Influence of Bead Geometry on Weld Distortion in Laser Micro-welding of Thin Stainless Steel Sheet with High-speed Scanning

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Abstract

In this study, the thermal deformation of thin stainless steel sheet was investigated in bead-on-plate welding by using a single-mode fiber laser with Galvano scanning system. The numerical simulation was carried out to calculate temperature and stress fields, and its deformation characteristics were discussed. It was suggested that a specimen firstly deformed downward in the same direction of laser irradiation, and then deformed in the reversed direction after laser scanning. The final distortion angle in the negative direction, which is concave shape from the view direction of laser irradiation, was generated under the heat conduction and quasi-penetration welding mode, and the positive angle was obtained as the final distortion angle under the full-penetration welding mode. On the other hand, a small distortion could be achieved by the proper weld bead geometry in micro-welding of thin sheet, but the welding mode of minimum distortion conditions varied with specimen thickness. However, these relationships obtaining a small distortion could be understood by the relationship between aspect ratio of weld bead and distortion angle. Minimum angle of distortion could be achieved around maximum aspect ratio of weld bead regardless of specimen thickness and spot diameter, when an inflection point appeared in relationship between aspect ratio of weld bead geometry and distortion angle.

Key words: micro-welding, weld distortion, bead geometry, single-mode fiber laser, high-speed scanning

1. INTRODUCTION

Recently, micro-joining of small components has been strongly required, since electronic devices have become smaller, thinner and lighter in industrial applications to satisfy the requirements such as higher functionality and lower cost. For these parts, austenitic stainless steel SUS304 with high weldability has been widely used. However, distortion often occurs due to the heat input in welding process. Laser micro-welding is one of attractive methods in the micro-joining technique, since the high quality laser beam enables high spatial and temporal control of heat input\(^1\),\(^2\). In addition, there is an advantage as non-contact processing, in which the reaction force does not load to an object. Thus, a high-precision joint can be expected even at the side wall of narrow cavity and for the combination of dissimilar materials, which were difficult to weld by conventional welding methods. In general, it is important to control heat input to specimen in micro-welding of thin steel sheet, since burn-through, weld distortion and the weld bead geometry have an influence on the quality of weld joint\(^3\),\(^4\).

The weld bead geometry is determined by laser power, scanning velocity and beam spot diameter, and its geometry is very essential to evaluate the weld joint. It is considered that precision micro-joining with a small heat affected zone would be performed by the laser micro-welding, but the weld distortion could not be ignored. The bending and distortion in the laser forming process had been reported\(^5\), but the weld distortion of thin stainless steel sheet by the laser micro-welding has not been clarified yet. Therefore, it is important to understand the relationship between weld distortion and weld bead geometry in order to accomplish precision weld joints in micro-joining of thin metal sheet.

In this study, thermal deformation of thin stainless steel sheet in laser micro-welding using a single-mode CW fiber laser with a Galvano scanning system was experimentally investigated, and the distributions of temperature and stress were discussed to clarify the distortion of specimen in micro-welding by the numerical calculation.

2. EXPERIMENTAL PROCEDURE

Figure 1 shows the schematic diagram of experimental setup. In this study, single-mode CW Yb fiber laser of 1090 nm in wavelength was used as a laser source. Laser beam was delivered by an optical fiber and focused by a telecentric type \(f_\theta\) lens of 100 mm in focal length. The laser scanning was carried out by Galvano scanner to achieve the high-speed beam scanning. The expander was installed between the isolator and the bending mirror to decrease the spot diameter of laser beam. The bead-on-plate welding on the austenitic stainless steel SUS304 of 20 \(\mu\)m and 50 \(\mu\)m thickness was carried out in shielding box filled by nitrogen at a constant supplying pressure 100 kPa. In order to evaluate the weld distortion, the distortion amounts were measured by a laser displacement sensor (LDS).
Figure 2 shows the schematic diagram of distortion measurement setup. A clamping plate with an opening slot of 2 mm was used to ensure the straightness of specimen sheets. The clamping plate was also designed with tighten screws to hold the specimen down to the supporting plate. The measurement of distortion was set to 2 mm width and 1 mm length. Each line was divided by 25 μm distance, and 80 points in total were measured. The distortion value of specimen was defined as the difference of measurement values before and after the laser irradiation experiment.

In this study, the weld distortion is evaluated as distortion angle of specimen as shown in Fig. 3. The distortion angle at an individual point $i$ is calculated from the measurement of the displacement in the z-direction before and after the laser irradiation experiment by the equation in the figure. The positive angle is defined as the distortion against the laser beam irradiation direction, while the negative angle means the distortion downwards in the laser beam irradiation direction.

