Effects of Thickness and Pre-stretching Ratio on Quenching Residual Stress in 7050 Aluminum Alloy Thick Plate

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Abstract. The quenching residual stress in 7050 aluminum alloy thick plate was simulated by using the finite element method (FEM). And the FEM model was verified the experimental results. Then the effects of thickness and pre-stretching ratio on quenching residual stress were studied using the FEM model. The simulation results showed that the quenching residual stress increases gradually with the increase of thickness. The residual stress increased rapidly with the increase of thickness when the thickness between 40mm and 80mm. While the residual stress increased slowly when the thickness exceeds 80mm. The quenching residual stress decreased gradually with the increase of pre-stretching, but the decreasing extent slowed down gradually. When the pre-stretching amount exceeded 2.5%, the reduction ratio can be achieved more than 95.0%. Considering the efficiency of the reduction of quenching residual stress as well as the economy, the pre-stretching ratio should be set between 2.5% and 3.5%.

1. Introduction
Aeronautical and aerospace structural parts are usually manufactured from 7050 aluminum alloy plates milled through direct processing. In the machining process, the deformation caused by the release and redistribution of initial residual stress in aluminum alloy thick plates has become one of the key technical difficulties in the manufacturing of aeronautical and aerospace structural parts [1-8]. When the quenching medium and quenching temperature are constant, the main factors affecting the residual stress of aviation aluminum alloy thick plate are the thickness, cooling speed, pre-stretching etc. [9-13].

In this paper, the effects of thickness and pre-stretching ratio on the quenching residual stress in 7050 aluminum alloy thick plate were analyzed by FEM. The residual stress on the surface of 7050 aluminum alloy thick plate after pre-stretching was measured by ultrasonic method. The simulated results were compared with the experimental results to verify the feasibility and accuracy of FEM model in this study. The simulation results of residual stress with different thickness and pre-stretching ratio can provide guidance in the design and modification procedure process and control technology of residual stress.

2. FEM Models
The material of the numerical simulation was 7050 aluminum alloy. The dimensions of the FEM model were 1200mm×220mm× (40mm, 80mm, 120mm and 160mm). The material parameters that used in this model were obtained by measurements. The finite element simulation software was used to build the quenching and pre-stretching FEM model in this study [14-17]. It was assumed that the thick plate was isotropic continuous medium, and the residual stress distribution are symmetrically distributed along the length and width directions respectively. To reduce simulation time, 1/4 model is
selected and the 8-nodethree-dimensional solid element(C3D8T) was used. The symmetry constraints were set on the symmetry plane, as shown in figure 1.

![Figure 1. Schematic diagram of FEM model.](image)

According to the clamping characteristics of pre-stretching process, contact constraints were established at the contact parts of chuck and cushion plate, clamp and 7050 thick plate, and guide rail and clamp. The schematic and dimensions of the pre-stretching model are shown in figure 2. The clamping position structure and detail size are shown in figure 3. The clamping length is assumed to be 200mm. After pre-stretching, the load is removed and the clamping force is released.

![Figure 2. Pre-stretching finite element model.](image) ![Figure 3. Clamping position structure and detail size.](image)

3. Experimental Verification

3.1. Formatting the Title

In order to verify the simulation results, the residual stress in the pre-stretched 7050 aluminum alloy plate was tested by experiment.

The experimental material is 7050 aluminum alloy thick plate, and the size is 1400mm×220mm×80 mm. After solid solution and heat preservation, the plate was quenched at room temperature immediately (transfer time is less 10s). After cooling process, the plate was pre-stretched with the ratio of 2.5% within 2 hours.

3.2. Experimental Results and Analysis

The ultrasonic method was used to measure the residual stress measured [18-20]. Ultrasonic method has the advantages of nondestructive testing, small size and convenient testing, and it has attracted more and more attention in testing of residual stress [21-23]. HT1000 ultrasonic stress detector was used in this experiment. The frequency of transmitting and receiving probe was 5 MHz and the distance between probes was 30 mm. The propagation depth of critical refraction wave (LCR wave) in aluminum alloy was about 1.4 mm.
Five points of rolling direction are selected as test positions that are 200 mm away from clamping position. Figure 4 is the result of surface residual stress measurement and simulation of 7050 aluminum alloy thick plate. It was shown that the error between test results and simulation results is less than 20.0 MPa, which indicates that the model that adopted in this study has a high reference value for practical application.

