Numerical simulation of aluminum alloy quenching by direct thermal-mechanical coupling method and evolution of the elastic-plastic area

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Abstract

7075 aluminum alloy plate quenching process is simulated using direct thermal-mechanical coupling method, and the corresponding experimental results verify the numerical simulation with high accuracy. Based on the simulation results to study the Variation in the aluminum alloy plate during the quenching process, such as the conversion law between tensile stresses and compressive stresses and the evolution of elastic-plastic deformation area, and these two changes have been compared and analyzed, the results show that, there is always a transition region in the aluminum alloy plate during the quenching process, the region has very small or zero plastic strain, and the quenching residual stress extremes occurs in the region. The existence of the transition region is leading to the quenching residual stress distribution along the thickness direction has "turning point" and is the main reason for the W-shaped distribution.

Keywords: direct thermal-mechanical Coupling, aluminum quenching, numerical simulation, elastic-plastic evolution

1 Introduction

High strength and high toughness aluminum alloy material is an essential key material of modern aviation, aerospace, weapons and equipment [1], However, machining deformation caused by residual stress is the bottleneck problem of aviation aluminum alloy plate automated manufacturing fields [2]. Academic study of the state of stress and strain within the quenched aluminum alloy plate is not comprehensive enough, which leads to the formation mechanism of quenching residual stresses have been relatively vague, the formation mechanism is a not yet fully understanding problem. Due to lack of deep understanding of the formation mechanism, it is difficult to obtain a new breakthrough in the technical field of abatement and control the quenching residual stress [3].

Currently, the finite element simulation technology has become an advanced and effective method used to study the formation mechanism and distribution of quenching residual stresses; it has made quite a lot of research and established a variety of theories and models to explain the formation mechanism and distribution of residual stress [4-8]. Researchers explain the formation mechanism of quenching residual stress from the perspective of microstructure or mechanical effect, but most are general qualitative analysis, lack of quantitative analysis based on evolution data in the quenching process.

In this paper, the quenching process of 7075 aluminum alloy plate was simulated by direct thermal-mechanical coupling method, and the evolution of the elastic-plastic area was used to make comparative analysis, through the careful study based on the simulation data, a clearer description of aluminum alloy quenching process and a new supplementary explanation of aluminum alloy plate quenching residual stress formation mechanism have been obtained, it provides a reference for the formulation and development of new residual stress reduction techniques.

2 The basic theory of numerical simulation of quenching process

Numerical simulation of aluminum alloy quenching process is a technical method based on thermodynamic and elastic-plastic mechanics. The purpose of aluminum alloy quenching is to suppress the phase change to preserve the supersaturated after solid solution treatment, and phase transition generally does not occur when the aluminum alloy is quenching [3]. Aluminum alloy quenching is an interaction process of heat transfer and thermal stress, and relates to the conversion of the thermal Elastic - plastic deformation.

2.1 DIRECT THERMAL – MECHANICAL COUPLING DURING QUENCHING

Thermodynamic equilibrium equations represented with displacement components:

$$(\lambda+G)\frac{\partial e}{\partial x_i}+G\nabla^2 u_i-\beta\frac{\partial t}{\partial x_i}+X_i=0, \tag{1}$$

where X_i indicates the component of body force per unit volume in three-dimensional Cartesian coordinate axes and

$i = 1, 2, 3$, ∇^2 indicates the Laplace operator, λ indicates the Lame constant, G indicates the Shear modulus, u_i indicates the displacement component in the three-dimensional Cartesian coordinate axes, e indicates the volumetric strain, β indicates the thermal stress factor.

Because the flow stress properties of aluminum alloys, the impact of the acceleration term must be considered in thermodynamic equilibrium process [9], In this case, the heat conduction process should be used Modified Fourier Heat equation:

$$\lambda \nabla^2 T = C_\varepsilon \frac{\partial T}{\partial \tau} + T_0 \beta \frac{\partial e}{\partial \tau}, \tag{2}$$

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

Equation (2) contains three displacement components and an amount of temperature, so it can not be solved independently, in order to calculate the unknown quantity it must join equation (2) and equation (1). In the solution process, the temperature and stress fields interact to form a coupling relationship, which is the “direct thermal-mechanical coupling” solving method, which is different from the "so-called coupling" method to separate temperature field and stress field into a two-step calculation [10- 12].