3. THERMO-MECHANICAL ANALYSIS METHOD AND CONDITIONS BY FINITE ELEMENT METHOD

Figure 4 shows the dimension of geometry model with 1 mm length, 2 mm width, and 50 μm thickness. Gaussian distribution of laser energy was used as a heat source, which is considered the summation of surface heat source on the top surface and volume heat source along the thickness direction. The constant absorption rate of 27% was used in this study. The clamping of sheet at both ends was used as the boundary condition in structural analysis. The displacement of specimen was zero at the edge of sheet. The analysis condition was set at laser power 50 W, scanning velocity 1 m/s, and spot diameter 35.0 μm for 50 μm specimen thickness. The general finite element program ‘ANSYS Rev. 14.0’ was used for the three-dimensional finite element analysis.
The temperature-dependent mechanical and thermophysical properties used in this numerical simulation are shown in Figs. 5 (a) and (b), which were taken from references 7) and 8). Material properties above melting point were assume as constant values of melting point. Since it was reported that there was little influence on the thermal stress by the phase change9), the effect of phase change on the thermal stress was not considered in this numerical simulation.

4. NUMERICAL SIMULATION RESULTS AND DISCUSSION

Figure 6 shows the cross-sectional views of the weld beads obtained by experiment and numerical simulation under the same laser scanning condition. The highest temperature of contour color in the analysis result shows the melting point of stainless steel, and its isothermal shape of melting point agrees well with the molten zone in the experiment. The temperature, stress, displacement fields were evaluated by this simulation result.

Figure 7 shows the longitudinal stress fields and temperature distributions at the center of scanning line, where the laser beam is located at 500 μm from the edge of specimen (Point A at top surface, Point B at the bottom surface). It can be clearly seen that the point A rapidly reaches higher compressive stress because the expansion of the molten pool is restrained by the surrounding material. At this time, the point B shows the tensile stress, due to the restriction of surrounding material. During the cooling period, the compressive stress rapidly decreases due to the rapid cooling and change to the tensile stress due to the contraction of the material at the point A. On the other hand, the compressive stress is generated at the point B to balance the tensile stress at the top surface of point A. Therefore, the final distortion shape of specimen after the cooling period is affected by the difference of magnitude stress between both surfaces.

Figure 8 (a) schematically shows the longitudinal residual stress distribution ($\sigma_{xx}$). It can be considered that the residual tensile stress is generated at the center of weld line, and it is balanced with compressive stress at base material to maintain the original length significantly during the cooling period. The longitudinal tensile stress in the molten zone is higher than the longitudinal compressive stress.
stress in the base material, and the stress gradient within the molten zone is large by high temperature gradient at this region. On the other hand, it is considered that the transverse residual stress distribution \( \sigma_{yy} \) is influenced on the angular distortion in Fig. 8 (b). It can be noticed that the high residual tensile stress is generated around the weld line and the compressive stress is generated at the both edges of the specimen along the width direction. The transverse residual stress is much smaller than the longitudinal stress, and reached its peak value close to the molten zone or heat affected zone, and gradually reduces toward to the edge of the specimen.

Figure 9 shows the shapes and displacement evaluated at the bottom surface of specimen along the width and scanning directions. The displacements are magnified in these figures to make them clearly visible, and the circles on the curved line indicate the locations of the laser beam. The angular deformation of specimen shows the tendency to become concave to the laser irradiation side until the end of cooling period. The specimen firstly deformed downward in the same direction of laser irradiation. Then it deformed in the reversed direction, but it still remained with the concave shape to the laser irradiation side. In addition, buckling deformation occurred during irradiation period at displacement along the welding direction, which is caused by compressive stress. This phenomenon leads to instability of weld distortion. Judging from these results, it was clarified thermal deformation was influenced by change of the stress field generated during the heating and cooling period. It is noticed that the change of stress field also depended on the weld bead geometry, which varied with the energy density and the power density.

5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Welding Experiments of 50 µm Thickness

In this experiment, thermal deformation was investigated with changing the power density, which greatly influences the welding mode and weld bead geometry. The bead-on-plate experiment was carried out 3 times under the same irradiation condition, and their averages were calculated as the distortion angle. Figure 10 shows the experimental results of measured displacement at the top surface of specimen and distortion angle at the constant scanning velocity of 1 m/s with a spot diameter of 35.0 µm. The displacement is the subtraction value between the final displacement after the welding process and the initial displacement before the welding process. In terms of weld bead geometry, the weld bead became larger with the increase of laser power, and a large weld bead depth was observed in quasi- and full-penetration welding modes under higher power density condition. It shows that a large distortion was also generated under low laser power condition. The heat conduction (P: 30 W) and quasi-penetration (P: 50 W) welding modes induced the final distortion of concave shape to the laser irradiation side. In contrast, the final distortion in full-penetration welding mode (P: 60 W) resulted in a convex shape to the laser irradiation side. As shown in Fig. 9 (d), it was confirmed that the distortion angle also increased with increasing the penetration depth. In addition, this relationship suggests that the small weld distortion was achieved with proper control of laser power by obtaining the weld bead depth from 30µm to 50 µm for 50 µm thickness sheet.

