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Minjung Kang

Korea Institute of Industrial Technology

Jason Cheon

Korea Institute of Industrial Technology

Dong Hyuck Kam

Korea Institute of Industrial Technology

Cheolhee Kim

Portland State University, cheol@pdx.edu

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Minjung Kang,¹ Jason Cheon,¹ Dong Hyuck Kam,¹ and Cheolhee Kim^{1,2}

AFFILIATIONS

¹Joining Research Group, Korea Institute of Industrial Technology, 156 Gatbeol-ro, Incheon 21999, Korea

²Department of Mechanical and Materials Engineering, Portland State University, Portland, Oregon 97201

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ABSTRACT

A laser beam oscillation method using Galvano mirrors, which allows wide weld beads and controls thermal stress distribution, was suggested to suppress the formation of solidification cracks in laser welds. In order to understand the solidification cracking behavior in relation to the bead shape, laser beam oscillation welding was performed under various oscillation widths and frequency conditions. To evaluate the effect of the oscillation parameter on solidification cracking susceptibility, a regression analysis based on the shape of the bead was performed. Stress distribution generated during the laser beam oscillation welding process was also analyzed using finite element modeling simulation. From the results, it was demonstrated that a high shrinkage stress field at the bottom of the partial penetrated bead suppresses the solidification cracking.

Key words: laser welding, lap fillet joint, finite element modeling, hot cracking susceptibility, stress distribution

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I. INTRODUCTION

The laser welding of aluminum alloys, such as 2XXX,¹ 6XXX,^{2–4} and 7XXX,⁵ has limitations due to weld defects such as solidification cracks. Optimization of the weld composition using a filler metal is the conventional method used to prevent solidification cracking.⁶ In order to control the chemical composition of the weld metal, it is necessary to readjust the chemical composition of the aluminum base metal or to add auxiliary filler wire.

Many studies have attempted to suppress the formation of solidification cracks during laser welding by oscillating the laser beam and controlling the laser power with pulse waveforms. The effects of oscillating a heat source on microstructural evolution,⁷ solidification crack susceptibility,⁸ and welding strength⁹ have been investigated. Choi *et al.*¹⁰ applied a low-frequency laser oscillation on the 6K21 Al alloy to improve its joint strength. Notably, oscillation of the heat source changed the shape of the weld beads and solidification morphology¹¹ obtained through columnar and equiaxed dendritic growth.

Determining the behaviors of heat transfer and stress distribution around the molten pool are important to understand hot cracking formation. In laser welding, the high density of the focused laser beam was irradiated onto the substrate, and complex phenomena such as the temperature dependency of the material properties' phase transition (i.e., melting and evaporation) occurred in a short time. Numerical simulation of the welding process has been a major topic in welding research for several years. The results of simulations can be used to explain the physical essence of some complex phenomena in the welding process. The simulation of the laser welding process enables the estimation of transient stresses, residual stresses, and distortions. These can be used to evaluate structural misalignments and unexpected failures due to overstressing.¹² A number of numerical simulations for laser welding processes have been conducted to evaluate temperature and stress distribution and predict the residual stress and final distortions of structural components.^{13,14}

The aim of this study is to investigate the influence of high-frequency beam oscillations on the hot cracking susceptibility and

TABLE I. Chemical compositions measured with inductively coupled plasma and mechanical properties of applied base material.

Chemical compositions (wt. %)								
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.58	0.21	0.14	0.08	0.64	0.01	0.01	0.03	Bal.
Mechanical properties								
Tensile strength ^a (MPa)			Yield strength ^a (MPa)			Elongation at fracture ^a (%)		
234			126			24		

^aAveraged using three quasistatic tensile tests.

the bead appearance of aluminum alloy with a fillet joint. A comparison of the hot cracking length of welds showed that beam oscillation did reduce the hot cracking susceptibility. Considerable heterogeneity in stress distribution was calculated across the weld joint in the numerical simulation results due to the strong compressed stress at the bottom of the specimen during laser beam oscillation.

