Aluminum alloy quenching model based on direct thermal-mechanical coupling method

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Abstract
The similarities and differences between the direct coupling method and quasi-coupling method in solving the problem of thermal-mechanical coupling were compared and analyzed, so the direct thermal-mechanical coupling computer simulation model on 7075 aluminum alloy plate quenching was established, and tested to verify the accuracy of the simulation results, the results showed that the computer simulation model using the direct coupling method has better accuracy. The computer simulation data can clearly reveal the evolution of temperature field, strain field and stress field in the aluminum alloy sheet quenching process. And by analyzing the computer simulation data, the reason was found that the distribution curves appear "turning point" of the quenching residual stress along aluminum alloy plate thickness.

Key words: ALUMINUM ALLOY, QUENCHING, RESIDUAL STRESS, DIRECT COUPLING

1. Introduction

Aluminum alloy plates have been widely used in the manufacture of aviation as the whole piece of thin-walled structures. In particular, the overall structure is widely used in large-scale aircraft [1]. But the machining deformation caused quenching residual stress within the aluminum plate has seriously hampered the development of Aviation automated manufacturing [2, 3]. Determination of quenching residual stress test is only to measure the final residual stress after quenching completed, and it cannot to directly on-line monitor stress and strain in the aluminum plate during quenching process, so the formation mechanism of quenching residual stresses also remain in the qualitative analysis phase. Due to the lack of a clear understanding of the formation process of quenching residual stresses, it is difficult to systems analyze the distribution and formation mechanism of quenching residual stresses, it led to the technical aspects to eliminate and control quenching residual stress is difficult to obtain a new breakthrough [4].

Finite element computer simulation technology has become a practical and effective way to study the formation process and distribution of quenching residual stress, academia has established a variety of computing models to explore the formation mechanism and distribution [5-9]. But in solving computational models, most scholars separated the quenching process temperature and stress fields into two steps to solve (called quasi-coupling). In fact, the quenching process is a very short thermal-mechanical coupling process, while intertwined with the transient temperature field, stress and strain fields due to temperature changes and thermal effects caused by elastic-plastic deformation, along with a variety of thermal parameter varies with temperature such as strain hardening, thermal conductivity, etc [4].

In this paper, direct thermal-mechanical coupling computer model to simulate the quenching process of 7075 aluminum alloy plate was established in order to study the evolution and distribution of quenching residual stress, and the experimental tests to verify the accuracy of the computer simulation results was carried out. Through basic research on the evolution data of the quenching process, aluminum alloy quenching process was more clearly demonstrated and quenching residual stress formation mechanism had been added to explain, it provided a scientific reference for the development of new residual stress reduction processes.

2. Direct thermal-mechanical coupling calculation model and solving method

Computer simulation algorithm of quenching is based on the theory of combined thermal and mechanical, and it involves synchronous coupling analysis of heat transfer and thermal stress.

The thermodynamic equilibrium equations represented by displacement components:

$$\left.\begin{aligned}(\lambda+G)\frac{\partial e}{\partial x}+G\nabla^2 u-\beta\frac{\partial t}{\partial x}+X=0\\(\lambda+G)\frac{\partial e}{\partial y}+G\nabla^2 v-\beta\frac{\partial t}{\partial y}+Y=0\\(\lambda+G)\frac{\partial e}{\partial z}+G\nabla^2 w-\beta\frac{\partial t}{\partial z}+Z=0\end{aligned}\right\}\qquad(1)$$

Where X, Y and Z sequentially indicates the component of body force per unit volume in x-axis, y-axis and z-axis, u, v and w sequentially indicates the displacement components in x-axis, y-axis and z-axis, ∇^2 indicates the Laplace operator, G indicates the Shear modulus, λ indicates the Lame constant, e indicates the volumetric strain, β indicates the thermal stress factor.

Heat conduction equation:

$$\lambda\nabla^2 T=\frac{\partial Q}{\partial \tau}\qquad(2)$$

Where T indicates temperature, Q indicates heat flux.