2.2 THE THERMOELASTOPLASTIC STRESS-STRAIN RELATIONSHIP DURING QUENCHING

Non-uniform plastic deformation of quenching process is the prerequisite for producing quenching residual stress [13]. Quenching process exists material nonlinearity and geometric nonlinearity and other issues, because of these complexities, solving the quenching thermal stress field is usually regarded as transient nonlinear material problems, so the elastoplastic mechanical model is chosen and calculated using incremental theory. The stress-strain relationship of material in elastic or plastic state is shown below.

In the elastic region:

$$d\{\sigma\} = [D_e](d\{\varepsilon\} - d\{\varepsilon_T\} - d\{\varepsilon_0\}) \tag{3}$$

$$d\{\varepsilon_0\} = \frac{[D_e]^{-1}}{\partial T}\{\sigma\} dT, \tag{4}$$

where $[D_e]$ indicates the elastic stiffness matrix, $\{\varepsilon\}$ indicates total strain of elastic region, $\{\varepsilon_T\}$ indicates the thermal strain, $\{\varepsilon_0\}$ indicates the additional strain generated by the effect of temperature on the elastic modulus.

In the plastic region:

$$d\{\sigma\} = [D_{ep}](d\{\varepsilon\} - d\{\varepsilon_T\} - d\{\varepsilon_0\}) + d\{\sigma_0\}, \tag{5}$$

where $[D_{ep}]$ indicates the elastic-plastic stiffness matrix, $\{\varepsilon\}$ indicates total strain of elastic-plastic region, $\{\varepsilon_T\}$ indicates the thermal strain, $\{\varepsilon_0\}$ indicates the additional strain generated by the effect of temperature on the elastic modulus, $\{\sigma_0\}$ indicates the additional stress generated by the effect of temperature on the plastic modulus.

3 Numerical simulation of quenching process

3.1 THE BASIC ASSUMPTION OF THE NUMERICAL SIMULATION MODEL

Aluminum alloy quenching process generally does not occur phase transition [3], rolling residual stress has been re-balanced in the heating aluminum alloy plate process. Therefore, the impact of rolling residual stress on quenching residual stress is quite small [2, 7], so the numerical simulation assumptions are as follows:

(1) Aluminum alloy plate was regarded as isotropic elastic-plastic material.
(2) The phase change problem of quenching process was not being considered.
(3) The initial stress state was deemed to be zero stress state.

3.2 ESTABLISH NUMERICAL SIMULATION MODEL

Based on the above assumptions, initial and boundary conditions for the numerical simulation model was symmetrical, and since the symmetrical structure of the aluminum alloy plate, In order to reduce the computation of numerical simulation, 1/8 of aluminum alloy plate structure was taken for three-dimensional modeling. Modeling object is 7075 aluminum alloy plate, its sizes and finite element model are shown in Figure 1. Where point O is the center point of the entire plate, Points A, B, C, D and M are the vertex of finite element model, the specific location are shown in Figure 1.

The simulation model was meshed with temperature-displacement coupling elements, symmetry constraints were applied to three symmetry plane of the model, so rigid displacement of aluminum alloy plate was fixed, and the deformation of aluminum alloy plate was not affected during quenching process.

The solid solution temperature of 7075 aluminum alloy plate was set at 473 ℃, after solid solution treatment, the plates were rapidly quenched into water of 26 ℃. Due to quenching in the pool filled with flowing water, the process of aluminum alloy plate into the water was ignored, and the changes in water temperature were also considered very small, so the water temperature was assumed to be constant. And the model solution was to use the explicit dynamic analysis.

