Prediction of residual stress field on the surface of quenched 7055 aluminium alloy plates

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Keywords: aluminium alloy, quenching residual stress, finite element method, stress measurement, stress prediction method

Abstract

The effect of width on the surface quenching residual stress distribution in 7055 aluminium alloy plates of different width values was studied. The distribution of quenching residual stresses of the plates were studied by both simulation and experiment. Numerical simulation was carried out by using the Finite Element Method (FEM), and experimental measurements were conducted to verify the simulation work. The results show that the experimental distributions are approximately consistent with the simulation distribution. The stress fluctuations exist in the edge of the plate and the ratio of the fluctuation region decreases as the width increases. Considering the consistency of the centre point stress and actual length of the fluctuation region, we proposed a method to predict the surface residual stresses distribution using two-step data processing, providing a more convenient method for predicting the stress distribution of the plate with a large dimension by the plate with a small width.

1. Introduction

7000 series aluminium alloys (Al-Zn-Mg-Cu series) have the combination of high tensile strength, toughness, fatigue life and corrosion resistance, which have been widely used in the aerospace [1–3]. Generally, the quenching process is necessary for the aluminium alloy to achieve the supersaturated solid solution. Therefore, in the subsequent aging process, adequate strengthening phase precipitates to ensure desired mechanical properties [4]. However, a large temperature gradient happens during the quenching processes, which will lead to a high residual stress. Residual stresses can significantly affect the mechanical properties, such as fatigue strength. Moreover, the quenching residual stress on the surface of the plate is compressive, which is detrimental to the fatigue strength [5, 6].

The quenching residual stresses on the surface of aluminium alloy plates have been studied both experimentally [7–9] and theoretically [10, 11]. The commonly used measurement methods of the quenching residual stress include the hole-drilling method [12, 13], x-ray diffraction method [14, 15], etc. A hole-drilling and phase-shifting moiré interferometry combined system was developed to determine residual stresses by Ya [16]. Khan [17] presented a combined study using synchrotron x-ray diffraction and nanoindentation to determine the residual stresses around scratches in aluminium alloys. In addition, FEM simulations of quenching residual stress distributions have been investigated by researchers. Yazdi [18] combined numerical and experimental techniques to investigate the through-thickness residual stress field. The effect of parameters on residual stress magnitude in the cold compression and stretching processes was studied by using FEM simulation [19, 20]. Şimşir and Gür [21] studied the effect of asymmetric geometry on residual stress distribution in steel cylinders through 3D FEM simulation. Yang [22] focused on the effect of geometry
dimensions on residual stress distribution in A357 aluminium alloy cylindrical bars. For large aluminium alloy plates, Zhang [23] reported that the thickness can affect the residual stress level in quenched aluminium alloy plates with thicknesses ranging from 20 to 70 mm. However, the effects brought by the length and width on the quenching residual stresses remain to be studied. Our group’s preliminary research [24] showed that the length, especially the width will affect the quenching residual stress. However, it is limited to simulation studies.

In the present work, 7055 aluminium alloy plates of different width values were employed to study the width effects on the distribution and magnitude of the quenching residual stress on the surface. The hole drilling method, x-ray diffraction method and FEM simulation were used for mutual authentication. The effect of width on the surface residual stress distribution was discussed. Finally, a method to predict the surface quenching residual stress was proposed.

2. Experimental and simulation

2.1. Material and quenching details
The material used in this study was a rolled aluminium alloy plate with the composition (in wt%) of Zn-8.0, Mg-2.1, Cu-2.3, Zr-0.17, rest-Al. The dimensions of the specimens were 270 mm (longitudinal direction) × 81/108/135/189/243 mm (long transverse direction) × 27 mm (short transverse direction), encoded as 1# / 2# / 3# / 4# / 5# respectively. The specimens were solution heat-treated at 475 °C for 2 h and quenched into cold water at 20 °C. To ensure that the quenching process can be repeated and consistent with the simulated boundary conditions, a fixed quenching method was carried out as shown in figure 1. Black arrow was the direction of bubbles escaping and the bottom of the specimen was contacted with loose wires. The specimen was immersed into the water quickly and stood on a stable stand. There was no mixing and outside interference in the quenching process. The cooling water volume was sufficient and the increasing of temperature was less than 3 °C after quenching.