Assuming the quenching process is a quasi-steady problem, it means the transition process that the temperature field evolved from a steady state to next steady state is assumed to gradually balanced process, so the impact of the acceleration term is ignored. In this context, the heat conduction equation and the thermodynamic equilibrium equations are independent, the displacement components should be solved comply with the equation (1), the temperature field should be solved comply with the equation (2). That is, the temperature field and the stress field will be calculated in two steps. The two are not really coupled, which is the method for solving quasi-coupling method for computer simulation of quenching process.

Because of the flow stress properties of aluminum alloys at high temperature, the impact of the acceleration term must be considered in the thermodynamic equilibrium process [10], In this case, the heat conduction process should be described by the modified Fourier Heat equation:

$$\lambda\nabla^2 T=C_\varepsilon\frac{\partial T}{\partial \tau}+T_0\beta\frac{\partial e}{\partial \tau}\qquad(3)$$

Where T_0 indicates the initial temperature, C_ε indicates constant volume specific heat.

Equation (3) contains three displacement components and an amount of temperature, so it cannot be solved independently unless the combination of equation (3) and equation (1). Such problems, the temperature fields and stress fields influence each other, forming a coupling relationship, which is the method for solving direct coupling method for computer simulation of quenching process. It is different from quasi-coupling method that the temperature fields and stress fields are separated into two steps to solve [11-12].

3. Direct coupling computer simulation model

3.1. Assumptions

Aluminum alloy plates were re-balance the stress during the heating holding process, so the residual stresses before quenching were negligible [2,9]. Aluminum alloy is quenched in order to maintain solid solution state, the phase transition is generally not occur [4]. Quenching jobs were in large water-filled pool that can be considered a small change in the temperature of quenching medium during quenching.

Assumptions as follows:

(1)Aluminum alloy plates were regarded as isotropic materials.

(2)The phase transition would not occur during quenching aluminum alloy plates.

(3)The initial stress was zero before quenching.

(4)The process of aluminum alloy plates into water was ignored.

(5)The temperature of quenching medium remained unchanged.

3.2. Model establishment

The structure of aluminum alloy plate was symmetrical, and based on assumptions, the initial and boundary conditions of the computer simulation model were also symmetrical, so only 1/8 of aluminum alloy plate structure was taken to model. The simulation model was defined as 7075 Aluminum alloy material, the model shown in Figure 1. Where O was the center point of the entire plate, A, B, C, D and M were the vertex points of the simulation model structure.

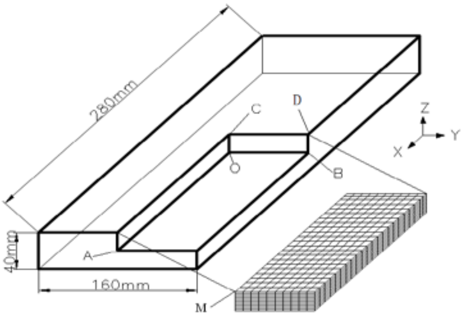


Figure 1. Schematic diagram of simulation model structure and marked points

The steps of establishing model were as follows:

(1) Reduced integration eight-node hexahedral temperature-displacement coupling unit was employed to mesh.

(2) Symmetry constraints were imposed in three symmetry plane, only rigid body motion of aluminum alloy plate was fixed, while the internal deformation of the aluminum alloy plate was not constrained.

(3) The initial temperature of the entire model range was set to 473 ℃, and the temperature of the heat exchange medium was set to a constant 26 ℃.

4. Simulation results and analysis

Dynamic explicit algorithm was used to solve the model, it was solving the equations combined formula (1) and formula (3).

4.1. The temperature field

In order to visually observe the changes in the temperature field, although the simulation model only took 1/8 of aluminum alloy plate structure, the temperature field throughout the plate was calculated with symmetry principle. Figure 2 shows the temperature distribution on surface OBDC in a moment of quenching.

