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Simulation of the buttonhole formation during laser welding with wire feeding and beam oscillation

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Abstract

The gap bridge ability in laser welding of butt joints can be enhanced by wire feeding and beam oscillation. However, effects of them on the molten pool like the surface improvement by the so-called buttonhole discovered and named in previous experimental research by the authors are not understood. Thus, comprehensive models to simulate wire feeding and melting behavior in combination with beam oscillation are newly suggested in this work. A three-dimensional transient simulation has been conducted for laser welding of butt joints with large gaps. As result, realistic solid wire feeding and its melting behavior as well as the formation of the buttonhole can be shown by simulations. It was found that the buttonhole is induced by the keyhole in the molten pool and the formation is affected by the shape of wire tip.

Keywords: numerical simulation; laser welding; wire feeding; beam oscillation

1. Introduction

Using additional filler wire has advantages in laser welding such as good gap bridge ability even with large air gap and controlling metallurgical properties. Aalderink et al., 2010, used dual beams, generated by beam shaping optics, with filler wire to increase gap bridging capability. However, the misalignment of the wire can cause problems. Coste et al., 1994, suggested a laser welding process with a combination of wire feeding and beam oscillation to compensate positioning errors of the wire. Albert et al., 2016, showed a positive influence of oscillation without filler material on weld seams by reducing defects. Haglund et al., 2013,

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studied autogenous laser welding of thin metal plates without beam oscillation and found a comparatively wide keyhole and named the process laser donut welding. In typical laser keyhole welding having a deeper depth than a width of the weld, the surface tension acts to close the keyhole, whereas the recoil pressure tries to keep it open, see e.g. Volpp et al., 2016. However, a hole which is larger than the typical keyhole was found when the hole had catenoid shape having the smallest surface area. In pulsed welding, the catenoid shape helps to improve weld qualities but in continuous wave welding it is recommended to avoid catenoid formation because it can remain as a defect in the solidified seam, see Aalderink et al., 2007.

Similar phenomena were also reported and explained in the former experimental research of the authors. Schultz et al., 2014 and 2015, studied laser welding of 1 mm thin aluminum sheets with air gap using wire feeding and beam oscillation. The process design enhanced gap bridging ability significantly (maximum gap size > 300% of the thickness of the sheet). The so-called buttonhole was discovered and named during the investigation for 1 mm air gap, see Vollertsen, 2016. It seems that the process design – especially with buttonhole formation – improves the surface quality but the effects have not been fully understood. Thus, in this study comprehensive models of wire feeding and melting behavior in combination with beam oscillation are newly suggested to understand the buttonhole welding using CFD simulations (Computational Fluid Dynamics).

2. Method

An IPG fiber laser was used for welding aluminum alloy sheets (AlSi1MgMn) of 1 mm thickness with air gap of 1 mm. Aluminum alloy filler wire (AlSi5) of 1.2 mm diameter was used to fill up the gap. Laser beam focused on the upper surface of the sheets was oscillated transversal to the welding direction. In combination with the process feed a sinusoidal shaped path resulted on the workpiece. Schematic description of the process is shown in Fig. 1 and welding parameters are given in Table 1. Four cases with different oscillation frequencies were tested on the purpose of analyzing their effect on buttonhole welding. Fig. 2 shows a schematic description of the computational domain. Solid (room temperature) wire feeding and laser beam oscillation are modeled. The minimum size of cells used around molten pool region is 0.2 mm. The total number of cells is about 0.1 million. Thermophysical material properties of aluminum alloy and pure aluminum used in numerical simulations are shown in Table 2. In the computational domain, the governing equations of mass, momentum and energy conservation equations were solved to simulate molten metal flows. In addition, the Volume-of-Fluid (VOF) method was used to calculate the free surface being especially necessary to understand the buttonhole formation. Finally, a scalar conservational equation for the solid wire fraction was adopted to calculate the mixing of filler wire in molten pool. A single-phase, incompressible laminar flow with Newtonian viscosity was assumed for simplicity.

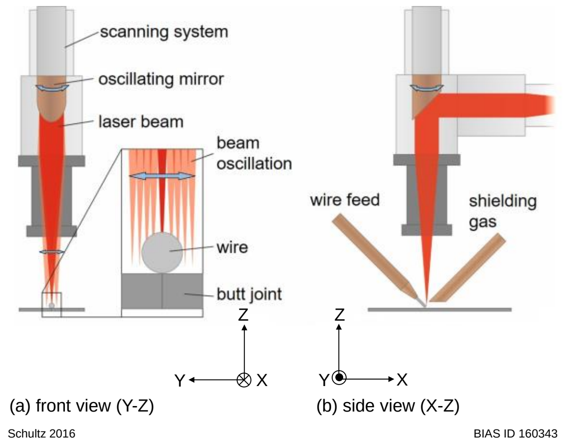

Fig. 1. Schematic illustration of the experimental setup

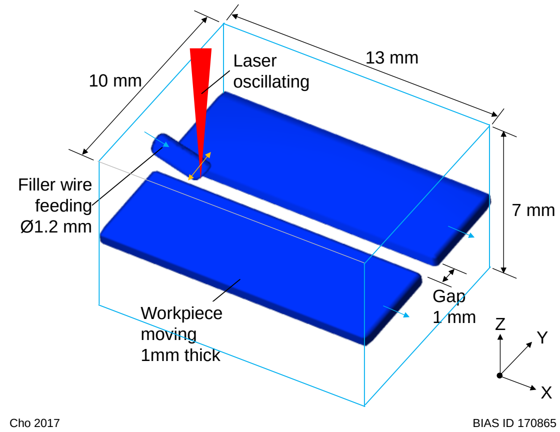

Fig. 2. Computational domain of the laser welding process with wire feeding and beam oscillation