II. EXPERIMENTAL SETUP

For the welding process, a continuous-mode fiber laser, YLS-3000 (IPG Photonics, Oxford, MA, USA), was applied and delivered through a two-axis scanner, D30 (IPG Photonics, Oxford, MA, USA), with a focal length of 250 mm. The laser beam was perpendicularly irradiated to the specimen and was focused on the upper surface of the workpiece with a beam diameter of 0.28 mm. Ar shielding gas was provided to the side during welding. The base material was a 1 mm-thick of Al 6014-T4 alloy. Chemical compositions and mechanical properties are presented in Table I. In this study, circular patterns were adopted and compared with general linear motion. In order to evaluate the effect of welding parameters on hot crack susceptibility, the oscillation width and frequency were varied.

To evaluate the hot cracking susceptibility of lap joint welds, a modified self-restraint test specimen was adapted, as shown in Fig. 1. During the laser welding, tensile and rotational stress were generated near the fusion zone [Fig. 2(a)],¹⁵ and finally formed a

FIG. 1. Schematic image of specimen applied hot cracking susceptibility testing.

(a)

(b)

FIG. 2. (a) Schematic images of active force during the laser welding, and (b) crack generated at the center of a lap fillet joint.

FIG. 3. Laser beam patterns oscillated circularly at a welding speed of 3 m/min, with an oscillation width of 0.8 mm and oscillation frequency of (a) 100 and (b) 200 Hz.

TABLE II. Laser welding conditions used in experiments.

Laser power (W)	2300
Welding speed (mm/s)	50
Oscillation width (mm)	0, 0.2, 0.4, 0.8, 1.6
Oscillation frequency (Hz)	0, 100, 200, 400
Focal position (mm)	0 (on upper sheet)
Offset (mm)	0
Beam tilting angle (°)	0
Beam pattern	Circle
Shielding gas	Ar shielding

solidification crack at the center of the weld bead [Fig. 2(b)]. Figure 3 shows the laser beam path for the circular beam patterns at different frequencies at 100 and 200 Hz, respectively. The laser power and welding speed were fixed as 2300 W and 3 m/min, respectively. The laser beam was subjected to the edge of the upper plate and started at the narrow edge and ended at the wide edge. The details of the laser welding conditions are presented in Table II.

After welding, a nondestructive x-ray test was conducted to measure the hot cracking length using XSCAN-H160 (XAVIS,

Seongnam, Gyeonggi, Korea). The surface of the samples was polished and etched with Keller's etchant. To characterize the effect of bead shape on cracking, the section of welds was observed in two separate samples.

III. RESULTS AND DISCUSSION

A. Influence of laser beam oscillation on bead appearance and hot cracking susceptibility

Laser beam oscillation is beneficial to obtain a smooth bead appearance. This means that oscillation width and frequency affect the bead appearance. As the oscillation width increased, the edge near the fusion line became smooth [Fig. 4(c)], while an undercut was found in narrow oscillation cases, as shown in Figs. 4(a) and 4(b). However, when the oscillation width was wider than the critical width, the joint did not melt sufficiently due to the lack of heat input.

Figure 5 shows sectional images of the specimens according to oscillation frequency. To evaluate the effect of oscillation on bead appearance, factors derived from sectional images were defined and named a_1 to a_5 and s_1 . As shown in Fig. 5(a), bead width at the interface is a_1 , bead width at the top surface is a_2 , the thickness of the throat is a_3 , the bead width at the bottom surface is a_4 , the

FIG. 4. Bead appearance under various oscillation width conditions of (a) 0.2, (b) 0.4, (c) 0.8, and (d) 1.6 mm. Specimens were fabricated at an oscillation frequency of 200 Hz under a laser power of 2300 W and welding speed of 50 mm/s.

FIG. 5. Definition of geometrical factor (a) and macrosectional images for various oscillation frequencies of (b) 0, (c) 100, (d) 200, and (e) 300 Hz. Oscillation width was fixed at 0.8 mm.

FIG. 6. Hot cracking susceptibility depending on oscillation width and frequency.

penetration depth is a_5 , and the molten area is s_1 . Compared to linear welding [Fig. 5(a)], the bead width at the bottom surface (a_3) decreased and the depth of the bead (a_5) became shallower when using oscillating laser beams. The full penetration weld beads were obtained at small oscillation width and frequency condition.