As can be seen from Figure 2, the temperature field of aluminum alloy plate presents multi-ring isothermal region during quenching, and the isothermal region of the core portion emerged gradually "necking" trend, one reason was that heat transfer coefficient, thermal conductivity and specific heat and other thermal parameters were all functions of temperature, and another intuitive reason can be seen from the simulation data curve in Figure 3, and in the figure, the point D was set as the origin of the abscissa.

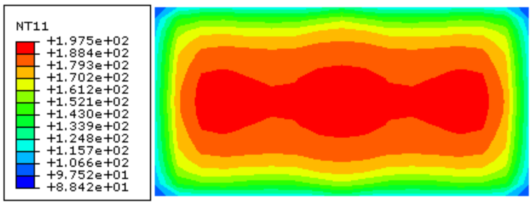
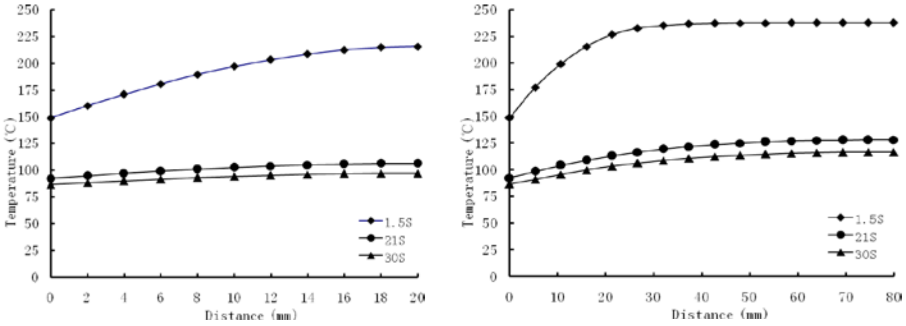


Figure 2. The temperature distribution on surface OBDC in a moment of quenching



(a) Path DC

(b) Path DB

Figure 3. Temperature distribution curves along surface OBDC edge lines in different quenching moment

In Figure 3, a plurality of curves have the same trend, it is that temperature at point D has been lower than the temperature at point B and point C in the quenching process, and the temperature gradually increases along the path DC and path DB. This shows that the temperature difference between the outer surface region near Points B, C and the center region near the point O is always smaller during quenching. Temperature difference smaller lead to the smaller heat transfer, therefore, the area near point O there is a relatively high temperature region during quenching.

4.2. The strain field

The temperature field and temperature gradient changes rapidly during quenching, it leads thermal strain to transient changes, and when the thermal deformation beyond the elastic range, plastic deformation occurs, and the unrecoverable characteristics of plastic deformation lead to inconsistent deformation displacement in the interior of the aluminum alloy plate, so the residual stress generates after quenching. Thus, the change of plastic strain is an important factor in quenching residual stress [13]. Figure 4 shows the distribution area of equivalent plastic strain on surface OBDC at different quenching moments.

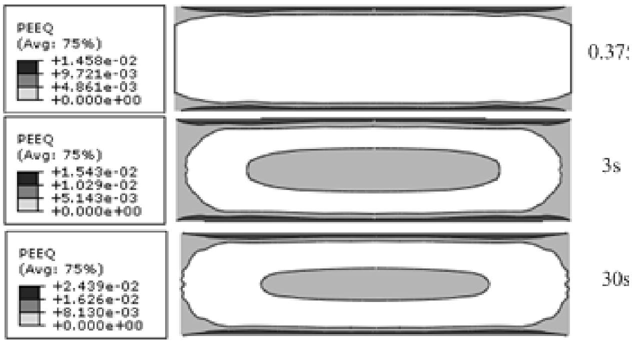


Figure 4. Euivalent plastic strain distribution area on surface OBDC at different moments

As can be seen from Figure 4, in the quenching process, plastic deformation occurred first in the outer layer of aluminum alloy plate, and it occurred later in the center region of the plate. There was always a transition region between the outer surface region and the center region, plastic strain in the transition region is small or even zero, so it could be determined that the region mainly in the elastic deformation stage during quenching.