**Figure 4.** The result of residual stress measurement and simulation of 7050 thick plate.

**4. Discussions**

In order to analyze the influence of plate thickness and pre-stretching ratio on quenching residual stress in 7050 aluminum alloy thick plate, the residual stress in the representative positions are extracted from the results (The surface stress from face centered position, the heart from the body centered position). Figure 5 shows the studied paths in the model.

**Figure 5.** Residual stress extraction path.

Figure 6 shows the change of the surface and core residual stress with the thickness of 7050 aluminum alloy thick plate after quenching. It is shown that the quenching residual stress of 7050 aluminum alloy thick plate is compressive stress state on the surface and tensile stress state in the center. And the magnitude and distribution of stresses in the rolling direction and transverse direction are similar, both for the surface residual stress and the core residual stress. With the increase of thickness, the quenching residual stress of 7050 aluminum alloy thick plate increases gradually. This is because with the increase of thickness, the temperature gradient between the surface and the interior of 7050 aluminum alloy thick plate increases gradually, thus the material deformation tends to be uneven and the residual stress increases gradually. When the thickness increases from 40mm to 80mm, the surface and core residual stresses increase greatly. When the thickness increases from 80mm to 160mm, the surface and core residual stresses increase inconspicuously.
In order to analyze the variation of quenching residual stress of 7050 aluminum alloy thick plate with the thickness, the surface and core residual stresses of 7050 aluminum alloy thick plate with different thickness were extracted in the model, as shown in table 1. It is shown that, with the increase of thickness, the surface residual stress increases from about 84.0 MPa to about 200.0 MPa, and the core residual stress increases from about 95.0 MPa to about 202.0 MPa for the model used in this paper. When the thickness increases from 40 mm to 80 mm, the increase of the surface residual stress is 110.0 MPa, and the increasing ratio is 131.0% in the rolling direction, in the transverse direction, the increase was 112.0 MPa, and the increasing ratio is 127.3%. The core residual stress increase was 95 MPa, and the increasing rate reaches 92.2% in the rolling direction, in the transverse direction, the increase was 95.0 MPa, the increasing ratio is 100.0%. When the thickness increases from 80mm to 160.0mm, the surface residual stress and core residual stress increase less than 5.0 MPa.

The results show that, when the thickness of the plate is between 40 mm and 80mm, the residual stress increases rapidly with the increase of thickness. And when the thickness of the plate is over 80mm, the residual stress increases slowly or even does not increase significantly with the increase of thickness.

Figure 6 shows that residual stress variation trend of 7050 aluminum alloy thick plate with different thickness after different pre-stretching ratio (0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, 3.0% and 3.5%). It is shown that, after different pre-stretching ratios, the residual stress of 7050 aluminum alloy thick plate still shows compressive stress in the surface and tensile stress in the core. And the magnitude and distribution of stress are similar in the rolling direction and transverse direction. Under the same pre-stretching ratio, the residual stress of 7050 aluminum alloy thick plate still increases with the increase of thickness. When the thickness is fixed, the residual stress of 7050 aluminum alloy thick plate
decreases gradually with the increase of pre-stretching ratio. When the pre-stretching ratio is between 0% and 2.5%, the residual stress decreases greatly. When the pre-stretching ratio is over 2.5%, the residual stress decreases greatly.

Table 1. Quenching residual stresses of 7050 aluminum alloy plate with different thickness.

| Thickness/mm | Surface stress/MPa       | Core stress/MPa       |
|--------------|-------------------------|-----------------------|
|              | Rolling direction | Transverse direction | Rolling direction | Transverse direction |
| 40           | -84.0                  | -88.0                 | 103.0             | 95.0                 |
| 80           | -194.0                 | -200.0                | 198.0             | 190.0                |
| 120          | -195.0                 | -200.5                | 202.2             | 191.0                |
| 160          | -194.0                 | -200.5                | 203.0             | 187.0                |

![Figure 7](image-url)

**Figure 7.** Quenching residual stress of 7050 thick plate with pre-stretching: (a) Surface in rolling direction, (b) Surface in transverse direction, (c) Core in rolling direction, (d) Core in transverse direction.

