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Probabilistic Evaluation of a Method for Reduction of Residual Stress in Welded Structure Using Vibration

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Reliability of structures is sometimes statistically evaluated since strengths of structures, inner and external forces in structures are statistically distributed. Inspection planning of structures, which plays important roll in health management, is also determined in a probabilistic manner in those cases. In this paper, residual stresses in welded structures are focused on as welding is widely used for construction of many structures. Residual stress is generated near the bead because of locally given heat. Tensile residual stress on the surface of metal degrades fatigue strength and related to reliability of welded structures. Reduction probabilities of tensile residual stresses are examined. The authors have proposed a method for reduction of residual stress using vibration during welding and have shown the effectiveness of the method. Residual stresses are statistically distributed. The effectiveness of the proposed method is examined in a probabilistic manner. Thick plates are used as specimens and ultrasonic vibration and low frequency vibration are applied. Some specimens of same size and material are welded using vibration during welding under the same conditions of amplitudes or frequencies. Reduction probabilities of residual stress are obtained from the expected values and the standard deviations of residual stresses assuming the normal distribution.

1. Introduction

Inspection is one of the most important factors for health management (Bragatto et al., 2012). Reliability of structures is sometimes statistically evaluated since strengths of structures, stresses in structures and applied loads are statistically distributed (Lin, 1967; Zhang and Mahadevan, 2000). In those cases, inspection planning of structures is also determined in a probabilistic manner (Straub and Faber, 2005). Estimation of strength of structure is an important factor for decision of inspection planning. In this paper, as one example, residual stresses in welded structures are focused on. Tensile residual stress degrades fatigue strength (Frost et al., 1999). In order to improve reliability of welded structures, reduction probabilities of tensile residual stresses are examined.

Welding is widely used for construction of many structures. Since welding is a joining method using heat, residual stress is generated near the bead. Methods for reduction of residual stress have been studied. Some of them are practically used, for example, heat treatment (Nakacho, 2002) and shot peening (Meo and Vignjevic, 2003). However, special equipment is needed in those methods and it takes a long time to reduce residual stress. A method using vibration after welding is also proposed. The effectiveness of the method is not confirmed (Gnirss, 1988). Then, it is required to develop a method to reduce residual stress in a short period of time. The authors have proposed a new method for reduction of residual stress using vibration during welding. They have shown that residual stresses are reduced using some types of vibrations, for example, relatively low frequency vibration (Aoki et al., 2004), random vibration (Aoki et al., 2005) and ultrasonic vibration (Aoki et al., 2007).

It is well known fact that residual stresses are statistically distributed (Paddea et al., 2012). In order to examine the effectiveness of the proposed method using vibration during welding, residual stresses of many specimens should be measured under the same conditions. Sufficient data were not available for examination of the effectiveness of the proposed method. In this paper, residual stresses are measured using many specimens and the effectiveness of the proposed method is examined in a probabilistic manner. Thick plates are used as specimens. Ultrasonic vibration and low frequency vibration are used. Some different amplitudes of vibration are selected for ultrasonic vibration. Some different frequencies of vibration are selected for low frequency vibration. 3 specimens of same size and material are welded using vibration during welding under the same conditions. Some specimens are welded without vibration for comparison. The expected values and the standard deviations of residual stresses are obtained. Comparing those values of specimens using welding with those without vibration, reduction probabilities of residual stress are obtained. Normal distribution is assumed for distribution of residual stresses. The best conditions of amplitude and frequency for reduction of residual stress are evaluated in a probabilistic manner.

2. Experiment for ultrasonic vibration and low frequency vibration

Specimens are welded using ultrasonic vibration and low frequency vibration during welding and residual stresses are measured. Some specimens are welded under the same conditions.

2.1 Experimental setup

Figure 1 and Figure 2 show size of specimens for ultrasonic vibration and low frequency vibration, respectively. Material of the specimen is rolled steel for general structure (JIS 400). Figure 3 shows experimental setup. Specimen is set on the supporting plate. Ultrasonic vibration is applied at excitation point as shown in Figure.1 and on the upper side of the specimen. Low frequency vibration is applied at the center of the specimen under the supporting plate as shown in Figure 3. Specimen is welded along the lines using automatic arc welding machine. Shield gas is a mixed gas of argon and carbon dioxide. Length of the bead is 150mm. Ultrasonic vibration and low frequency vibration are applied before and during welding for 30 s after welding. Velocity of welding is 2 mm/s, diameter of the wire is 1.2 mm, voltage is 21 V and current is 180 A.