Table 1. Welding parameters

Parameter	Values
Laser power	3.0 kW
Focus diameter	100 μm
Welding speed	6.0 m/min
Wire feeding speed	9.0 m/min
Oscillation frequency	100, 150, 200, 250 Hz
Oscillation width	1.4 mm

Table 2. Thermophysical materials properties

Properties	Values
Density	$2.7\ g/cm^3$
Thermal conductivity	1.7×10^7 erg/cm K s
Viscosity	1.15×10^{-2} g/cm s
Surface tension*	871 dyne/cm
Surface tension gradient*	-0.155 dyne/cm K
Specific heat	8.5×10^6 erg/g s K
Latent heat of fusion	3.36×10^9 erg/g s
Latent heat of vaporization*	1.05×10^{11} erg/g s
Solidus temperature	847 K
Liquidus temperature	905 K
Boiling temperature*	2743 K

*Data for pure aluminum.

Further information to laser beam welding models can be found in previous works of the authors, Cho at al., 2010 and 2012. In this study, 177 energy bundles with the Gaussian-like distributions are predefined along the axis of the beam. Then, a ray-tracing algorithm is used to estimate the multiple reflections on the free surface. A Fresnel reflection model is used to calculate reflectivity of the circularly polarized laser beam on the material. In addition, recoil pressure model, Allmen et al., 1995, the buoyancy force and the bubble model are considered. However, models of the shear stress on the keyhole surface and of the heat transfer to the molten pool via a plasma plume are not considered because vapor can escape very easily because of conditions of the formation of the buttonhole as well as full penetration.

As boundary conditions on the free surface, energy and pressure conditions are considered. The energy balance of the laser heat flux, the heat dissipation by convection and radiation is expressed by Eq. (1).

$$k\frac{\partial T}{\partial \vec{n}} = q_L - q_{conv} - q_{rad} = q_L - h(T - T_0) - \varepsilon_r \sigma (T^4 - T_0^4) \quad (1)$$

Here, $\vec{n}$ is the vector normal to the local free surface, □ is the convective heat transfer coefficient, T_0 is the ambient temperature, ε_r is the surface radiation emissivity, and σ is the Stefan-Boltzmann constant. The pressure balance is expressed as shown in Eq. (2).

$$p = p_r + \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \quad (2)$$

Here, R_1 and R_2 are the principle radii of the surface curvature by the Young-Laplace equation. If $R_1 = -R_2$ in the second term of the right-hand side of Eq. (2), which means that the surface has a catenoid shape, and $p_r = 0$, the local surface pressure is equal to zero in Eq. (2). However, the same situation is unlikely to happen in real welding because of the surface tension gradient of materials and different boundary conditions. But, it would be still helpful to explain the phenomenon that a big hole separable with typical keyhole can be formed and maintained.

All the governing equations with upper mentioned models are discretized and solved by finite-difference (or finite-volume) approximations in the Flow3D CFD commercial code, Flow Science, Inc., 2016. Simulating 0.1 s of laser welding requires the wall clock time of about 13 minutes, with Intel® Xeon® CPU E5649 and 48 GB RAM.

3. Results

Fig. 3 and 4 show high speed camera images of experiments and numerical results of simulations for the different oscillation frequencies of 100 Hz and 250 Hz, respectively. The formation of the buttonhole could be calculated by simulations. At the low frequency, a keyhole was shown at both ends of oscillation. However, it did not grow up to the size of a buttonhole. The buttonhole started to be observable at the higher frequencies. The length of wire tip L_t became shorter and the wire melting angle Θ between the wire front and the welding direction became larger with increasing frequency. At the low frequency, the wire having a long, sharp cutting edge could interrupt the movement of the enlarged keyhole to the molten pool center as shown in Fig. 5. The buttonhole could obtain at the high frequency because the wire did not interrupt the movement of the enlarged keyhole as shown in Fig. 6.

