Reduction Method for Residual Stress of Welded Joint Using Two Ultrasonic Vibrations with Different Frequencies

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Abstract. A reduction method of tensile residual stress using two ultrasonic vibrations with different frequencies is proposed. Advantage of the method to using one ultrasonic vibration is examined. Obtained results are summarized as follows. 1. Thick plate is buildup welded using ultrasonic vibration is used during welding in experiment. Residual stress of specimen using one ultrasonic vibration is reduced compared with that without ultrasonic vibration. Residual stress of specimen using two ultrasonic vibrations is reduced compared with that using one ultrasonic vibration. 2. Using two-dimensional model, residual stress is calculated by simulation method. Same results as experiment are obtained.

Introduction

Welding is used for construction of many structures. It is well known fact that residual stress is generated near the bead because it is joining method using locally given heat. Tensile residual stress degrades fatigue strength of material. Some reduction methods for reduction of tensile residual stress are proposed. Heat treatment and shot peening are practically used. However, in these methods, special equipment is required and it takes long time to reduce tensile residual stress. Relation between residual stress and vibration has been studied and it has been expected to reduce residual stress using vibration. The authors have been examined to reduce residual stress using vibration during welding [1]. For butt welding of thin plates, tensile residual stress is reduced using low frequency vibration and ultrasonic vibration. The authors tried to reduce residual stress for buildup welding of thick plate. In such a case, ultrasonic vibration is effective to transmit vibration. Tensile residual stress is reduced using ultrasonic vibration during welding. In order to reduce residual stress more, amplitude of vibration should be increased. For ultrasonic vibration in their study, the maximum amplitude is used and amplitude cannot be increased more. Two or more ultrasonic vibrations should be used to reduce tensile residual stress more.

The aim of this paper is to show advantage of a method using two ultrasonic vibrations to that using one vibration for reduction of tensile residual stress for buildup welding of thick plate. When frequencies of two ultrasonic vibrations are same, phase should be adjusted to get large amplitude and it is not desired to use ultrasonic vibrators under such a condition because of resonance. Then, ultrasonic vibrations with different frequencies are used. First, from experiment, advantage of the method using two ultrasonic vibrations is examined. Second, from simulation using an analytical model, results of experiment is demonstrated.

Experiment

A thick plate is buildup welded using two ultrasonic vibrations and results are compared with those using one ultrasonic vibration.
Experimental Method

Figure 1 shows size of specimen. Material is the rolled steel for general structure (SS400). In order to eliminate residual stress in rolling, specimen is heated at 850°C for 3 hours and cooled in furnace for 24 hours.

![Figure 1. Size of specimen.](image1)

Figure 2. Experimental setup.

Specimen is put on table horizontally as shown on Figure 2 and welded using ultrasonic vibrations in the direction of thickness. Specimen is welded using an automatic arc welding machine. Mixed gas of argon and carbon dioxide is used as shield gas. Welding is completed through one pass. Combinations of ultrasonic vibrations are 27.5kHz and 37.5kHz, 37.5kHz and 47.5kHz. For comparison, specimen welded using one ultrasonic vibration and that without vibration are prepared. Specimen is welded along the center line and length of welding is 150mm as shown in Figure 1. Velocity of welding is 2mm/s and welding is completed in 75 seconds. Diameter of wire is 1.2mm, voltage is 21V and current is 180A.

Ultrasonic vibrations are applied at the points 20mm from edge of specimen as shown in Figure 3. For one ultrasonic vibration, vibration is applied at the point near start of welding. Specimen is welded from point B to point C. Before welding, acceleration time histories are measured at point A, B and C. Power spectra are obtained and ultrasonic vibrations are well transmitted to specimen.

Residual stress is measured using X-ray diffractometer with a scintillation counter after removing quenched scale chemically using hydrochloric acid having a concentration of 6mol/L and smoothing surface of the bead using CPL (chemical polishing liquid) and protecting from rust. Measuring points of residual stress are shown in Figure 3. Residual stresses are measured at 15 points. Residual stresses in the direction of the bead are measured. 3 specimens are made in same condition and the mean value of residual stresses is obtained.

![Figure 3. Measuring points of acceleration and residual stress (mm).](image2)
Results of Experiment

Some examples of power spectra of ultrasonic vibration measured at point A (center of specimen) are shown. Figure 4(a) shows power spectrum of specimen using 27.5kHz ultrasonic vibration. Figure 4(b) shows that of specimen using 37.5kHz ultrasonic vibration. Figure 4(c) shows power spectrum of specimen using 27.5kHz and 37.5Hz ultrasonic vibrations. Amplitudes of both frequencies are 1500m/s². From Figure 4(a) and Figure 4(b), peaks are located at 27.5kHz and 37.5Hz, respectively. Peak values are almost same. From Figure 4(c), peaks are located at 27.5kHz and 37.5Hz and peak values are almost same. Same results are obtained at other points and frequencies. Ultrasonic vibrations are transmitted to specimen without interference.

Figure 5(a) shows residual stress of specimen using 27.5kHz and 37.5kHz ultrasonic vibrations. ▲ shows residual stress of specimen without ultrasonic vibration. △ shows that using 27.5kHz ultrasonic vibration. ○ shows that using 37.5kHz ultrasonic vibration. ● shows that using 27.5kHz and 37.5kHz ultrasonic vibrations. Residual stress of specimen using one ultrasonic vibration is reduced compared with that of specimen without ultrasonic vibration. Residual stress of specimen using two ultrasonic vibrations is reduced more compared with that of specimen using one ultrasonic vibration. Residual stress at center of the bead is higher than that at end of the bead. However, from 35mm to 115mm from start of welding, distribution of residual stress is small.

