Study of the Residual Stress in 2A97 Al-Li Alloy Using Different Methods

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Abstract. The contour method and X-ray diffraction have been used to measure the quenching stress in 2A97 Al-Li alloy. The surface stresses were measured by X-ray diffraction. Besides, the 2-D distribution of stresses have been given by the contour method. The differences between the two methods can be more than 100 MPa. In addition, finite element model which is suitable for evaluation of residual stresses in this material was established. There is very good correlation between the contour method and finite element model (FEM). The differences are less than 50MPa. The model has high precision to forecast the residual stress in 2A97 Al-Li alloy.

1. Introduction

With the development of aviation industry, new materials with high specific strength are in great demand [1]. The 2A97 Al-Li alloy has been widely used in aircraft structure parts because of the low density and improved specific strength [2,3]. In this high-strength alloy, residual stress is an important aspect which can influence the processability and service performance [4,5].

Residual stresses in materials are self-equilibrating [6,7]. They may be ignored in material processing [8]. However, residual stresses can seriously affect processing property and service performance of materials, such as causing deformation and cracking of materials, and reducing fatigue strength [9,10]. It is necessary to characterize residual stresses in the life-cycle of materials.

In this work, the residual stress was introduced into 2A97 Al-Li alloy by solution treatment (i.e. quenching). The X-ray diffraction, contour method, and finite element model were used to evaluate the residual stresses from surface to core of the sample. The differences of the test results between these methods had been explained explicitly. A finite element model of residual stress in 2A97 Al-Li alloy was established.

2. Materials and experimental procedures

2.1. Specimen preparation

A 2A97 Al-Li Alloy rolling plate was used for residual stress measurement. The chemical compositions of this alloy are listed in Table 1. The size of the specimen is 126mm(RD)×58mm
The plate was solution treated at 480°C for 5 hours followed by water quenching to 20°C.

Table 1. Chemical composition of 2A97 Al-Li alloy.

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Zn  | Ti  | Zr  | Li  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Wt.%    | 0.15| 0.15| 2.0-| 0.2-| 0.25-| 0.17-| 0.001-| 0.08-| 0.8-| Bal.|

2.2. X-ray diffraction
The residual stresses in X-direction was calculated by \{311\} crystal face diffraction. Experiments were applied on the X-ray Stress Analyzer (ST, China) with Cr-Kα radiation. The irradiated area was 2mm in diameter. Test points were shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** The test points of X-ray diffraction

2.3. Contour method
In this experiment, the cutting was implemented on a SODICK AQ400LS WEDM (Wire Electrical Discharge Machining) using a 200μm diameter brass wire. The cutting speed was about 0.1mm/min. The coordinate was aligned with the side of the sample (Figure 2). During the cutting, the aluminium sheet was fixed on the sample stage (Figure 3). The sample was cut in half. A CMM (Coordinate Measuring Machine) was used to test the profile of the two cutting surfaces. The particular experiment was applied on a HEXAGON Performance CMM. The measurement accuracy was about 3μm.

![Figure 2](image2.png)

**Figure 2.** The cut of the specimen

![Figure 3](image3.png)

**Figure 3.** The fix of specimen

The sample was cut in half. A CMM (Coordinate Measuring Machine) was used to test the profile of the two cutting surfaces. The particular experiment was applied on a HEXAGON Performance CMM. The measurement accuracy was about 3μm.

3. Results

3.1. X-ray diffraction
X-ray diffraction was used to measure the residual stress after quenching. The measured position is shown in Fig. 1. Four of them locate in the centre of the four surfaces, and the others are with 14.5mm interval from the midpoints. The residual stress direction is parallel to X-axis.
Table 2 shows the residual stress results. Most of them are compressive stress. During the solution treatment, thermophysical properties of materials change with temperature, expressing as surface compression stress. The second position shows abnormal tensile stress. It is because of the difference of cooling rate of the sample during quenching [11].

