Numerical and Experimental Investigation of Pulsed Laser Welding with Trailing Heat Sink of Hastelloy C-276 Alloy Sheets

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Abstract. To reveal the thermal-mechanical behaviors during the pulsed laser welding (PLW) with trailing heat sink in a Hastelloy C-276 butt-welded joint, a three-dimensional finite element model (FEM) was established by using the ANSYS code. Experiments were carried out to measure the welding temperature histories and residual distortions. The simulation results agree well with the corresponding experimental measurements. Based on the validated FEM, the effect of the cooling distance on welding residual stresses and distortions was investigated. According to the numerical simulations, the cooling distance has a great influence on the magnitude and the distribution of residual stresses and distortions are changed significantly in comparison to the conventional PLW. The peak values of the longitudinal residual compressive stresses and the maximum deflections in longitudinal direction decrease as the cooling distance decreases from 12 to 3 mm. The magnitudes of the transverse shrinkage distortions increase as the cooling distance decreases from 12 to 3 mm. The proper cooling distance to reduce the residual stresses and distortions of the PLW with trailing heat sink is detected at 6 mm.

Introduction

Hastelloy C-276 alloy is widely used in chemical, aerospace and nuclear industries because of its high corrosion resistance and high strength at elevated temperature. Today, Hastelloy C-276 alloy components may be joined using mechanical fasteners and some welding techniques. Although it is possible to use continuous wave lasers in welding process, the use of a pulsed laser offers the advantages of very low distortion and the ability to welding heat sensitive components. Kim et al. [1] predicted the molten zone of PLW in 1 to 3 mm thick AISI 304 stainless steel plates with the designed heat source, and confirmed that the finite element method was effective for determining suitable laser conditions. Ventrella et al. [2] investigated the effect of pulse energy on weld joint characteristics of PLW in AISI 316L stainless steel thin foil, and found that the ultimate tensile strength of the welded joints increased at first and then decreased as the pulse energy increased.

Although the pulsed laser has the ability to weld thin components, the welding distortions often occur obviously in welded thin structures due to high residual stresses and low stiffness. Han et al. [3] investigated the effects of trailing heat sink on residual stresses and distortions of friction stir welding in Al sheets, and found that the trailing heat sink could effectively control the distribution. Zhang et al. [4] investigated the effect of heat sink parameters on residual stresses and deformations during continuous laser welding of Ti6Al4V thin plate, and found that both flexural deformations and residual stresses could be reduced, and the microstructure could be altered due to faster cooling rate. Although many studies have been conducted to reduce welding residual stresses and distortions, there is very limited literature describing thin sheets, especially for those welded structure whose sheet or wall thickness is less than 1 mm under both the fixture restraint and the trailing heat sink during the PLW process.

In this study, a FEM was established to simulate the thermal-mechanical behaviors of PLW in a Hastelloy C-276 alloy sheets considering fixture restraint and trailing heat sink. The corresponding
experiments were conducted to validate the reliability of the FEM. Then, based on the FEM, the effect of the cooling distance on residual stresses and distortions was analyzed.

Numerical Simulation Model

Geometry Model and Mesh. Because the welded Hastelloy C-276 alloy sheets are symmetrical about the welding line, only half of the weldment is modeled to reduce the calculation cost. The dimensions of the analysis model are 100 mm × 25 mm × 0.5 mm. Due to the relatively thin thickness of the welded sheet, the Shell57 and Shell181 of the three-dimensional shell elements were adopted for the thermal and mechanical analyses, respectively. A dense mesh was used in the area along the weld line, as shown in Fig. 1.

Heat Source and Heat Sink. Fig. 2 shows the schematic diagram of PLW with trailing heat sink, where the cooling distance \( d \) represents the distance between the center of the laser spot and the center of the heat sink. A Gaussian distribution of heat flux deposited onto the surface of the workpiece was employed in the thermal analysis. The heat flux distributions of the Gaussian (surface mode) type of heat source can be expressed by the following equation:

\[
q(r) = q_0 \exp(-Cr^3),
\]

(1)

Where \( q(r) \) is the heat flux at a radius \( r \) from the heat source center, \( q_0 \) is the maximum heat flux and \( C \) is an adjustable constant.

The intense cooling effects of the trailing heat sink at some distance behind the laser beam is also modeled in the numerical simulation, and the average heat transfer coefficient \( h \) of the forced convective heat transfer between the water jet and the weldment bottom surface can be calculated from the following equation:

\[
h = \frac{\lambda \overline{Nu}}{D}.
\]

(2)

Where \( h \) is the average heat transfer coefficient, \( \lambda \) is the thermal conductivity of the water, \( \overline{Nu} \) is the average Nusselt number and \( D \) is the diameter of the cooling nozzle.

During the whole welding process, the effective radius of heat sink and the average heat transfer coefficient \( h \) are 2 mm and 10000 W/(m\(^2\)·K), respectively. In addition, the heat sink moves at the same velocity along the welding line with the welding heat source.