Figure 5(b) shows residual stress of specimen using 37.5kHz and 47.5kHz ultrasonic vibrations. ▲ shows residual stress of specimen without ultrasonic vibration. △ shows that using 37.5kHz ultrasonic vibration. ○ shows that using 47.5kHz ultrasonic vibration. ● shows that using 37.5kHz and 47.5kHz ultrasonic vibrations. As shown in Figure 5(a), residual stress of specimen using two ultrasonic vibrations is reduced more compared with that of specimen using one ultrasonic vibration.

Examination by Simulation Method

From experiment, it is obvious that residual stress is reduced using ultrasonic vibration during welding and residual stress is reduced more when two ultrasonic vibrations are used. Yield stress near the bead immediately after welding is very low and it is easy to give plastic deformation by small load. It is assumed that plastic deformation is given by vibrational load and residual stress is reduced by
releasing strain. Based on the assumption, results of experiment are examined qualitatively by simulation using a simplified analytical model [2].

![Figure 5. Residual stress.](image)

**Analytical Model and Equation of Motion**

Figure 6 shows two-dimensional model considering above conditions. The model is focused on vibration near the bead. x-axis is direction perpendicular to the bead, y-axis is direction of the bead.

For simplicity, parts of specimen from excitation point to the bead are modeled by springs as shown in Figure 6(a). Although spring constant and yield force depend on temperature, these values are assumed to be constant in order to focus on the effect of plastic deformation. In order to represent residual stress, springs are extended by $k_y Z_e$ from equilibrium position as shown in Figure 6(b). $k_y Z_e$ corresponds to residual stress of specimen without ultrasonic vibration. Each spring is assumed to have elastic-perfectly-plastic restoring force characteristic. Figure 7 shows relation between restoring force and relative displacement $z(x-u)$ in x-axis. $x$ and $u$ are absolute displacement of mass and excitation, respectively. $F_x$ is yield force and $Z_{pr}$ is yield displacement. $Z_{pr}$ is displacement where velocity is positive to negative. X-axis and y-axis are assumed to be directions of principal stresses. Springs yield following Tresca yield criterion as shown in Figure 8.

![Figure 6. Two-dimensional model.](image)

The bead is subjected to vibrations with different frequencies from both sides. However, from Figure 4, vibrations are transmitted to the bead, it is assumed that the bead is subjected to vibrations with different frequencies from both sides. Acceleration of excitation is expressed as

$$\ddot{u} = U \sin 2\pi f_1 t + V \sin 2\pi f_2 t$$

(1)

In Eq.(1), $t$ is time. $U$ and $V$ are amplitudes of ultrasonic vibrations. As in Figure 4, peak values of power spectra of both ultrasonic vibrations are almost same. $U$ and $V$ are assumed to be equal. $f_1$ and $f_2$ are frequencies of ultrasonic vibrations. According to Tresca yield criterion, change of yield force is considered and change of residual stress is calculated. Ratio of residual stress of specimen without ultrasonic vibration to yield force $k_y Z_e/F_y$ is assumed to be 0.9 [2].

![Figure 7. Relation between restoring force and relative displacement.](image)

![Figure 8. Tresca yield criterion.](image)
Results of Analysis

Ratio of residual stress of specimen using ultrasonic vibration to that without ultrasonic vibration $F_{yf}/k_1Z_e$ is obtained. $F_x/mU$ is ratio of yield force to force of ultrasonic vibration. Table 1 shows results for specimen using ultrasonic vibration and Table 2 shows results for specimen using two ultrasonic vibrations. In table 1 and Table 2, Ratio is less than 1 in all conditions. This means that residual stress is reduced when specimen is welded using ultrasonic vibration. With the increase of amplitude of excitation, that is, with the decrease of $F_x/mU$, residual stress is reduced more. Comparing results in Table 1 with those in Table 2, residual stress is reduced more when two ultrasonic vibrations are used.

<table>
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<th>Frequency</th>
<th>$F_x/mU$</th>
<th>$F_{yf}/k_1Z_e$</th>
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<tr>
<td>27.5kHz</td>
<td>0.86</td>
<td>0.93, 0.97</td>
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<tr>
<td>37.5kHz</td>
<td>0.92</td>
<td>0.97, 0.98</td>
</tr>
<tr>
<td>47.5kHz</td>
<td>0.95</td>
<td>0.98, 0.99</td>
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<table>
<thead>
<tr>
<th>Frequency</th>
<th>$F_x/mU$</th>
<th>$F_{yf}/k_1Z_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.5kHz+37.5kHz</td>
<td>0.70</td>
<td>0.81, 0.89</td>
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<tr>
<td>37.5kHz+47.5kHz</td>
<td>0.79</td>
<td>0.87, 0.93</td>
</tr>
</tbody>
</table>

Conclusions

A reduction method of tensile residual stress using two ultrasonic vibrations with different frequencies is proposed. Advantage of the method to using one ultrasonic vibration is examined. Obtained results are summarized as follows.

1. Thick plate is buildup welded using ultrasonic vibration is used during welding in experiment. Residual stress of specimen using one ultrasonic vibration is reduced compared with that without ultrasonic vibration. Residual stress of specimen using two ultrasonic vibrations is reduced compared with that using one ultrasonic vibration.

2. Using two-dimensional model, residual stress is calculated by simulation method. Same results as experiment are obtained.

References