4.3. The stress field

After quenching, Residual stresses in the thickness direction of aluminum alloy plate is usually small so that negligible [14], the main factors causing machining distortion is the residual stresses in the longitudinal direction and the width direction, and the residual stresses in both directions have similar distribution [15]. Figure 5 shows the change process of the longitudinal direction stresses at point C and point O during quenching.

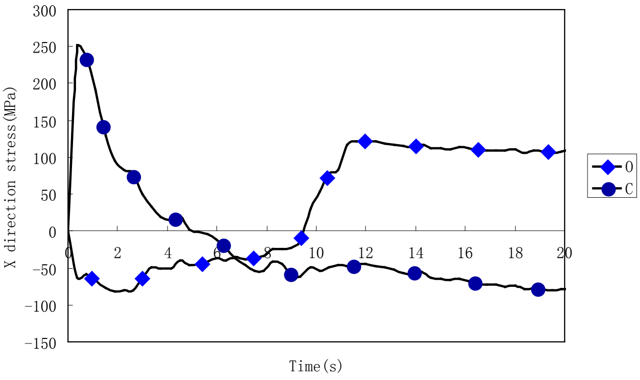


Figure 5. The versus time curves of X-direction stresses at point C and point O

As can be seen from Figure 5, the stress peak generated in the initial stages of quenching, meanwhile aluminum alloy plate was still at high temperature, and its yield strength and tensile strength were relatively small, therefore, the aluminum alloy plate most likely to occur uneven plastic deformation at this stage. And with the continuation of quenching, the outer surface region from the initial "tensile stress" evolved into the ultimate "compressive stress", while the center region was just the opposite. This phenomenon can be more fully demonstrated in Figure 6.

Figure 6 shows X-direction stress distributing on surface OBDC at different quenching moments, which zero stress as the criterion, the tensile stress region was marked in black and the compressive stress region was marked in gray.

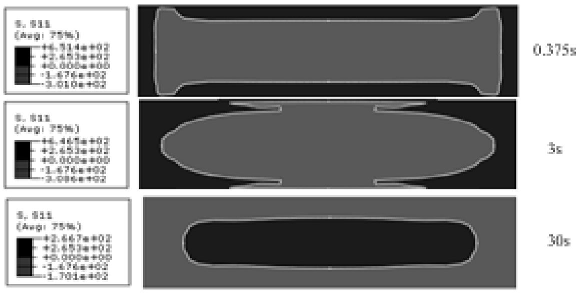


Figure 6. Tension - Compression conversion Schematic diagram of X-direction stresses on surface OBDC

As can be seen from Figure 6, the outer surface region and the center region while undergoing a conversion between tensile stress and compressive stress, but the tensile stress and compressive stress always maintain internal force balance.

5. Test and verification

7075 aluminum alloy plate quenching experiments and residual stress tests had been done. The test pieces dimensions and quenching conditions were consistent with the Computer simulation model. First, the test pieces was heated in a salt bath furnace to 473 ℃ and holding enough time, and then quenched in a large pool, last the residual stresses were tested using the drilling method. Test points were selected along the path CM, and the tests were repeated five times to take the average. Figure 7 shows the test equipment and test pieces.

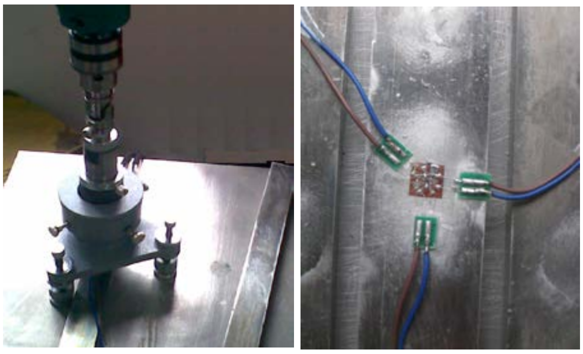


Figure 7. Test equipment and Test pieces photos

The simulation results and test results of the residual stress distributed along path CM were contrasted in Figure 8, and in the figure, the point O was set as the origin of the abscissa.

