the largest extent of the melting temperature isotherm in direction of the feed was defined as melt bath length. In addition, the set temperatures used for the temperature-controlled experiments is shown (black

diamonds with dashed line). These experimental set temperatures were used as an set point value for the virtual PID controller in the simulation. The simulation is in good agreement with the experimental data.

2.2. Thickness of the intermetallic layer

The results obtained from the thermal modelling were used for calculating the layer thickness of the intermetallic phases at the contact zone in a post processing step. This post processing is based on diffusion as described by Fick's laws. Referring to Jost, 1960, the diffusion coefficient is temperature dependent and can be described by using the Arrhenius functions. Solving Fick's second law for one-dimensional diffusion for the system Al-Fe as shown by Radscheit, 1997, and using the temperature dependent description of the diffusion coefficient obtains the diffusion length

$$x^2(t) = \int_{t_{start}}^{t_{end}} 2 \cdot k_0 \cdot exp\left(\frac{-Q}{R \cdot T_{interface}(t)}\right) dt \qquad (1)$$

where x is the diffusion length, k_0 is the pre-exponential diffusion factor, t is the diffusion time, Q is the activation energy for the diffusion, R is the universal gas constant and $T_{interface}$ is the absolute temperature at the interface. The point in time when $T_{interface}$ exceeds the melting point of aluminum is defined as t_{start}. The point in time when $T_{interface}$ falls below the melting point of aluminum again is defined as t_{end}.

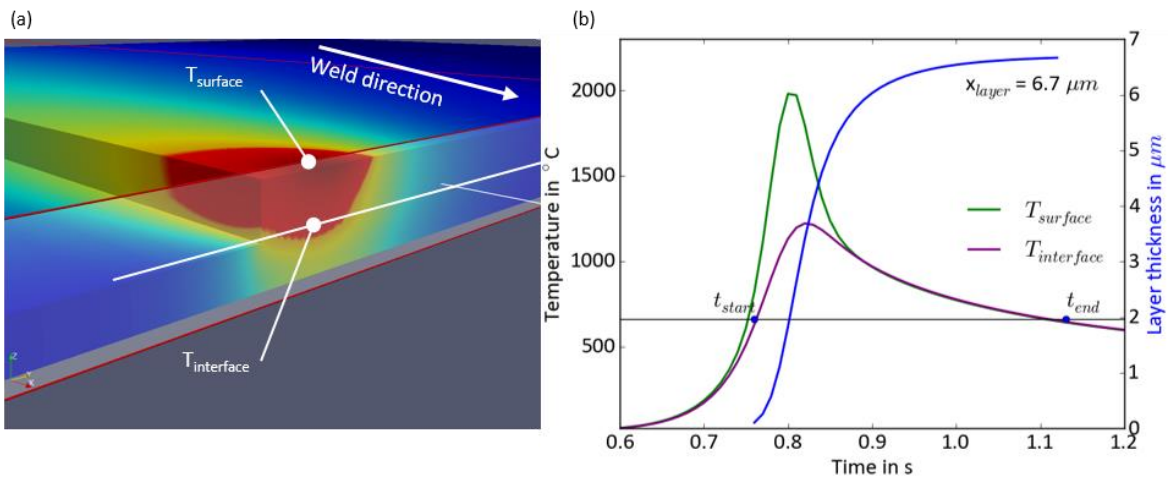

Fig. 2. (a) Section transverse to the weld direction showing the position of $T_{surface}$ and $T_{interface}$ in the simulation at t = 0.8 s; (b) $T_{surface}$ (green line) and $T_{interface}$ (purple line) as a function of time. Growth of intermetallic layer (blue line, right y-axis) as a function of time. (d_f = 2250 µm, set temperature T_{set} = 2000°C, edge distance to centre of beam a = 1.5 mm, v = 1.8 m/min).

In Fig. 2 (a) a section of the simulated temperature field transverse to weld direction is depicted. For this simulation a beam diameter of $d_f = 2250\ \mu m$, a set temperature of $T_{set} = 2000°C$ and a feed rate of $v = 1.8\ m/min$ was used. The distance from the edge of the sheet to the center of the laser spot was $a = 1.5\ mm$. Fig. 2 (a) shows the positions for the evaluation of $T_{surface}$ and $T_{interface}$ from the simulation, which are plotted in Fig. 2 (b) as a function of time. In previous work by Bouayad et al., 2003 it was shown that Fe_2Al_5 is the main intermetallic phase growing at temperatures slightly above the melting temperature of aluminum. Therefore, we assumed the formation of Fe_2Al_5 as only occurring intermetallic phase in our calculations. For the diffusion coefficient of Fe_2Al_5 we used data from a study about hot-dip aluminized

coatings for the corrosion-resistance of steel sheets by YIN et al., 2013. For an aluminum alloy with a content of silicon of 3.0% the pre-exponential diffusion factor is $k_0 = 0.69 \cdot 10\text{-}3\ m^2 \cdot s^{-1}$ and the activation energy is $Q = 172\ kJ \cdot mol^{-1}$. The amount of silicon correspondents approximately to the 6000 series multi-alloy aluminum from Novelis used in the experiments as shown by Bezençon et al., 2014. Applying the modelled temperature curve of $T_{interface}$ shown in Fig. 2 (b) to equation 1, the layer thickness of the intermetallic phase results in $x_{sim} = 6.7\ \mu m$ which agrees very well with the value obtained from experiments of x_{exp} = 6.4 µm.

3. Summary

With the presented thermal modelling and the simplified assumptions for the calculation of the thickness of the intermetallic phase, it was possible to correlate the process parameters speed, focal diameter, and laser power to the resulting intermetallic phase layer responsible for the mechanical properties of the joint. The results of the simulation were in a good agreement with the experiments.

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