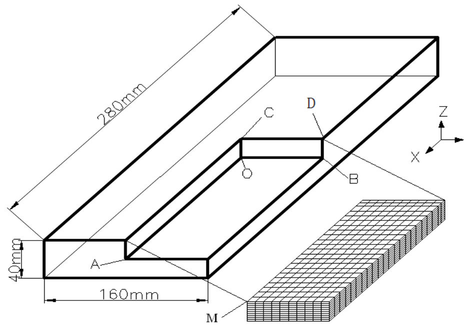


FIGURE 1 Structure and test points schematic of 7075 aluminum alloy plate

4 Results and Analysis

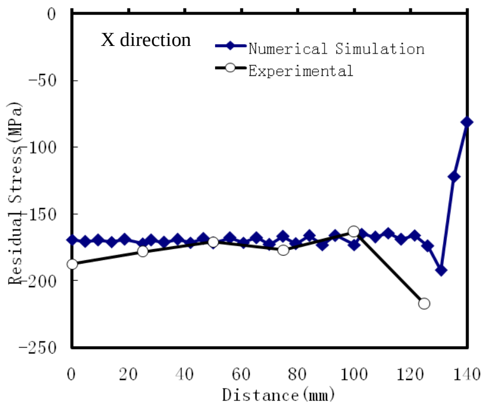
4.1 EXPERIMENTAL VERIFICATION OF SIMULATION RESULTS

In order to verify the accuracy of the numerical simulation of the quenching process, the quenching residual stresses had been tested by experiment. The experimental procedure was divided into solid solution heat, quenching and residual stress test, and several other processes. Experimental material is 7075 aluminum alloy, the dimensions and quenching conditions were consistent with the numerical simulation, heating and insulation used salt bath furnace, quenching used the pool having a flow of water, and residual stress measurement used the drilling method. Figure 2 shows the experimental equipment and specimens.

Drilling and testing the residual stress started at 30 minutes after completion of quenching, each point testing was repeated 5 times and taken the average, the test points were selected from a straight line, and the straight line corresponded to the path CM of the finite element model. The comparison between numerical simulation results and experimental results of residual stress along path CM was shown in Figure 3, Where, O is the origin point of the horizontal axis.

FIGURE 2 Description of the experiment equipment and the plate sample

As can be seen from the comparison of Figure 3, the test results and the simulation results were close, it validated that numerical simulation has enough accuracy.



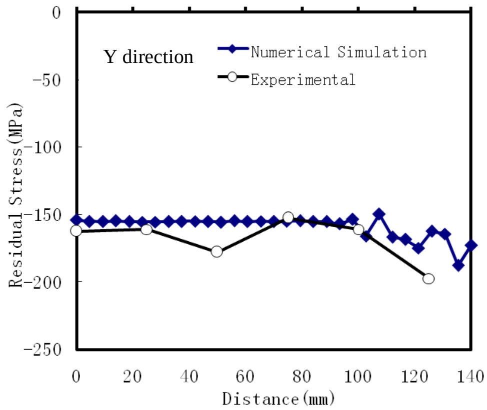


FIGURE 3 Quenching residual stress comparison along path CM

The simulation results of final residual stress along path CM were treated symmetrically, and the results were compared with the experimental results in Figure 2 of literature [14], the comparative results were shown in Figure 4.