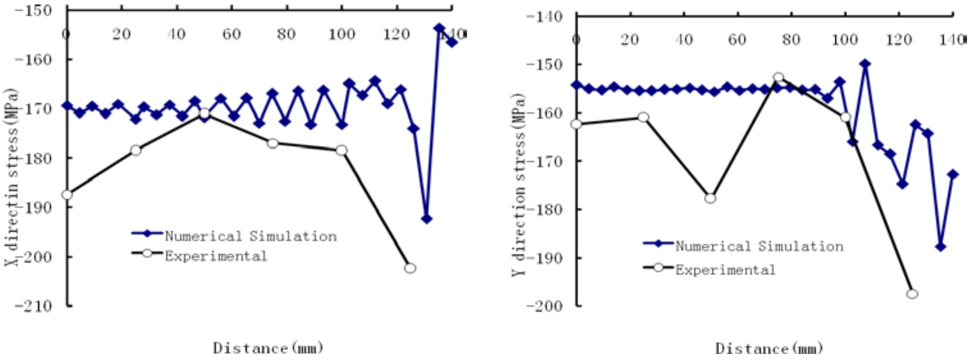


Figure 8. Comparison of quenching residual stress distributed along path CM

In Figure 8, test values and simulated values are close to validate the computational simulation has good accuracy.

Figure 9 shows that the simulation results of residual stress on path OC was compared with the experimental results In Figure 2 of literature [15].

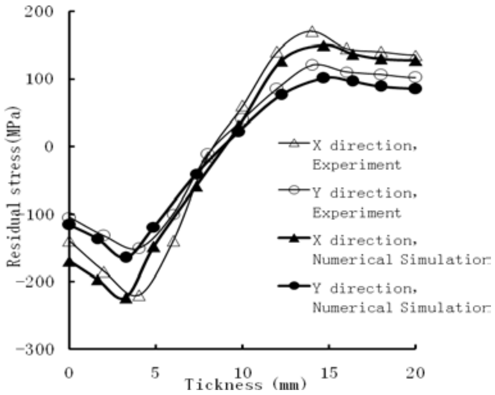


Figure 9. Comparison of residual stress distribution along the thickness

As can be seen from Figure 9, although there are some errors between computer simulation results and experimental results, but the change trends of the two curves are consistent. In terms of the changes of residual stress distribution curves along the thickness, the quasi-coupling method simulation results are monotonous, yet the direct coupling method simulation results are non-monotonic, it can see that the simulation results of the direct coupling method are closer to the actual situation. The reason is that temperature field and stress field were divided into two steps to calculate when using quasi-coupling method; the calculated temperature field is used to calculate the stress field, so the monotonic changes of temperature field and temperature gradient lead to the changes of stress field should be monotonic. However, when using direct coupling method, not only temperature field but instantaneous strain rate determines the stress field, so the final changes of the stress field is no longer monotone and closer to the actual quenching process.

6. Conclusions

(1) Computer simulation results and experimental results of quenching residual stresses are in good agreement, computer simulation can accurately estimate quenching residual stress of aluminum alloy plate, and be able to show the change process of temperature, strain and stress inside the plate, and can provide reference data for the study of the mechanism of quenching residual stress.

(2) There are multiple inflection points on the residual stress distribution curve along the thickness, and direct coupling method than quasi-coupling method to more accurate simulations of the non-monotonic change.

(3) There has been a transition region between the outer surface region and the center region of aluminum alloy plate during quenching, the plastic strain in the transition region is always very small or even close to zero, but quenching residual stress peak has appeared in the transition region.

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