Electromagnetic ultrasonic measurement for welding residual stress detection - comparison between experiment with numerical simulation

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Abstract. In order to study the feasibility of electromagnetic ultrasonic method on the welding residual stress detection in Q345R plate, experiments and numerical simulations were carried out. The welding residual stress in the plate was firstly measured by electromagnetic acoustic transducer (EMAT). Then, finite element model of welding process was established to predict the residual stress in plate, who’s rationality was verified by blind hole experiment. At last, the average of numerical simulation results at five points along the plate’s thickness direction was compared with the electromagnetic ultrasonic measurement results. The results show that the residual stress measured by EMAT is consistent with those from numerical simulation in direction of the weld. However, in the vertical direction of the weld, the deviation between EMAT results and numerical simulation is relatively large near the weld fusion line. This phenomenon is also found in the junction between the heat affected zone and the base metal.

1. Introduction
Welding residual stress not only causes harmful deformation, but also reduces fatigue resistance of structure. Besides, it can lead to stress corrosion and cracks in structure [1]. Therefore, the detection of welding residual stress is of great significance for both the safety assessment and fatigue life assessment of welded structures. Currently, the blind hole method, the X-ray diffraction method, the magnetic method, the piezoelectric ultrasonic transducer and the electromagnetic acoustic transducer (EMAT) are widely employed in the detection of welding residual stress. Among them, EMAT is a promising option owing to its advantages of no coupling agent, no surface treatment and fast detection speed [2].

Domestic and foreign scholars have contributed a lot of researches in the measurement of residual stress by electromagnetic ultrasonic method. Mitani et al. used longitudinal waves and shear waves generated by EMAT to measure the residual stress caused by shaping and processing [3]. Pei et al. proposed a method of generating ultrasonic waves using pulsed lasers and measured the residual stress of the bearing balls with EMAT. The results were in good agreement with the simulation results [4]. Ding et al. converted the shear wave to longitudinal wave by EMAT and measured the bolt axial stress [5]. Khlybov et al. excited and received surface wave to test mechanical stresses with EMAT, and the zero-crossing signal method yielded less computational error [6]. So far, the research on the measurement of residual stress in welding using electromagnetic ultrasonic at home and abroad is in its infancy.
In this paper, the welding residual stress in different areas of the butt welded joint of Q345R steel plate was firstly measured by EMAT. Then, the numerical simulation of the residual stress field in the plate was calculated by commercial software Simufact.Welding and verified by the blind hole experiment. At last, the average of numerical simulation results at five points along the plate’s thickness direction was compared with the electromagnetic ultrasonic measurement results.

2. The electromagnetic ultrasonic method

The electromagnetic ultrasonic probe generates ultrasonic waves and the Lorentz force is the dominant transduction effect [7]. The ultrasonic excitation mechanism is shown in Figure 1. The probe is mainly composed of a magnet and a coil. The magnet is used to provide an external magnetic field and the coil is used to generate a high frequency eddy current. During the measurement, the probe is placed on the surface of the workpiece and a high-frequency pulse current is introduced into the coil. Due to electromagnetic induction, an eddy current opposite to the direction of current is induced in the test piece. The eddy current generates a Lorentz force under the action of an external magnetic field. Then the Lorentz force will drive the charged particles in the workpiece to generate high-frequency vibration and propagate ultrasonic waves inside the workpiece. After the ultrasonic wave is reflected back to the surface from the bottom surface of the material, the particles at the surface of the workpiece vibrates. Therefore, the electromotive force at both ends of the excitation coil changes under the action of the magnetic field, and the eddy current is received and amplified by the receiving device.

![Figure 1. Schematic diagram of electromagnetic excitation.](image1)

![Figure 2. Electromagnetic ultrasonic transducer.](image2)

The electromagnetic ultrasound instrument used in the experiment is shown in Figure 2. The probe has a diameter of 25 mm. The probe can generate two transverse waves whose propagation direction is perpendicular to the incident surface and whose polarization directions are orthogonal to each other, shown in Figure 3. The probe can also receive the ultrasonic transverse wave reflected from the bottom surface of the plate. Then, the propagation time of the two ultrasonic waves are obtained directly by EMAT to calculate ultrasonic speeds respectively combining the thickness of workpiece. Finally, according to the relationship between stress and ultrasonic speed, the stress at the measurement site can be obtained. Considering the anisotropy of the material, the relationship is given by Equations (1) and (2):

\[
\left( v_1 - v_2 \right) / v_0 = \alpha + A\sigma_1 + B\sigma_2 \tag{1}
\]

\[
\left( v_1 + v_2 - 2v_0 \right) / 2v_0 = C\sigma_1 + D\sigma_2 \tag{2}
\]

where \( v_1 \) and \( v_2 \) are the shear wave velocities, \( \sigma_1 \) and \( \sigma_2 \) are the principal stress components, \( A, B, C, D \) are the acoustoelastic constants, \( v_0 \) is the mean shear wave velocity in the absence of stress and \( \alpha \) is anisotropic parameters:

\[
v_0 = \left( v_1^0 + v_2^0 \right) / 2 \tag{3}
\]
\[ \alpha = \left( \frac{v_1^0 - v_2^0}{v_0} \right) \]  

Where \( v_1^0 \) and \( v_2^0 \) are the shear wave velocities in the absence of stress.