2.2. Residual stress measurements
The surface quenching residual stresses through the long transverse direction were measured using the x-ray diffraction method and the hole-drilling strain-gauge method. The measuring points of 1# and 2# plates are shown in figure 2. In the long transverse direction of the centre point on the surface, eight measuring points were settled every 5 mm beginning from the edge. In the range from 40 mm to the centre point, the measuring distance increased according to the width. The numbers of x-ray diffraction measuring points were 9/10/11/13/15 for 1# / 2# / 3# / 4# / 5# plates respectively. The x-ray diffraction method was performed on a Stresstech XStress3000 x-ray diffractometer and the Al {222} planes were chosen as the diffraction plane and the diffraction angle was about 156.7 °, nine scans were performed for each stress measurement using different \( \psi \) values within the range \( 0 \leq \psi \leq 40^\circ \), where \( \psi \) is the angle between the surface normal and the bisector of source and diffracted x-ray beam [25]. These nine scans were used to calculate the straight-line \( d \) (lattice spacing) versus \( \sin^2 \psi \) plots. The calculation of residual stress was made using standard theory [26].

An ASMB2–32 Strain Indicator and electric resistance rosette strain gauge were employed in the hole-drilling strain-gauge method. Since the spacing was too small to stick the strain gauge in the original position, the hole-drilling points had a 20 mm offset arrangement and equivalence points on the back surface were efficient with considering the symmetry of the plate and the uniform stress distribution in the longitudinal direction. The
The distribution of hole-drilling points is shown in Figure 3. It can be seen that the position and centring of measuring points were precise. Before attaching the strain gauge rosette to the measurement regions, the surface was grounded with 600 emery paper. The drill was positioned at the rosette centre using an optical microscope. Holes were drilled in 2 mm depth with a diameter of 1.5 mm. During the drilling operation, the relieved strain was detected by the strain gauge rosette and displayed on the strain indicator. Then the longitudinal stress ($\sigma_L$ or $\sigma_x$) and long transversal stress ($\sigma_{LT}$ or $\sigma_y$) can be calculated as follows:

$$\sigma_L = \frac{E(\varepsilon_0 + \varepsilon_{90})}{4A} - \frac{\sqrt{2}E}{4B} \sqrt{(\varepsilon_0 - \varepsilon_{225})^2 + (\varepsilon_{225} - \varepsilon_{90})^2}$$

$$\sigma_{LT} = \frac{E(\varepsilon_0 + \varepsilon_{90})}{4A} + \frac{\sqrt{2}E}{4B} \sqrt{(\varepsilon_0 - \varepsilon_{225})^2 + (\varepsilon_{225} - \varepsilon_{90})^2}$$

$$\tan 2\alpha = \frac{2\varepsilon_{225} - \varepsilon_0 - \varepsilon_{90}}{\varepsilon_0 - \varepsilon_{90}}$$

where $E$ is Young’s modulus; $\varepsilon_0$, $\varepsilon_{90}$, $\varepsilon_{225}$ are strain measured at the angel of 0°, 90° and 225° compared with longitudinal direction, respectively; $A$ and $B$ are the calibration coefficients, which are calculated as follows:

$$A = \frac{-1 + \mu \left( \frac{r_0}{r} \right)^2}{2}$$

$$B = \frac{-1 + \mu}{2} \left[ \frac{4}{1 + \mu} \left( \frac{r_0}{r} \right)^2 - 3 \left( \frac{r_0}{r} \right)^4 \right]$$

where $\mu$ is the poison’s ratio; $r_0$ is the hole radius; $r$ is the distance from the centre of the strain gauge rosette to the hole centre.
2.3. FEM modelling

The quenching process was simulated by using the ANSYS software. The quenched material used in the simulation model was a 7055 aluminium alloy plate. The starting temperature of the quenching process was 475 °C and the plate had a stress-free state at the beginning. The temperature of the water was 20 °C. The thermal and mechanical properties of 7055 aluminium alloy [27] were shown in table 1 and a 1/8 model of the plate was used due to the symmetry feature of the plate. The model used in the simulation is illustrated in figure 4(a) and the studied path is shown in figure 4(b). The heat transfer coefficients (HTCs) were used as the boundary condition and uniformly loaded on the three surfaces in the temperature field model. Symmetry constraints were set on the three symmetric surfaces in the stress calculation process. The HTCs were measured by using an iterative method. Figure 5 illustrates the flow chart of the iterative method. Before quenching, a thermocouple was buried into the specimen to record the cooling curve during the quenching process. The calculated heat transfer coefficients of 20 °C water are listed in table 2. The total brick elements were 9000.