**Table 2. The results of X-ray diffraction. (Unit: MPa)**

| Test Point | Residual Stress | Test Point | Residual Stress |
|------------|-----------------|------------|-----------------|
| 1          | -85.5           | 5          | -141.6          |
| 2          | 69.3            | 6          | -105.3          |
| 3          | -70.3           | 7          | -91.4           |
| 4          | -85.5           | 8          | -64.5           |

### 3.2. Contour method

Figure 4 illustrates the range of data from CMM results. The range of X-axis is 0~60mm, the Y-axis is 0~30mm and the Z-axis is -0.08~0.02mm. On the two surfaces, each point is 2mm (y direction)×0.5mm (x direction) away from each other.

Theoretically, the two surfaces are symmetric. However, because of the errors of cutting and CMM, they are asymmetric. It is because of the errors of cutting and CMM. Thus, the surfaces should be averaged and fitted. In this work, cubic spline was used and the calculation was developed on MATLAB. Figure 5 illustrates the calculation results. The random errors and anti-symmetric cutting errors had been removed by the above step. The smooth surface was used to simulate stress reconstruction by ANSYS.

![Figure 4. CMM data of the cutting surfaces](image-url)

![Figure 5. Cubic spline surface](image-url)

In stress determination, the model of the half specimen was created, and curved surface data was input to be a displacement boundary condition of the finite element model (FEM). Fig.6 illustrates the distribution of the residual stress which was calculated by the linear elastic analysis method developed by ANSYS APDL. The Young’s modulus of 2A97 Al-Li alloy is 77GPa, and the Poisson ratio is...
The peak stress magnitude is about 100MPa (in the material core). The maximum compressive stress locates on the subsurface. The stress of local positions on the sample surface is tensile. It is consistent with the result of X-ray diffraction.

![Stress Distribution](image)

**Fig. 6.** Distribution of the residual stress

### 3.3. Finite element model

#### 3.3.1. Construction of FEM model.

In order to solve the stress problem, heat conduction should be first calculated [12]. According to Fourier's law and the law of energy conservation, heat conduction equation can be described as the follow equation:

\[
\frac{\rho c}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + q \varepsilon
\]

There are two key aspects of heat conduction, which are initial condition and boundary conditions [13]. In this problem, the initial condition was the temperature at the beginning of quenching. The balance state of quenching temperature was used as the boundary condition.

A model of the sample was established. Because the temperature gradient of the sample was small during the quenching process. Finite element model had been constructed by uniform mesh. The element size was set to 2mm×2mm×2mm. Fig 9 illustrates the grid partition.

![Grid Partition](image)

**Fig. 7.** The grid partition of finite element model

Thermophysical properties of materials change with the temperature. The analysis of temperature and stress fields of quenching process was a nonlinear transient problem. If the changes of material parameters were ignored, the errors will be large. Table 3 shows the properties of the alloy with temperature changing.

![Table 3](image)

**Table 3.** Properties of Aluminum alloy with temperature changing

| Temperature (°C) | Specific heat (J/kg°C) | Thermal conductivity (W/m°C) | Temperature range (°C) | Coefficient of thermal expansion (10^-6 °C^-1) |
|------------------|------------------------|-----------------------------|------------------------|---------------------------------------------|
| 20               | 795                    | 176                         | 20-100                 | 21.4                                        |
| 100              | 837                    | 180                         | 20-200                 | 22.6                                        |
| 200              | 879                    | 184                         | 20-300                 | 23.8                                        |
| 300              | 963                    | 184                         | 100-200                | 23.7                                        |
| 400              | 1005                   | 188                         | 200-300                | 26.26                                       |
3.3.2. Simulation results
The results of FEM are illustrated in Fig 10. From the surface to core, the residual stresses magnitude increases from -40MPa to 80MPa. It is related to the thermophysical properties of the material.