The acoustoelastic constants and anisotropic parameters of different areas of the welded joint can be obtained by tensile test [8], and the results are shown in Table 1.

| position          | acoustoelastic constants | Anisotropic parameters α |  
|-------------------|--------------------------|--------------------------|  
|                   | A           | B           | C           | D           |  
| Weld              | -9.1026E-6 | 1.2982E-5  | -1.4352E-6 | -1.4847E-6 | -1.1253E-2 |  
| Heat affected zone| -8.3005E-6 | 1.4845E-5  | -1.5470E-6 | -2.4757E-6 | -9.0660E-3 |  
| Base metal        | -1.2351E-5 | 1.3552E-5  | -3.0252E-6 | -3.4398E-6 | -8.8367E-3 |  

In the experiment, the center of the probe is placed on the path shown in Figure 4. The distance between the measuring points is 5 mm. The propagation time of the two ultrasonic waves is measured three times at each point and the average value is used to calculate the welding residual stress at the measuring point.

![Figure 3.](image1.png)  
**Figure 3.** The propagating direction of ultrasonic wave and the stress direction.  

![Figure 4.](image2.png)  
**Figure 4.** Measuring paths of electromagnetic ultrasonic method.

3. Finite element simulation

3.1. Establishment of finite element model

A full-scale complete model is built. The two welded plates are 350x125x20mm with V-shaped groove. There are 4 welds totally. The model is meshed with high accurate hexahedral solid. The element size of 2 mm is used in the weld and the heat affected zone, where the temperature gradient changes significantly. The element size away from the heat affected zone increases with the increase in distance. The mesh is shown in Figure 5.

Base material Q345R and electrode material H10Mn2+SJ101 have similar chemical composition, physical properties and mechanical properties, therefore, the welding joints in the model use the parameters of the Q345R steel, which can be provided by the commercial software Simufact.Welding. Table 2 shows the physical properties of Q345R steel plates at different temperatures.

This simulation uses a double ellipsoid heat source model. The heat source parameters are continuously adjusted based on the macroscopic dimensions of the weld, so that the weld fusion line in the numerical simulation is similar to the actual weld fusion line, as shown in Figure 6. The numerical
values for heat source parameters are shown in Table 3 in conjunction with the welding process parameters shown in Table 4.

Finally, the double ellipsoid heat source model is loaded on the weld, and the residual stress field is simulated.

![Finite element mesh for the model.](image)

**Figure 5.** Finite element mesh for the model.

| Physical property parameters of Q345R. |
|----------------------------------------|
| temperature $T$(°C)                   |
| 20          | 100       | 300       | 500       | 700       | 900       | 1100      | 1300      |
|-----------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| thermal conductivity $\lambda$(W∙m$^{-1}$∙K$^{-1}$) | 50.7      | 48.2      | 41.5      | 34.2      | 31.8      | 25.3      | 26.8      | 29.6      |
| specific heat capacity $c$(J∙kg$^{-1}$∙K$^{-1}$) | 470       | 490       | 550       | 645       | 784       | 565       | 584       | 620       |
| density $\rho$(kg∙m$^{-3}$)               | 7820      | 7785      | 7740      | 7680      | 7640      | 7570      | 7480      | 7375      |
| poisson ratio $\mu$                       | 0.28      | 0.28      | 0.29      | 0.29      | 0.30      | 0.32      | 0.33      | 0.33      |
| linear expansion coefficient(10$^{-5}$∙K$^{-1}$) | 1.25      | 1.3       | 1.34      | 1.38      | 1.50      | 1.52      | 1.53      | 1.55      |
| elastic modulus $E$_{el}(GPa)             | 209       | 197       | 183       | 149       | 71        | 30        | 18        | 7         |
| yield strength $\sigma_s$(MPa)            | 345       | 332       | 300       | 230       | 89        | 43        | 21        | 13        |

![Actual and simulated weld fusion line.](image)

**Figure 6.** (a) Actual weld fusion line; (b) Simulated weld fusion line.
Table 3. Numerical values of heat source parameters.