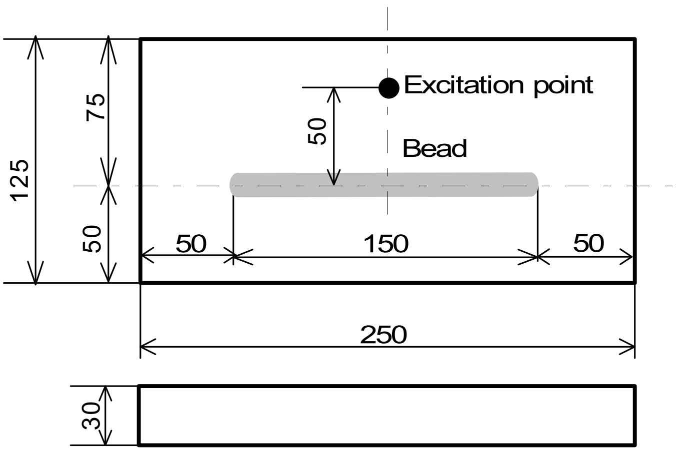

Figure 1: Size of specimen for ultrasonic vibration (mm)

For ultrasonic vibration, frequency is fixed and amplitudes are changed. For low frequency vibration, amplitude is fixed and frequencies are changed. Frequency of ultrasonic vibration is fixed as 37.5 kHz. Amplitude is determined by the effective value. The condition is selected as the specimen does not uplift from the supporting plate. Amplitudes are selected as 10, 100, 300, 500, 700, 1000, 1500 m/s^2. 3 specimens are used under the same conditions. Amplitude of low frequency vibration is fixed as 10 m/s^2. Since the fundamental natural frequency of the specimen is 46 Hz, frequencies are selected as 25 Hz and every 50 Hz from 50 Hz to 300 Hz. 3 specimens are used under the same conditions.

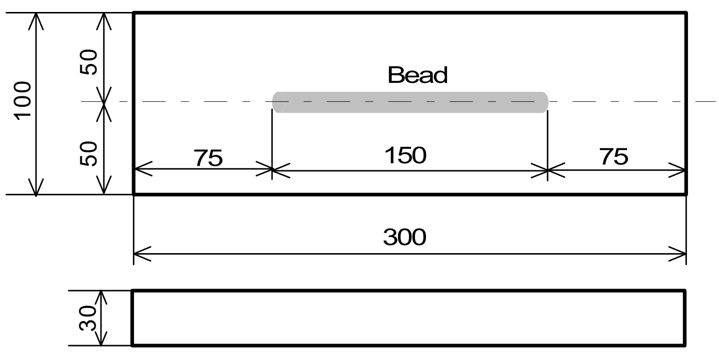

Figure 2: Size of specimen for low frequency vibration (mm)

Residual stresses are measured using X-ray diffractometer with a scintillation counter after removing quenched scale chemically using hydrochloric acid having a concentration of 6 mol/L and smoothing surface of the bead using CPL (chemical polishing liquid). Figure 4 shows measuring points of residual stresses. Residual stresses in the direction of the bead and perpendicular to the bead are measured at 15 points every 10 mm, which start at 5 mm from welding start point.

2.2 Measurement of vibration

Amplitude and frequency of ultrasonic vibration and low frequency vibration are measured. Vibrations are measured using acceleration pickup at the center of the bead before welding. Amplitude is measured by digital meter of amplifier. Frequency is measured by power spectral density function (PSD) using FFT analyzer. Figure 5 shows PSD of measured acceleration for ultrasonic vibration. Frequency component of 37.5 kHz is predominant. Ultrasonic vibration is transmitted to the surface of the specimen. For low frequency vibration, same results are obtained. Low frequency vibration is transmitted to the surface of the specimen.