3. Results and discussion

3.1. Quenching residual stress distributions on the paths

Figure 6 illustrates the quenching residual stress distributions on the surface of 81 mm and 108 mm width plates. The x-ray diffraction method, hole-drilling strain-gauge method, and FEM simulation were used to verify the accuracy of measurement and simulation mutually. The simulation results show that the residual stress on the surface is compressive, which ranging from 150 MPa to 200 MPa except for the edge region. Stress fluctuation exists in the edge regions. The measurement results by the x-ray diffraction method and hole-drilling strain-gauge method have the same tendency except for the edge region of x-component stress distributions in...
### Table 1. Material properties of 7055 aluminium alloy used in the FEM model [27].

| T (°C) | Density (Kg·m⁻³) | Thermal conductivity (W·m⁻¹·K⁻¹) | Specific heat (J·kg⁻¹·K⁻¹) | Elastic Modulus (GPa) | Thermal expansion (K⁻¹) | Yield strength (MPa) | Poisson ratio |
|--------|------------------|----------------------------------|----------------------------|----------------------|------------------------|----------------------|--------------|
| 20     | 2840             | 145                              | 852.3                      | 72.0                 | 21.67 × 10⁻⁶           | 412                  | 0.33         |
| 100    | 2828             | 152                              | 894.5                      | 65.2                 | 24.39 × 10⁻⁶           | 382                  | 0.33         |
| 200    | 2807             | 160                              | 940.5                      | 56.3                 | 28.02 × 10⁻⁶           | 370                  | 0.33         |
| 300    | 2787             | 167                              | 982.5                      | 38.0                 | 31.65 × 10⁻⁶           | 120                  | 0.33         |
| 400    | 2761             | 171                              | 1003.2                     | 31.5                 | 35.28 × 10⁻⁶           | 50                   | 0.33         |
| 500    | 2735             | 178                              | 1045                       | 25.0                 | 38.91 × 10⁻⁶           | 20                   | 0.33         |

### Table 2. Heat transfer coefficient of 20°C water quenching.

| T (°C) | Heat transfer coefficient (W·m⁻²·K⁻¹) |
|--------|--------------------------------------|
|        | 30     | 75     | 100    | 150    | 200    | 300    | 400    | 500    | 10     |
|        | 500    | 8000   | 25000  | 32000  | 20000  | 8000   | 100    | 10     |

3.2. Effect of width on the surface residual stress distribution

To explain the effect of width on the surface residual stress distribution more concisely, the simulation results are employed because of their accuracy and regularity. Figure 8 illustrates the surface residual stress distributions on the studied path with different widths. The stress distribution fluctuations in the edge are obvious. It can be seen that the ratio of the fluctuation region decreases as the width increases. However, the stress magnitudes at the centre-point of 81 mm, 108 mm, and 135 mm widths are consistent. The ratios of the fluctuation region and uniform-stress region are shown in table 3. There are no uniform-stress regions for the samples with 81 mm, 108 mm, and 135 mm widths. The actual length of the fluctuation region is about 135 mm, five times the thickness, which remains unchanged regardless of width variation. Thus, the surface residual stress distribution of 135 mm width contains the whole fluctuation area while the stress distributions of 81 mm and 108 mm widths contain partial fluctuation areas.

The edge effect of the quenching process can explain the fluctuation area. The edges under a two-dimensional heat transfer condition have a higher cooling rate than the other areas under a one-dimensional heat conduction. The thermal stresses in the edges decrease significantly because yield occurs. Thus, the edges maintain low-level stress. To balance the stress field in the edge, high-level stresses were generated in the regions near to the edge. Uniform stresses exist far away from the edges, so the ratio of the uniform-stress region increases as the width increases since the actual length of the fluctuation region is about 135 mm.
Figure 6. Comparison of the surface quenching residual stress distributions between FEM simulation and experimental measurement (x-ray diffraction and hole-drilling): (a) x-component stress of 81 mm width, (b) y-component stress of 81 mm width, (c) x-component stress of 108 mm width and (d) y-component stress of 108 mm width.
Figure 7. Comparison of the surface quenching residual stress distributions between FEM simulation and x-ray diffraction measurement: (a) x-component stress of 135 mm width, (b) y-component stress of 135 mm width, (c) x-component stress of 189 mm width, (d) y-component stress of 189 mm width, (e) x-component stress of 243 mm width and (f) y-component stress of 243 mm width.
3.3. Prediction of the residual stress field on the surface

Considering the consistency of stress at the centre point and actual length of the fluctuation region, a two-step data processing is applied to the results in figure 8. The first step was to align the stress distributions of various widths at the edge, as shown in figure 9(a). Then, the stress of the centre point was set to 1 and other data were normalized by the centre point. The processed results are shown in figure 9(b). It can be seen that the residual stress distributions on the surface of 135 mm, 189 mm, and 243 mm widths nearly overlap except for the stress distributions of 81 mm and 108 mm widths.