Figure 11 shows extremely small distortion for 50 µm thickness sheet in the bead-on-plate welding.
As can be seen from the figure, the distortion was very small, and the distortion angle was almost resulted in 0 degree. In the case of 50 W as shown in Fig. 10 (b), the distortion angle was large, and the penetration depth was smaller than 30 μm. On the other hand, the penetration depth was approximately 35 μm for 50 μm thickness of specimen, when the distortion angle was almost 0 degree.

Figure 12 schematically shows distortion shapes under each laser irradiation condition in the bead-on-plate welding for 50 μm thickness sheet. This figure summarizes the influence of power density, which defined as laser power divided by spot area. It can be noticed that the power density has related to not only the welding mode but also distortion shape. It is considered that laser micro-welding with very small distortion was achieved by the proper weld bead geometry, in which the penetration depth was a little smaller than the thickness of specimen. Thermal contraction was caused by the rapid cooling, and the tensile stress generated in and around the molten zone as residual stress. However, the balance of stress was different by the penetration depth and specimen thickness, and the difference of tensile stress value was occurred between the top and the bottom surface of specimen. The equivalent penetration depth to the thickness of specimen led to the minimal distortion, since the tensile stress was balanced at the top and bottom sides of specimen.

5.2 Effect of Thickness and Spot diameter on Weld Distortion

In order to investigate the relationship between the weld distortion and the weld bead geometry for other specimen thickness, the weld distortion was evaluated by using 20 μm thickness sheet. Figure 13 shows the measured results of final displacement for
shows the measured results of final displacement for 20 µm thickness sheet. It was confirmed that the penetration depth increased with increasing the power density. The final distortion of specimen was also resulted in concave shape in the quasi-penetration welding mode. On the other hand, in the full-penetration welding mode, both the flat shape and the convex shape were obtained as the final weld distortion. It was considered that the bead width against 20 µm thickness was wider than that against 50 µm thickness, and it was also different at the top and bottom surface, which resulted in the large transverse shrinkage as shown in Fig. 13 (c).

Figure 14 shows the comparison of distortion angle and weld bead geometry between 50 µm and 20 µm thickness. It can be noticed that, even in the same aspect ratio of weld bead geometry, the distortion characteristics were different by the specimen thickness. Therefore, it was clarified that the weld distortion was influenced by not only the weld bead geometry but also the thickness of specimen. It is important to understand the balance of stress with the relationship between weld bead geometry and specimen thickness.

The aspect ratio of weld bead geometry were calculated in order to clarify the relationship between the specimen thickness and the weld distortion for both 20 µm and 50 µm specimen thicknesses. Figure 15 shows the relationships between the aspect ratio of weld bead geometry and the angle of distortion for different specimen thickness. All plots in the figure are connected by a solid line with increasing the laser power from left lower to center upper positions. It shows that the distortion angle increased with increasing the aspect ratio of weld bead in both heat conduction and quasi-penetration welding mode, and it decreased in full-penetration welding mode. On the other hand, minimum distortion angle was obtained around the inflection points for both 20 µm and 50 µm specimen thicknesses. It is considered that the transverse residual stress was balanced at the top and bottom
surface around maximum aspect ratio for both specimen thicknesses, and the distortion of specimen can be reduced.

Figure 16 shows relationships between distortion angle and aspect ratio of weld bead for different spot diameter in the case of 20 µm specimen thickness. A smaller spot diameter of 17.5 µm was obtained with twice larger diameter of input laser beam to the same focusing lens. Other experimental setup is the same as the case of 35.0 µm spot diameter. As shown in the figure, burn-through phenomena appeared due to excessive heat input, when higher laser power was used in the case of smaller spot diameter of 17.5 µm. The boundary range between the burn-through and the full-penetration welding mode was narrow, and the fine control of laser power is required in order to obtain good welding condition. Thus, high-scanning speed is useful to control of both weld bead geometry and welding mode in the case of thin metal sheet. On the other hand, minimum distortion angle can be obtained around maximum aspect ratio of weld bead, which is similar tendency to the results of specimen thickness as shown in Fig. 15. A smaller weld distortion can be expected regardless of specimen thickness and spot diameter, when an inflection point appeared in relationship between aspect ratio of weld bead and distortion angle. Therefore, precision weld joint was accomplished by understanding the relationship between distortion angle and aspect ratio of weld bead geometry in micro-welding of thin stainless steel sheet.

6. CONCLUSIONS

Influence of weld bead geometry on thermal distortion in laser micro-welding of thin stainless steel sheet with high-speed scanning were numerically and experimentally investigated. The main conclusions obtained in this study are as follows:

(1) The specimen firstly deformed downward in the same direction of laser irradiation, and then deformed largely in the reversed direction after laser scanning due to a large shrinkage in the perpendicular to scanning direction.

(2) The extremely small distortion could be achieved by the proper weld bead geometry for the specimen thickness in micro-welding of thin stainless steel sheet, but the welding mode of minimum distortion conditions varied with the specimen thickness.

(3) Minimum angle of distortion could be achieved around maximum aspect ratio of weld bead regardless of specimen thickness and spot diameter, when an inflection point appeared in relationship between aspect ratio of weld bead and distortion angle.

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