The laser beam oscillation also affected the hot cracking behavior. In the present study, hot cracking susceptibility was defined as the ratio of the crack length to the entire weld length. Cracking was generally initiated and propagated along the welding trajectory. The length of cracks were measured using a nondestructive x ray and are presented in Fig. 6. Hot cracking susceptibility varied depending on the welding parameters. Shorter cracks were observed at higher oscillation width and frequency conditions. As the oscillation width increased at an oscillation frequency of 100 Hz, the specimen was less sensitive to hot cracking.

To evaluate the correlation between hot cracking susceptibility and bead shape, the details of the bead shape factors according to the laser beam oscillation parameters were analyzed and are presented in Table III and Fig. 7. In the correlation analysis [Table III] of the shape

factor and hot cracking susceptibility, it was revealed that the bead width at the bottom surface (a_3) and molten area (s_1) were strongly correlated compared with the others. Meanwhile, the shape factors of a_1 and a_2 were independent of the oscillation width and frequency.

B. Finite element modeling of laser beam oscillation welding

A thermomechanical analysis was conducted to compare the stress fields at the start of solidification without oscillation (full penetration, FP) and at 200 Hz oscillation (0.8 mm oscillation width, partial penetration, PP). A conical volumetric heat source^{16,17} was employed to calculate the laser welding process as follows:

$$\dot{q}''' = \frac{\delta 9 \eta P \exp(3)}{\pi (\exp(3) - 1)} \cdot \frac{1}{C} \exp\left(-3 \left(\frac{x^2 + z^2}{r_0^2}\right)\right), \quad (1)$$

$$C = (z_T + z_B)(r_T^2 + r_B^2 + r_T r_B), \quad (2)$$

$$r_0 = r_T - \frac{(r_T - r_B)(z_T - z)}{z_T - z_B}, \quad (3)$$

where the P and η are laser power ($=2300$ W) and process efficiency ($=0.24$), respectively. z was treated as a moving coordinate with a 50 mm/s welding speed, and r_i and z_i are the radii and heights of the heat source, respectively. The subscript i represents the location of the heat source, the bottom (B) and the heat source top (T), as shown in Fig. 8(a). As shown in Fig. 9, for the case with an excessive volume of heat source on the weldment feature, the calculated heat amount of void volume will be missing while active volume is accounted. To avoid the volumetric mismatching problem, a volume loss compensation parameter, δ , was employed in this study. The total volume and active volume were calculated using a commercial CAD program. For this study, the volume loss compensation parameters of the FP and PP cases were 1.8389 and 2.56, respectively.

A schematic of the analysis domain is shown in Fig. 8(b). The heat source moves along the longitudinal direction (z direction). The minimum size of the mesh is $0.2 \times 0.2 \times 0.2$ mm³. The gap between the top and bottom plate was considered to be 0.05 mm-thick elements. Solving the conductive energy equation, the temperature history and distribution were calculated as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{q}''', \quad (4)$$

TABLE III. Laser welding conditions used in experiments.

Factor	a_1	a_2	a_3	a_4	a_5	s_1
Pearson correlation	0.272	-0.212	0.861*	0.491	0.740	0.818*
Significantly change	0.393	0.509	0	0.105	0.006	0.001
Model	Sum of squares	Degree of freedom	Mean square	R square	F	Significantly change
Regression	9044.241	1	9044.241	0.741	28.548	0.00
Residual	3168.072	10	316.807			
Total	12 212.313	11

FIG. 7. Analysis of bead appearances according to the oscillation width and frequency. (a) Bead width at the interface (a_1); (b) bead width at the top surface (a_2); (c) thickness of the throat (a_3); (d) bead width at the bottom surface (a_4); (e) depth of the welds (a_5); (f): molten area (S_1).

where T , ρ , C_p , and k are the temperature, density, specific heat, and conductive heat transfer coefficient, respectively. To reproduce the convective heat transfer effect, k of the liquid state was treated as tripled value of ambient condition. The

convective and radiated surface heat loss were considered with a 15 W/m^2 convective heat coefficient and 0.2 surface emissivity. The thermal properties¹⁸ are given in Table IV and Fig 10.