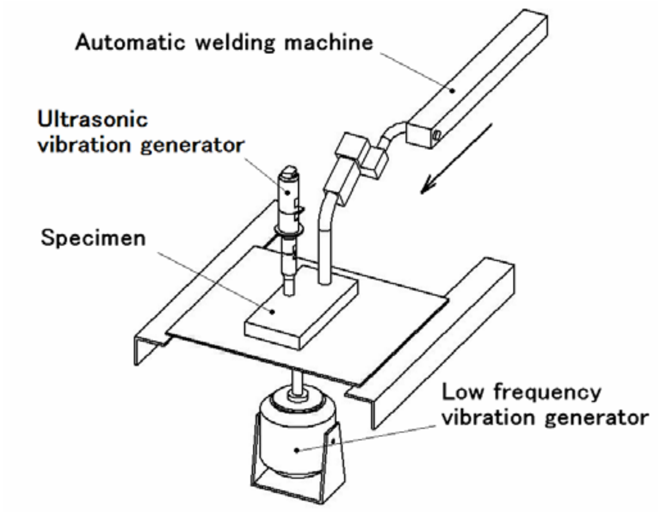

Figure 3: Experimental setup

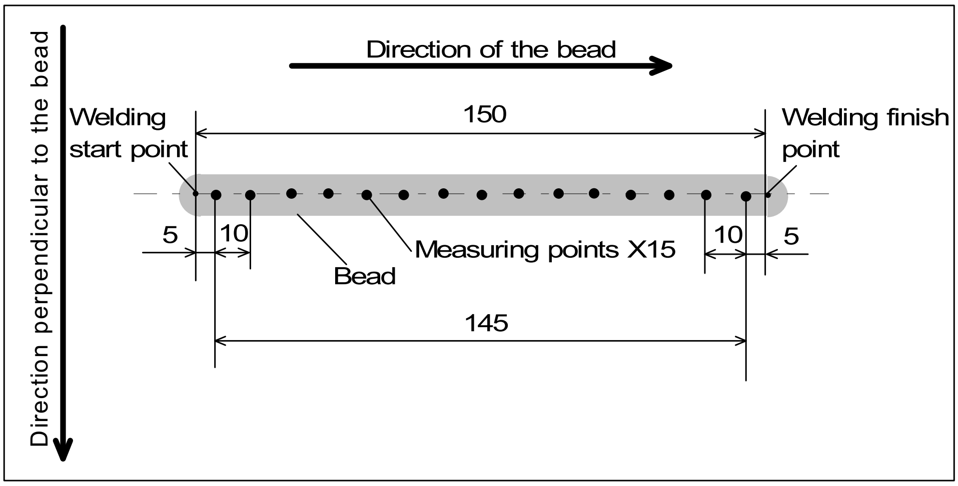

Figure 4: Measuring points of residual stress (mm)

2.3 Results of experiment

Figure 6 and Figure 7 show examples of residual stresses for ultrasonic vibration and low frequency vibration. Solid lines are residual stresses in the direction of the bead and broken lines are those in the direction perpendicular to the bead. Especially, residual stresses in the direction of the bead are low in both ends of the bead. The expected values are obtained in the area expect for both ends of the bead as shown in Figure.6. In the second columns of Table 1 and Table 2, the expected