When the quenched plate is stretched, no matter the surface metal that under compressive stress or the core metal that under tensile stress, they will deform when being subjected to external force. When the stretching stress exceeds the yield strength, plastic deformation will occur [24]. Because the core metal of the plate has residual tensile stress, it exceeds the yield strength and triggers the plastic deformation firstly. This obviously results in a more rapid deformation rate of inner metal than that of surface metal. However, as the plate is still a whole, surface metal will restrain the deformation of inner metal [25-27]. The essence of pre-stretching after quenching is to redistribute the residual stress...
of the plate. While eliminating the residual stress, the plate will produce larger deformation, and the plastic strain increases with the increase of the pre-stretching amount. Eliminating the residual stress by pre-stretching is at the cost of increasing the plastic deformation [28].

In order to analyze the variation of residual stress in 7050 aluminum alloy thick plate with pre-stretching ratio, the residual stresses in 160mm thick 7050 aluminum alloy plate under different pre-stretching amount were extracted in the model, as shown in Table 2. It is shown that, with the increase of pre-stretching ratio, the residual stress of 7050 aluminum alloy thick plate decreases gradually, but the decreasing extent slows down gradually.

When the pre-stretching ratio is 2.5%, the surface residual stress decreases from 194.0MPa to 8.7 MPa, the reduction ratio is 95.5% in the rolling direction, in the transverse direction, the decreases from 200.5MPa to 10.6MPa, the reduction ratio is 94.7%. The core residual stress decreases from 198.0MPa to 8.0MPa, the reduction ratio is 96.0% in the rolling direction, in the transverse direction, the decreases from 187.0MPa to 7.5MPa in the transverse direction, the reduction ratio is 96.0%.

When the pre-stretching ratio is 3.5%, the surface residual stress decreases from 194.0MPa to 4.8 MPa, the reduction ratio is 97.5% in the rolling direction, in the transverse direction, the decreases from 200.5MPa to 3.4MPa, the reduction ratio is 98.3%. The core residual stress decreases from 198.0MPa to 5.0MPa, the reduction ratio is 97.5% in the rolling direction, in the transverse direction, the decreases from 187.0MPa to 2.3MPa, the reduction ratio is 98.8%.

Therefore, in order to effectively reduce the residual stress (the reduction rate is more than 95.0%) and prevent excessive residual stress from having adverse effects on subsequent plate processing, the pre-stretching amount should be set between 2.5% and 3.5% from the practical point of the factory.

Table 2. Residual stresses of 160mm 7050 aluminum alloy thick plate under different pre-stretching amount.

| Pre-stretching ratio/% | Surface stress/MPa | Core stress/MPa |
|-----------------------|--------------------|----------------|
|                       | Rolling direction  | Transverse direction | Rolling direction | Transverse direction |
| 0                     | -194.0             | -200.5           | 198.0             | 187.0             |
| 0.5                   | -90.7              | -139.0           | 61.8              | 103.0             |
| 1.0                   | -39.2              | -61.7            | 30.0              | 44.5              |
| 1.5                   | -20.1              | -31.0            | 15.9              | 22.1              |
| 2.0                   | -12.7              | -18.0            | 10.9              | 12.9              |
| 2.5                   | -8.7               | -10.6            | 8.0               | 7.5               |
| 3.0                   | -6.2               | -5.8             | 6.2               | 3.9               |
| 3.5                   | -4.8               | -3.4             | 5.0               | 2.3               |

5. Conclusion

The effects of thickness and pre-stretching ratio on the quenching residual stress in 7050 aluminum alloy thick plate were studied in this work, and the conclusions are drawn:

(1) By compared with the experimental results, the model that adopted in this study is verified to have a high reference value for practical application.

(2) The quenching residual stress of 7050 aluminum alloy thick plate shows compressive stress in the surface and tensile stress in the core. And it increases with the increase of thickness. When the thickness increases from 40mm to 80mm, the surface and core residual stresses increase greatly. When the thickness increases from 80mm to 160mm, the surface and core residual stresses increase inconspicuously.

(3) With the increase of pre-stretching ratio, the residual stress of 7050 aluminum alloy thick plate decreases gradually, but the decreasing extent slows down gradually. When the pre-stretching ratio is
2.5%, the reduction ratio reaches 98.3%. When the pre-stretching ratio is 3.0%, and the reduction ratio is more than 97.0%. In order to effectively reduce the residual stress, the pre-stretching amount should be set between 2.5% and 3.5% from the practical point of the factory.

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