Simulation of the Dissimilar Joining Process of Aluminum and Steel by Laser Assisted Wetting

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Abstract. This paper shows an analysis of the transient dynamics during the dissimilar joining process of aluminum-steel along with a comparison of the final results with experimental data. The development of a multiphysical model within OpenFOAM® simulation software comprising diffusion and reaction physics allowed to simultaneously obtain both, macro- and mesoscale effects, such as the surface wetting and the growth of the intermetallic layer.

1 Introduction

Laser welding of dissimilar materials usually presents the challenge of complex material interactions and process mechanisms that are not yet fully understood on the profoundest level. Dissimilar laser welding has been studied extensively over the last decades by means of empirical methods. However most of the numerical studies on dissimilar laser welding were aimed at providing thermal reference profiles e.g. [1] and to this day works including the effects of melt pool dynamics are very few.

In this work we made use of a multi-physical model capable of simulating the whole process on macro- and mesoscale from melt pool dynamics to formation of intermetallic compounds.

2 Simulation model

The model is based on our multi-physical model for laser assisted processing developed within an OpenFOAM® environment. Detailed descriptions of the model can be found in [2-3]. Additional development of temperature-dependent models for diffusion [4] and species reaction [5] allowed to simulate the growth of the intermetallic layer.

3 Application to aluminum-steel welding

We made use of experimental results of former projects [6, 7], concerning laser beam welding of aluminum and steel in an overlap configuration. In a first instance, we reproduced the macroscopic features. After that, we made use of 2D simulations to obtain an estimation of the thickness of the intermetallic layer.

3.1 Experimental conditions

Joining of sheets of a low-alloyed steel (DC01) and a weldable AlMgSi aluminum-alloy (AW6016) had been chosen. Thickness was 1 mm for both steel and aluminum plates. The sample had been welded in an overlap configuration with an overlap factor of 1.5 mm. A 3 kW lamp pumped Nd:YAG laser guided by means of a 600 µm fiber had been used. The laser radiation had been focused by a lens of a focal length of 250 mm. Lateral alignment of the focal spot of the laser had been kept at a constant distance of 0.5 mm measured from the edge of the sample and the axial focal position 40 mm above the steel plate (surf. spot diameter of about 4 mm). Line energy had been 107 J/mm (scanning speed = 15 mm/s). Shielding gas (argon) had been used, as well as flux. Figure 1 shows the cross section of the weld joint.

3.2 Simulation of the macroscopic features

Figure 2 shows the different stages of the process for an exemplary cross section. The predominant energy source of the process is the absorption of the laser light by the steel plate. The amount directly absorbed by the aluminum plate does not play any relevant role compared to the direct heat conduction. Note that the isothermal lines reach the backside of the steel plate right at the end of the aluminum plate first, exactly at the end of the area of enhanced heat removal. Unsurprisingly this is the point where aluminum melting starts. At the same time also the steel surface has begun melting. As the melting front advances into the aluminum plate, wetting propagates to the other side. When the melting front reaches the edge of the steel plate, a second wetting along the edge.

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commences, providing an even more efficient heat removal from the steel plate. Once the laser has passed and the plates begin to cool down aluminum starts to solidify. Two confronting solidification fronts can be identified. Interacting adhesive and cohesive forces form different angles of the free surface over the region. As shown in Figure 1, this effect can be seen in the experimental sample under the same conditions. It must be accentuated that despite neglecting effects of welding flux or oxidation of the surfaces in the model the final length of the wetting achieved is about 3mm in simulation results, which is remarkably consistent with the experimental results.

3.3 Growth of the intermetallic layer

The advantage of laser wetting is that the process can be performed within temperatures marginally above the melting point of aluminum. Mixing of both metals in liquid state can be thus avoided limiting diffusion.

According to the iron-aluminum phase diagram, a solution with high concentration of aluminum at temperatures slightly above the melting point should only promote formation of FeAl$_3$. However, according to the literature Fe$_2$Al$_3$ grows much faster than FeAl$_3$ in the

Figure 1. (a) Cross section of the weld joint (laser light from underneath) [7]; (b) thickness of the intermetallic layer at the wetting front [7]; (c) thickness of the intermetallic layer at the corner [7].

Figure 2. Evolution of the joining process step by step for a cross section. (a) thermal profile (the arrow indicates the incidence of the laser light); (b) to (d) molten fractions of the metals.
homogeneous transversal growth. In that case, we can expect the phase to be gradually filling the cells from the interface outwards, thus its volume fraction multiplied by the transversal cell dimension yields the layer thickness. In the Figure 3 c) the cells at the interface have a width of 83 µm and a height of 28 µm. According to the phase level shown, the calculated layer thickness is less than 8 µm at the top and less than 3 µm at the right-hand side. Similarly, the calculated layer at the wetting front, in Figure 3 b), is less than 5 µm thick. These values are in reasonable agreement with the experimental results.

4 Summary and outlook

By using a multi-physical model for laser material processing it has been possible to simulate the welding of a complex dissimilar metal pairing such as aluminum and steel. The model applied for this study is being used with reasonable success for the simulation of other different processes namely laser assisted ablation, cutting and deep penetration welding among others at the same time. Further developments include the formation of different intermetallic phases and thermal-induced stress fields.

References