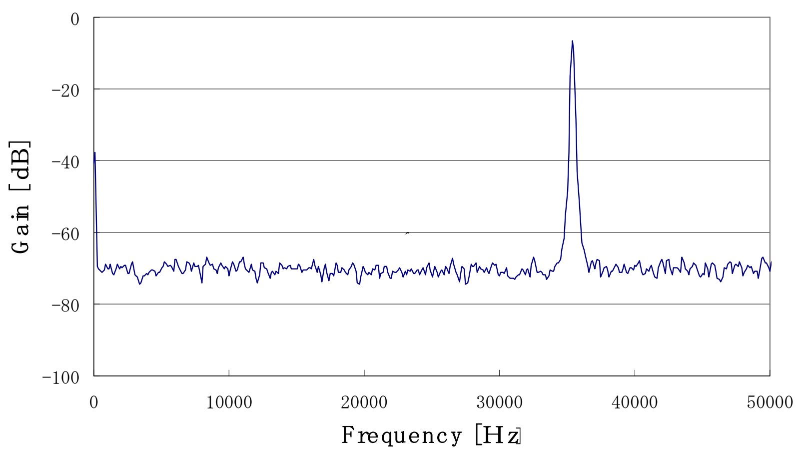

Figure 5: Power spectral density function for ultrasonic vibration

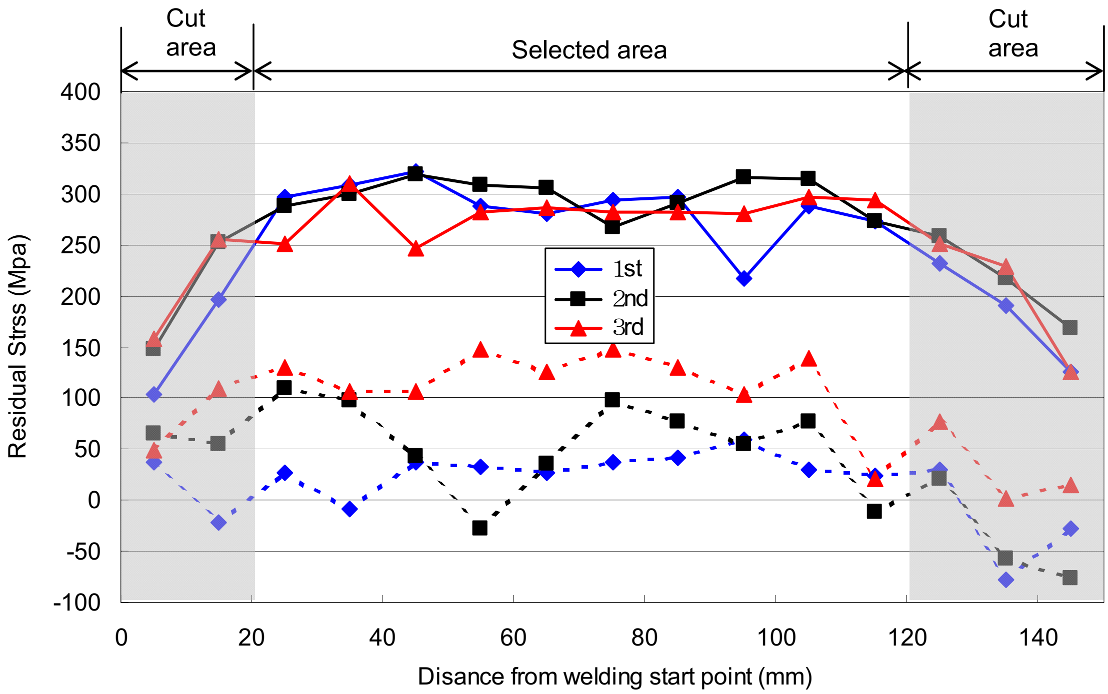

Figure 6: Residual stress using ultrasonic vibration (10m/s²)

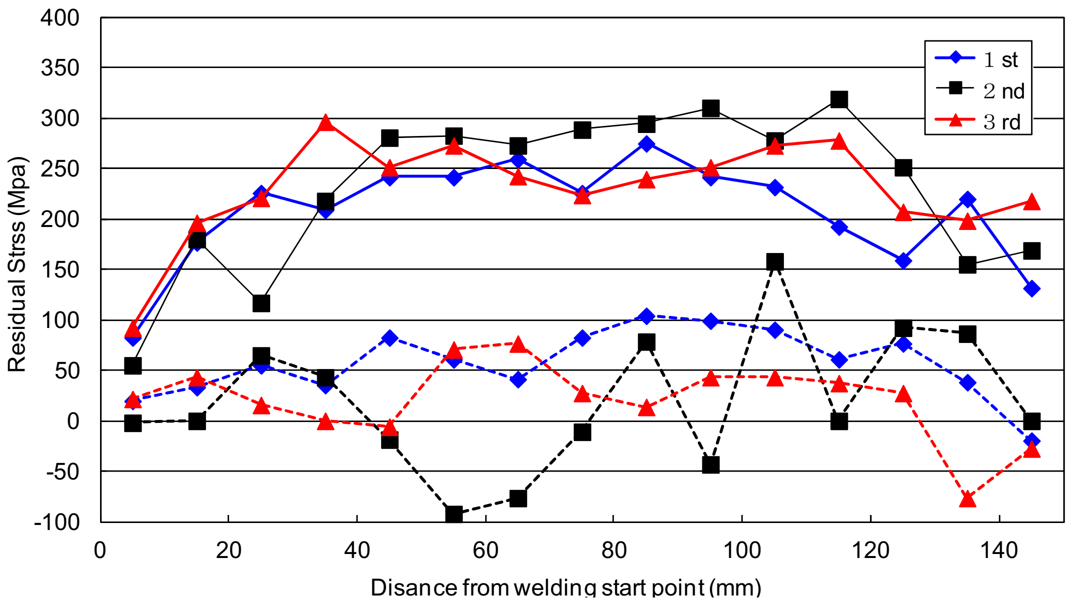

Figure 7: Residual stress using low frequency vibration (100Hz)

values are shown for residual stresses using ultrasonic vibration in the direction of the bead and that perpendicular to the bead, respectively. In the second columns of Table 3 to and 4, the expected values are shown for residual stresses using low frequency vibration. For ultrasonic vibration, reduction rate is large at amplitude of 500m/s². For low frequency vibration, reduction rate is large at frequency of 50Hz.

3. Reduction probability of residual stress

Residual stresses are statistically distributed as shown in Figure 8. The standard deviations of residual stresses are obtained in the selected area as shown in Figure 6. The normal distribution is assumed for statistical distribution of residual stress. Let μ_W and σ_W be the expected value and the standard deviation of residual stresses of specimens without vibration, respectively, and μ_V and σ_V are those of welded specimen using ultrasonic vibration or low frequency vibration. Reduction probability of residual stress is shaded area in Figure 8 and given as the following equation.

$$P_r = \Phi\left(\frac{\mu_W - \mu_V}{\sqrt{\sigma_W{}^2 + \sigma_V{}^2}}\right) \tag{1}$$

where $\Phi(\bullet)$ is the standard normal distribution.