| Weld | Length of front ellipsoidal $c_{f}$(mm) | Length of rear ellipsoidal $c_{r}$(mm) | Width of heat source $a$(mm) | Depth of heat source $b$(mm) |
|------|--------------------------------------|--------------------------------------|-----------------------------|----------------------------|
| 1    | 3.3                                  | 7.8                                  | 4.2                         | 6.0                        |
| 2    | 4.3                                  | 10.1                                 | 5.8                         | 5.2                        |
| 3    | 6.2                                  | 14.5                                 | 8.3                         | 7.2                        |
| 4    | 8.1                                  | 19.0                                 | 11.2                        | 8.1                        |

Table 4. Welding process parameters.

| Parameter                     | Value |
|------------------------------|-------|
| Welding voltage (V)          | 30    |
| Welding current (A)          | 500   |
| Welding process efficiency (%) | 75    |
| Welding speed (mm/s)         | 8     |

3.2. Verification of finite element model by blind hole experiment

In order to verify the accuracy of the finite element model, the numerical simulation results are compared with the results of blind hole experiment [8]. The position of the blind hole method is shown in Figure 7(a). Figure 7(b) shows the corresponding numerical simulation stress analysis paths L1, L2, L3 (both on the upper surface of the model).

Figure 7-Figure 9 show the comparison between the numerical simulation results and the blind hole method. It can be seen from Figure 8-Figure 10 that, the trends of residual stress distribution of the numerical simulation and the blind hole method are similar along the paths L1, L2, and L3. Therefore, the finite element model can be considered to be plausible and the rationality of electromagnetic ultrasonic measurement results can be verified based on the numerical simulation results.
Figure 8. Comparison of residual stress between numerical simulation and blind hole method along path L1.

Figure 9. Comparison of residual stress between numerical simulation and blind hole method along path L2.

Figure 10. Comparison of residual stress between numerical simulation and blind hole method along path L3.
4. Comparison between electromagnetic ultrasonic measurement and numerical simulation

In the lacking of available references about the welding residual stress detection using EMAT, the rationality of the present experimental results will be verified by the proposed numerical simulation results.

Because the results of electromagnetic ultrasonic measurement are the average value through the thickness of the weldment, 5 computational stress analysis paths are defined along the thickness direction at the same measurement path in the electromagnetic ultrasonic method. Then the average of stress on the 5 computational paths are compared with the results of electromagnetic ultrasonic measurement. Figure 11 shows the locations of the 5 computational paths of path D1-D4

![Diagram](image)

**Figure 11.** (a) Electromagnetic ultrasonic measurement paths; (b) Computational stress analysis paths.

Figure 12-Figure 14 show the comparison between the numerical simulation results (average value) with the electromagnetic ultrasonic measurement results along the paths D1-D3. It can be seen that along the path D1-D3, the numerical simulation results show good consistency with the results from electromagnetic ultrasonic method. But at both ends of the weld, the stress gradient (slope) of the numerical simulation is larger than that of the electromagnetic ultrasonic method. This is because the electromagnetic ultrasonic measurement results are the average stress within the coverage area of the probe, so the gradient of stress changes is reduced to some extent.
Figure 12. Comparison of residual stress between numerical simulation and electromagnetic ultrasonic method along path D1.

Figure 13. Comparison of residual stress between numerical simulation and electromagnetic ultrasonic method along path D2.

Figure 14. Comparison of residual stress between numerical simulation and electromagnetic ultrasonic method along path D3.
Figure 15 is a comparison of the numerical simulation results (average value) with the electromagnetic ultrasonic measurement results on the path D4. It can be seen that the trend of the residual stress distribution of the numerical simulation and the electromagnetic ultrasonic method is basically the same, but the deviation of the residual stress in weld fusion line obtained by simulation and EMAT is relatively large. This phenomenon is also found in the junction between the heat affected zone and the base metal. This is because along the path D4, the microstructure of the welded joint changes significantly, so that the value of the acoustoelastic constants in the relationship between the stress and the ultrasonic speed is not well applied to the boundary region.

![Comparison of residual stress between numerical simulation and electromagnetic ultrasonic method along path D4.](image)

**Figure 15.** Comparison of residual stress between numerical simulation and electromagnetic ultrasonic method along path D4.

5. Conclusions
The comparison between the welding residual stress measured by EMAT and numerical simulation indicate that in the direction of the weld such as path D1 (weld zone), D2 (heat affected zone) and D3 (base metal), the EMAT results shows good consistency with numerical simulation results. However, in the vertical direction, the deviation between the two methods are relatively high near the weld fusion line. This phenomenon is also found in the junction between the heat affected zone and the base metal. As a result, it can be concluded that EMAT can be used for welding residual stress detection.

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