The result of finite element model agrees well with the contour method. The maximum tensile stress of material is about 80 MPa. But the surface stresses could be different. Near the sample surface ($Z=0, Z=32$), the differences are more than 60MPa. It is related to the establishment of finite element model. During that process, the flow and temperature change of quench medium were ignored. The second-phase precipitation was neglected. They caused the differences of the two methods.

![Fig. 8. Differences between contour method and finite element model](image)

4. Discussions
X-ray diffraction, contour method and finite element can evaluate the residual stress, but they all have their own limitations.

4.1. Measurement of residual stress
In X-ray diffraction, the measurement is based on $\sin^2\psi$ method [14]. In this method, diffraction angle ($2\theta$) is only related to crystal orientation($\psi$). It can be described as the follow equation:

$$\sigma = K \cdot \frac{\partial^2 \theta}{\partial \sin^2 \psi}$$  \hspace{1cm} (2)

In the equation, ‘K’ is the X-ray elastic constants (XEC). It is determined by the material and diffraction crystal surface and can be got by a looking-up table [14]. In general, the condition for the above formula is that the material is isotropy in the radiation area. This linear relationship can be influenced by grain size and rolling texture [15]. The materials with large grains or texture are not very suitable to use $\sin^2\psi$ method. Figure 11 shows the relationship between $2\theta$ and $\sin^2\psi$. The results of all the test points satisfy the formula. So, the results are reliable.

![Fig. 9. Relationship between $2\theta$ and $\sin^2\psi$](image)
Residual stress in the core of material is suitable to be measured by contour method. The 2-D distribution of residual stress can be given [16]. But this method will cut the material, this is not acceptable for some precious samples. The uncertainty of test results is related to the cutting and the surface fitting [17]. In cutting, the cutting width can be hundreds of microns. Thus, the contour of the two cutting surfaces is asymmetric. This anti-symmetric error can be averaged by the data process [18]. However, cutting parameters fluctuate near the material surface. The cutting width will be abnormal as well. This error cannot be avoided. In the subsequent data processing, different fitting functions were used to enhance the reliability of results. Chebyshev, Fourier, Sigmoid, Quadratic spline and Cubic Spline functions are the common methods to fit surface. Among the above functions, Cubic Spline function is the best method [19]. It can restore the contour of the surface truthfully.

Fig 9 illustrates the differences of between X-ray diffraction and contour method. At some positions, the differences are over than 100MPa. But the distributions of the two results are in agreement.

The differences could be caused by the follows:

1) The chosen of XEC: A theoretical parameter was used. It might be deviated from the actual situation.
2) The error of cutting in the contour method: The cutting width could be abnormal and lead to volatility of the test results.
3) The problem of spatial resolution: The penetration of X-ray might be tens of microns. The results are average in this range. But in contour method, the point spacing is 0.5mm from the surface to core. The spatial resolution of contour method is far larger than micron level.

Fig. 10. Differences between X-ray diffraction and contour method

4.2. Simulation of residual stress

Finite element simulation of heat treatment involves energy exchange theory, heat transfer theory, phase transition theory, elastoplastic theory and etc. All of them should be considered [13]. But in existing models, some of them are used to solve the problem and the others are ignored. It increases the limitations of simulation and reduces the accuracy. In this study, neglect of second phase precipitation in 2A97 Al-Li alloy is unlikely to influence the distribution of macroscopic residual stress. The problems of heat conduction and deformation should be considered while building the model.

5. Conclusions

For the 2A97 Al-Li alloy, the quenching stresses of the surface are compressive and the core parts are tensile.

1) Compared with contour method, X-ray diffraction is more suitable for the measurement of the surface residual stress
2) There is a very good correlation between the contour method and finite element model, the differences are less than 50MPa.
3) For the contour method, cutting technology and data processing can be improved to reduce the cutting error of material surface and increase the reliability of the results.
4) Based on FEM software ANSYS, the thermal-mechanical coupling model of 2A97 Al-Li Alloy was established. Compared with the test results, reliable results are obtained. The feasibility of residual stress in 2A97 Al-Li alloy calculation is verified.

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