FIG. 8. (a) Schematic of conical volumetric heat source and (b) analysis domain.

FIG. 9. Schematics of (left) volumetric mismatching and (right) volume loss compensation parameter.

TABLE IV. Temperature independent properties.

Properties	Value
Solidus temperature	782.9 K
Liquidus temperature	926.5 K
Density	2700 kg/m ³
Latent heat of fusion	393 kJ/kg
Effective thermal conductivity of liquid state	501 W/mK

FIG. 10. Temperature dependent thermal conductivity and specific heat (Ref. 18).

The heat source size parameters, r_i and z_i , were tuned by the trial and error method to fit the experimental fusion zone shape and size in Figs. 5(b) and 5(d) for the FP and PP cases, respectively. The fusion zone used for comparison was selected on the longitudinal half cross section of the analysis domain. The best fit condition is given in Fig. 11, and the corresponding heat source size parameters are given in Table V. The stress fields were calculated on the isotropic hardening model by the calculated thermal history (Fig. 12). The observed time, at the solidification start, was 5.5 s for both cases. The thermomechanical properties¹⁹ are given in Figs. 13 and 14.

C. Stress distribution comparison between full penetration and partial penetration cases

The Mises stress distributions on the cross section of the FP and PP cases at 5.5 s are displayed in Figs. 15(a) and 15(b), respectively. The FP case has a relatively uniform distribution of Mises

FIG. 11. Fusion zone comparison between thermal analysis and experiment.

TABLE V. Conical volumetric heat source size parameters.

(mm)	r_T	r_B	z_T	z_B
FP	1.0	0.225	2.05	0
PP	1.6	0.425	2.05	0.8

FIG. 12. Thermal histories of the FP case (solid line) and PP case (dashed line). **FIG. 13.** Yield strength, tensile strength, and elongation (Ref. 19). **FIG. 14.** Young's modulus and coefficient of thermal expansion (Ref. 18). **FIG. 15.** Mises stress distribution in the (a) FP case, (b) PP case, (c) horizontal distribution on the middle line (line M) and bottom line (line B), and (d) vertical distribution on the vertical line (line V).

stress. However, the PP case has a high Mises stress on the middle and top while the bottom is low. As shown in Fig. 15(c), the horizontal stress distribution difference of the middle and bottom lines at the weld line have 2 MPa for the PP case while the FP case has less than 1 MPa. The lower Mises stress concentration of the bottom of the PP case was caused by the relatively lower thermal history, which is below the solidus temperature. As a result, the vertical stress distribution [Fig. 15(d)] on the weld line in the PP case has a relatively lower stress level than the FP case. Therefore, a higher resistance to cracking could be expected in the PP case than in the FP case at the low strength state of high temperature.

FIG. 16. Transverse stress distribution for the (a) FP case, (b) PP case, (c) horizontal distribution on the middle line (line M) and bottom line (line B), and (d) vertical distribution on the vertical line (line V).

The transverse stress distributions on the cross section of the two cases are shown in Figs. 16(a) and 16(b). The FP has a vertically uniform stress distribution around the weld line, while the PP has a higher compression stress distribution on the weldment bottom. The vertical stress distribution of the PP can prevent the propagation of cracks, which can start at the top of the fusion zone, while the FP case cannot.

IV. CONCLUSION

To evaluate hot cracking susceptibility, laser beam oscillation welding was performed on modified self-restraint test specimens with various oscillation frequencies and widths. The results showed that welding parameters influenced the hot cracking susceptibility. The penetration depth varied according to the oscillation width and frequency, and the length of solidification cracks was reduced with the decreasing width of the back bead.

In order to analyze the stress generated after the laser welding process, a laser heat source model was produced considering laser beam oscillations. Uniform Mises stress was distributed along the weld for the full penetration case, while the stress distribution was discontinuous in the partial penetration case. The difference in thermal history imposed on the specimen caused a heterogeneous stress field generation. As a result, it was demonstrated that a high shrinkage stress field at the bottom of the partial penetrated bead suppresses solidification cracking through the weld.

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