Table 1: Statistical characteristics of residual stresses in direction of the bead (Ultrasonic vibration)

Acceleration (m/s^2)	Expected value (MPa)	Standard deviation (MPa)	Reduction probability (%)
Without vibration	263.5	32.6	—
10	288.7	22.5	26.2
100	301.3	33.1	20.8
300	267.9	59.6	47.4
500	259.4	31.4	53.6
700	295.9	27.7	22.4
1000	276.7	22.7	36.9
1500	306.9	31.6	17.0

Table 2: Statistical characteristics of residual stresses in direction perpendicular to the bead (Ultrasonic vibration)

Acceleration (m/s^2)	Expected value (MPa)	Standard deviation (MPa)	Reduction probability (%)
Without vibration	113.1	36.2	—
10	67.3	49.9	77.1
100	97.3	65.8	58.3
300	-2.6	66.2	93.7
500	27.2	56.4	90.0
700	85.3	24.7	73.8
1000	75.9	32.6	77.8
1500	95.7	39.7	62.7

Table 3: Statistical characteristics of residual stresses in direction of the bead (Low frequency vibration)

Frequency (Hz)	Expected value (MPa)	Standard deviation (MPa)	Reduction probability (%)
Without vibration	263.5	32.6	—
25	258.0	19.8	55.7
50	230.0	21.3	80.5
100	251.6	40.2	59.1
150	289.5	34.2	29.1
200	268.4	32.7	45.8
250	280.7	31.3	35.2
300	308.1	34.9	17.5

Table 4: Statistical characteristics of residual stresses in direction perpendicular to the bead (Low frequency vibration)

Frequency (Hz)	Expected value (MPa)	Standard deviation (MPa)	Reduction probability (%)
Without vibration	118.1	36.2	—
25	78.1	34.4	75.9
50	-25.1	54.6	98.3
100	37.0	53.7	87.7
150	58.2	68.9	76.0
200	13.9	40.1	96.7
250	135.1	35.7	33.1
300	153.6	53.9	26.7

In the third and the fourth columns of Table 1, the standard deviation and reduction probability, respectively, are shown for residual stresses in the direction of the bead using ultrasonic vibration. In Table 2, those in the direction perpendicular to the bead are shown. In the direction of the bead, reduction probability is higher than 50 % when amplitude is 500m/s^2 and higher than 20 % at almost of all other conditions. In the direction perpendicular to the bead, reduction probabilities are high at all conditions.
In Table 3 and Table 4, the standard deviation and reduction probability are shown for residual stresses in the direction of the bead and in the direction perpendicular to the bead, respectively, using low frequency vibration. In the direction of the bead, reduction rate is the highest at 50 Hz and higher than 50 % in low frequency range. In the direction perpendicular to the bead, reduction probabilities are high at all conditions except for high frequency range.

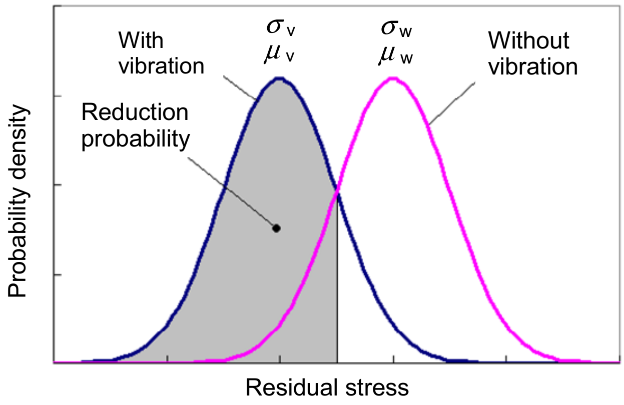

Figure 8: Reduction probability of residual stress

4. Conclusions

Method for reduction of tensile residual stresses using vibration during welding is proposed. Residual stresses are statistically distributed. The effectiveness of the method is evaluated in a probabilistic manner. As the type of vibration, ultrasonic vibration and low frequency vibration are applied. 3 specimens are welded under the same conditions in order to obtain the statistical characteristics of residual stresses. Residual stresses are measured for ultrasonic vibration with some amplitudes and for low frequency vibration with some frequencies. Probability distribution of residual stresses is assumed to be normal distribution and reduction probabilities of residual stresses are obtained. Best conditions for reduction of residual stresses are obtained.

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