Material Properties. The temperature-dependent material properties of Hastelloy C-276 alloy thin sheet were taken into account in the simulation. These data can be referenced from [5]. All the unknown values of the material properties on different temperature were obtained by linear interpolation method.

Initial and Boundary Conditions. Ambient temperature was assumed to be 20 °C. Both convection and radiation were applied to all free surfaces of the model except for the symmetrical plane. An adiabatic boundary condition was applied to the symmetry plane. The fixed displacements boundary conditions were imposed at the clamped positions (Fig. 2) during welding, and released to become free after the welded sample cools down to the ambient temperature. Moreover, in order to prevent rigid body displacement, the point \( k_1 \) (Fig. 1) was constrained in the \( x \)-direction and the
Experimental Procedure

To verify the FEM, the corresponding experiments were carried out using a Lumonics JK701H Nd:YAG pulsed laser welding machine. The optimized pulsed laser welding parameters selected in this study are given in Table 1. The material used was Hastelloy C-276 alloy thin sheets with dimensions of $100 \times 25 \times 0.5$ mm. The thin sheets were joined without gaps and fillers by means of the square butt welding. The fixture restraint distance $L=12$ mm (Fig. 2) remained unchanged, and the pure argon gas was selected as shielding medium to prevent oxidation.

Table 1 Optimized welding parameters

<table>
<thead>
<tr>
<th>Pulse energy [J]</th>
<th>Welding speed [mm/min]</th>
<th>Pulse duration [ms]</th>
<th>Pulse frequency [Hz]</th>
<th>Spot size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>100</td>
<td>5</td>
<td>30</td>
<td>0.6</td>
</tr>
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</table>

To measure welding temperature histories, two K-type thermocouples, each 0.3 mm in diameter, were spot welded to the top surface of the welded workpiece with different distances to the welding line along the mid-section. A personal computer with DasView 2.0 virtual instrument software and USB8516 data sample device was used to record real-time data. The amount of welding residual distortion was obtained through a measuring device, as shown in Fig. 3. The welded workpiece was put on the three adjustable support pins which can be fixed on the X-Y CNC worktable. A laser displacement sensor (Keyence LK-H025) was installed to the Z-axis of laser welding machine, and a personal computer with virtual instrument software and data sample device was used to record real-time z-displacement data. The space of measured lines was 2 mm along the welding direction. Been vertical to the welding direction, the space was 1/120 mm, which was set by the sample frequency of 1 kHz and the y-direction speed of 500 mm/min.

Results and Discussion

Fig. 4 shows the experimental and simulated temperature histories of two points at 1.5 and 2.5 mm distances to the welding line along the mid-section of the welded workpiece using the conventional PLW. It can be noted that the simulated results agree well with the experimental measurements except for the peak temperatures, and the largest relative error between these two results is less than 5%. Each point experiences its maximum temperature after the laser beam passes by the mid-section. When the distance to the welding line increases (i.e. $P_1$ to $P_2$), the peak temperature decreases while its presenting time increases. As shown in Fig. 5a and Fig. 5b, the welding residual distortion contours were obtained from numerical simulations and experimental measurements, respectively. It can be noted that the concave bending in the longitudinal direction and the convex bending in the transverse are produced after the fixture restraints are removed. The overall trends between the simulation predictions and the measured results are consistent on whole sheet, and the largest relative error between these two results is less than 10%.

The quantitative comparison of temperature histories and residual distortions between simulation and experimental results verifies that the FEM of PLW in Hastelloy C-276 thin sheets is reasonable.
Therefore, the FEM can be used to further predict the residual stresses and distortions of PLW with trailing heat sink in Hastelloy C-276 thin sheets under the fixture restraint condition.

Fig. 6 shows the simulated distributions of the longitudinal residual stresses along the mid-section for different cooling distance. Compared to the conventional PLW, the distribution and the magnitude of the longitudinal residual stresses are obviously changed by the different cooling distance. The magnitudes of the longitudinal residual compressive stresses decrease as the cooling distance decreases from 12 to 3 mm, which is good for decreasing or even eliminating the buckling distortions of the welded thin sheets. Fig. 7 shows the longitudinal deflections along the path $k_1k_2$ (Fig. 1) for different cooling distance obtained by simulation. The maximum longitudinal deflections are obviously much less than those of the conventional PLW and decrease as the cooling distance decreases from 12 to 3 mm. Fig. 8 shows the simulated distributions of the transverse shrinkage distortions (i.e. the difference $\Delta y$ along the $y$-direction before and after welding) along the $x$-direction for different cooling distance. The magnitudes of the transverse shrinkage distortions are larger than those of the conventional PLW and increase as the cooling distance decreases from 12 to 3 mm.

**Conclusions**

With the cooling distance decrease, the longitudinal residual compressive stresses and the deflections in longitudinal direction are decreased while the transverse shrinkage distortions are increased. A proper cooling distance can effectively reduce the residual stresses and buckling distortions, and make the transverse shrinkage distortions increased slightly, which is helpful to achieve the precision welding of thin sheets.

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**References**