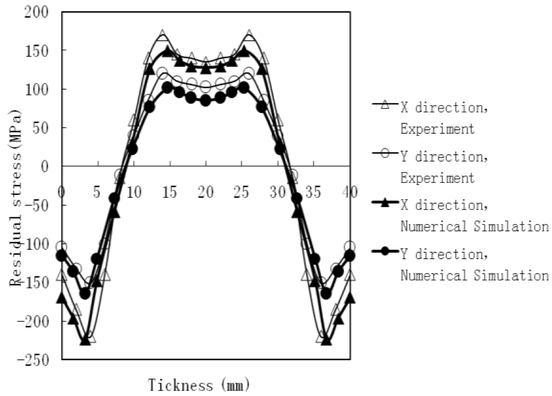


FIGURE 4 Comparison of residual stress distribution in thickness

As can be seen from Figure 4, the numerical simulation results and experimental results of residual stress distribution curve along the thickness were similar to the trend, only there were some errors in the values, one reason was that the experimental data were measured after aging [14], so that the residual stress decreased. Both the simulation results and experimental results showed a W-shaped curve distribution, the extremes of residual stresses (the maximum compressive stress and the maximum tensile stress) did not appear in the outer surface or center plane of aluminum alloy plate, but appeared at the position from these two planes at a distance. This non-monotonic trend has been accurately simulated with direct thermal-mechanical coupling method, it showed that the simulation method was closer to the actual situation.

4.2 THE STRESS FIELD AND STRAIN FIELD DURING QUENCHING

The negative factors caused by quenching aluminum alloy plate are mainly the residual stresses in the longitudinal direction (pre-stretching direction) and the width direction, the residual stresses in the thickness direction are usually negligible [15], and the residual stresses in the longitudinal direction and the width direction have a similar distribution [14]. Therefore, only the evolution of residual stresses in the longitudinal direction was the focus of research.

The conversion between tensile stresses and compressive stresses was bound to happen in aluminum alloy plate during quenching. In order to visually observe the change of quenching stress field, the simulation results of 1/8 structure were processed by symmetry principle into a whole stress field of the plate. Figure 5 shows the contours of the stresses at different moments in the quenching process, which taken from X-direction tensile stresses and X-direction compressive stresses on the plane OBDC, and zero stress was as a dividing line in order to facilitate observation, where dark areas indicated tensile stress areas and light areas indicated compressive stress areas.

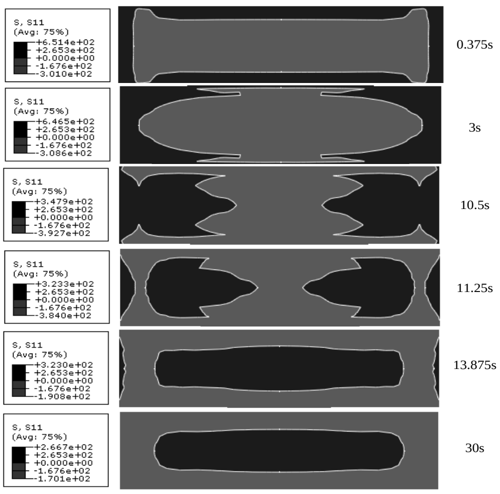


FIGURE 5 The areas evolution between tensile stress and compressive stress

As can be seen from Figure 5, the conversion process between tensile stress areas and compressive stress areas can be described as follows: tensile stress areas spread from the periphery toward the core along the width direction eventually converged in the core. Meanwhile, the compressive stress areas since the core outward expansion along the thickness direction, and ultimately converged at the periphery.

The phenomenon showed in Figure 5 reflected the intricacies of the stress field evolution during quenching, rather than simply by "peripheral tensile stress-internal compressive stress" to "peripheral compressive stress-internal tensile stress". In the quenching process, the area change between tension and compression was continuous in value, both the tension area and the compression area appeared the "separation-convergence" phenomenon. In the process of change, tensile stress and compressive stress always maintained a balance of internal forces in aluminum alloy plate.

Aluminum alloy plate was rapidly cooled during quenching process, and the temperature field of the plate rapidly changed. Because there was a temperature gradient, the temperature difference between the surface layer and the core portion was transients. Dynamic changes of the temperature difference leaded to transient thermal stress, plastic deformation occurred and leaded to additional stress until the thermal stress exceeded the yield limit, so lead to residual stress after quenching. Visible, the dynamic changes of elastic-plastic strain field and stress field during quenching are very important factors resulting in quenching residual stress, especially changes in plastic strain.