According to the results from figure 9, a method for prediction of the residual stresses field on the surface along the width direction of the plate is proposed. Firstly, there are two plates with the same length and thickness while the widths are encoded as width1 and width2, respectively, where width1 < width2 and width1/thickness > 5. Secondly, the surface stresses distribution along the width direction of the smaller plate (width1) can be obtained by simulation or experiment. Thirdly, the two-step data processing is applied to the stress distribution of the plate (width1), in which the stress field is normalized by the centre point on the surface of the plate. Fourthly, the distribution that extended from the edge with the ratio of width2/width1 is used as the

**Figure 8.** The original surface quenching residual stress distributions on the studied path with various widths: (a) x-component stress and (b) y-component stress.

| Width (mm) | Ratios of the fluctuation regions | Ratios of the uniform stress regions |
|------------|----------------------------------|-------------------------------------|
| 81         | 1                                | 0                                   |
| 108        | 1                                | 0                                   |
| 135        | 1                                | 0                                   |
| 189        | 0.70                             | 0.30                                |
| 243        | 0.55                             | 0.45                                |

3.3. Prediction of the residual stress field on the surface

Considering the consistency of stress at the centre point and actual length of the fluctuation region, a two-step data processing is applied to the results in figure 8. The first step was to align the stress distributions of various widths at the edge, as shown in figure 9(a). Then, the stress of the centre point was set to 1 and other data were normalized by the centre point. The processed results are shown in figure 9(b). It can be seen that the residual stress distributions on the surface of 135 mm, 189 mm, and 243 mm widths nearly overlap except for the stress distributions of 81 mm and 108 mm widths.

According to the results from figure 9, a method for prediction of the residual stresses field on the surface along the width direction of the plate is proposed. Firstly, there are two plates with the same length and thickness while the widths are encoded as width1 and width2, respectively, where width1 < width2 and width1/thickness > 5. Secondly, the surface stresses distribution along the width direction of the smaller plate (width1) can be obtained by simulation or experiment. Thirdly, the two-step data processing is applied to the stress distribution of the plate (width1), in which the stress field is normalized by the centre point on the surface of the plate. Fourthly, the distribution that extended from the edge with the ratio of width2/width1 is used as the
distribution of the larger plate (width2). Finally, the surface residual stresses distribution along the width direction of the plate (width2) is obtained by restoring the normalized distribution based on the stress measurement of the surface centre point. The relationship between stress distributions with different widths is established by the prediction method, providing a more convenient research method of stress distribution. Moreover, it can be indicated that the prediction method is also adapted to the prediction of the residual stress field along the length direction. With using this prediction method, the stress distribution of the industrial plate with a huge dimension can be simply predicted from the plate with a small dimension.

4. Conclusion

The surface quenching residual stress distributions with different widths of 7055 aluminium alloy plates were studied both experimentally and theoretically. The simulation distributions are approximately consistent with the experimental distributions. The FEM model has a satisfying accuracy in the prediction of surface quenching residual stress distributions.

The stress fluctuations in the edge are obvious. As the width increases, the ratio of the fluctuation region decreases while the ratio of the uniform-stress region increases. However, the residual stress on the surface centre point of 81 mm, 108 mm, and 135 mm widths plate are consistent. The actual length of the fluctuation region remains unchanged regardless of the width variation, which is five times the thickness.

A method to predict the surface residual stress distribution is proposed by using a two-step data processing. The relationship between stress distributions with different widths is established to conveniently predict the stress distribution by this method. The stress distribution of the plate with a large dimension can be simply predicted by the plate with a small width.

Figure 9. The quenching residual stress distributions on the surface after the two-step data processing on the studied path with various widths: (a) step 1: align at edges and (b) step 2: normalize by the centre point.
Acknowledgments

This study was financially supported by the National Key Research and Development Program of China (No. 2020YFF0218202, 2020YFF0218203).

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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