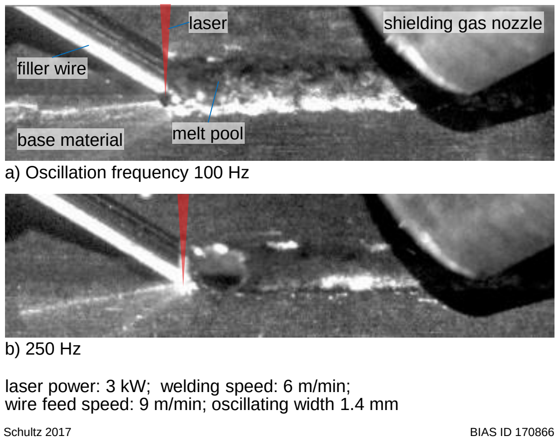

Fig. 3: High speed camera images of experiments

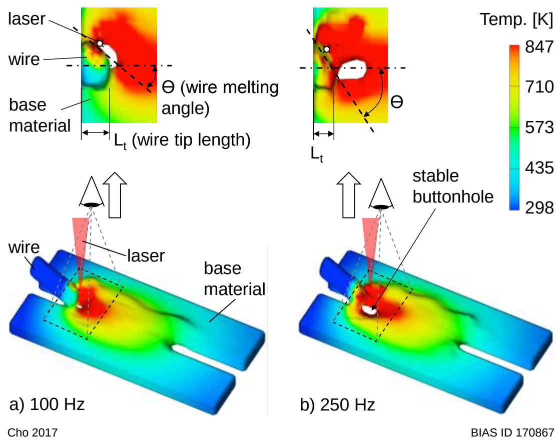

Fig. 4: Simulation results in a three-dimensional view

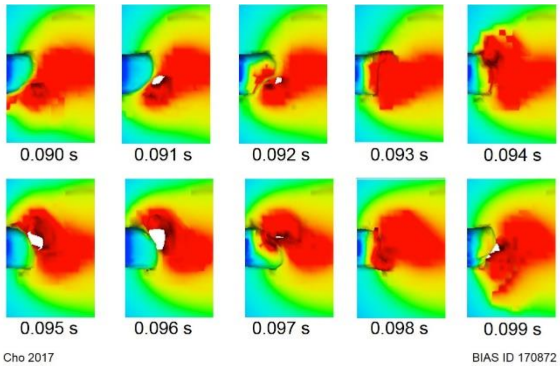

Fig. 5. Simulation results in a three-dimensional top view (oscillation frequency of 100 Hz, 1 cycle of oscillation)

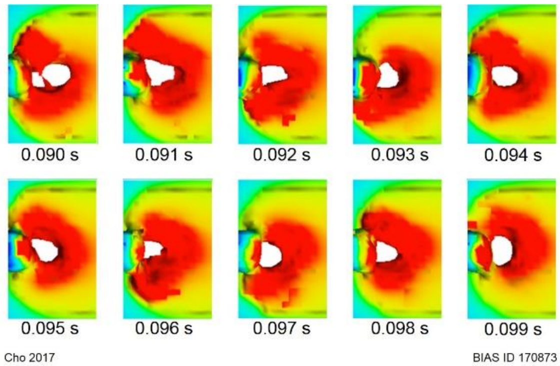

Fig. 6. Simulation results in a three-dimensional top view (oscillation frequency of 250 Hz, 2.5 cycles of oscillation)

Fig. 7 and 8 show the experimental and numerically calculated results of the weld bead cross section, respectively. The calculated fusion zone profiles are in good agreement with the experimental results except for the top surface.

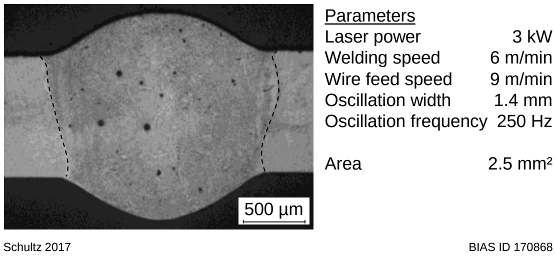

Fig. 7. Experimental fusion zone profile (250 Hz)

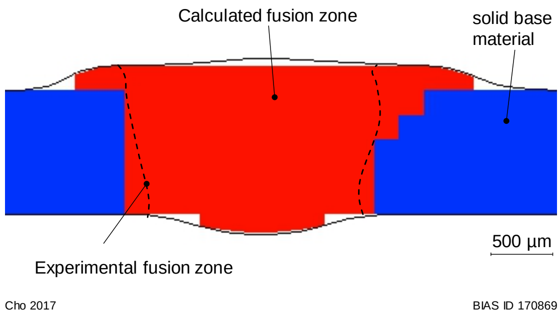

Fig. 8. Simulation results of the fusion zone profile in a cross-sectional front view (250 Hz)

4. Discussion

The buttonhole was shown only at the high oscillation frequency. With increasing the oscillation frequency, the wire became shorter and more even. Thus, it seems that more stable buttonhole can obtain with increasing frequency.

The numerical result showed wider top bead width than the experimental result. It might be related to the effect of oxidized layer of the real aluminum sheets. In the simulation, the effect of the oxidized layer was not considered and, thus, there could be more wettings on the surface.

5. Conclusion

It is possible to show the buttonhole formation by CFD simulations with wire feeding and laser oscillation. The formation of the buttonhole is affected by the shape of wire tip such as wire tip length and melting angle.

Acknowledgements

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