Figure 6 shows the evolution over time of equivalent plastic strain area in plane OBDC, in the initial stage of quenching aluminum alloy plate (for example, at 0.375s), plastic deformation appeared earliest in the outer layer of the plate. When the plastic deformation in the outer layer was gradually increased and extended as the quenching performed, other plastic deformation began to appear in the core of the plate (for example, from 3s to 30s).

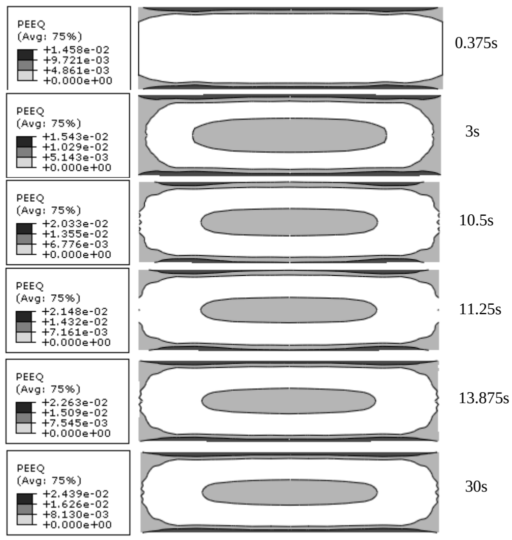


FIGURE 6 Evolution of equivalent plastic strain area in plane OBDC

4.3 ANALYSIS AND DISCUSSION

Equivalent plastic strain areas of both peripheral and central portion were gradually reduced in the end stage of quenching (as shown in Figure 6), one reason for this phenomenon was the mutual conversion between tension areas and compression areas (as shown in Figure 5), same meaning that the tensile stresses and the compressive stresses had mutually reverse. There was always a transition region between the peripheral region and the core region, and the plastic strain in the region was very small or even zero, so it can be determined that the region is mainly in the elastic deformation. And as shown in Figure 4, residual stress distribution along the thickness was a W-shaped curve distribution. Comprehensive analysis of these phenomena can be deduced as follows:

Aluminum alloy plate due to cold shrink principle caused the outer layer had an unrecoverable tensile plastic deformation in the quenching process, thus leaded to the length of the outer layer be slightly longer than the original length.

Meanwhile, the core layer had an unrecoverable compressive plastic deformation, thus leaded to the length of the core layer be slightly shorter than the original length.

Corresponding, the transition layer had very small plastic deformation or only elastic deformation, so the length of the transition layer closed to the original length.

Aluminum alloy plate as a continuum, it must satisfy deformation compatibility equations and internal force balance principles, the areas near the outer layer of the transition layer were under tension because it prevented the outer layer "longer", and the areas near the core layer of the transition layer were under pressure because it prevented the core layer "shorter".

Overall, the transition layers play an important link role in the processes of coordinating deformation and balancing internal forces. This is a main reason for the quenching residual stress extremes do not appear in the outer surface or the center plane. In particular, aluminum alloy quenching process is a very complex process of thermal-mechanical coupling, the formation of quenching residual stress is the result of many factors contributing, resulting in the formation mechanism of the quenching residual stresses have been relatively vague [3]. The above analysis and inference make an effective supplement on the formation mechanism of aluminum alloy quenching residual stress.

5 Conclusions

(1) That introducing the flow stress parameters by direct thermal-mechanical Coupling method to simulate aluminum alloy quenching process, it can get closer to the actual simulation results of residual stress.

(2) There are multiple inflection points in the quenching residual stress distribution along thickness of aluminum alloy plate, and direct thermal-mechanical Coupling method will be able to more accurately simulate the non-monotonously changes.

(3) Throughout the quenching process, there has been a transition region between the peripheral region and the core region, which is mainly elastic strain and plastic strain is always very small or even zero, and the quenching residual stress extremes occur in this region.

(4) The transition layers play an important link role in the processes of coordinating deformation and balancing internal forces during quenching aluminum alloy plates, and it is the main reason for that the quenching residual stress distribution along thickness of aluminum alloy plate exists "turning point" and showed W-shaped distribution.

Acknowledgements

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