Research on Measurement Technology of Residual Stress in Rolling Aluminium Alloys

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Abstract. In the measurement of textured materials such as Al Alloy sheet, the traditional method of X-ray residual measurement ($\sin^2 \psi$ method) cannot be applied to these materials. In this paper, 2A97 aluminium lithium alloy was used for the study on residual stress measurement of texted materials. The X-ray diffraction method was used to test the orientation distribution function. The elastic constant of the material was calculated theoretically by Ruess model, Voigt model and Neerfeld-Hill model. And the residual stress was calculated. The blind-hole method was used to verify the results. The blind-hole result agreed well with the Neerfeld-Hill model.

1. Introduction

Residual stress is one of the most important factors influencing processing and performance of materials[1,2]. Firstly, nonuniform residual stresses across the material surface can be harmful reducing material strength and causing premature fracture[3]. On the other hand, the compressive residual stress intentionally introduced to the surface of the material will enhance the fatigue life of the material significantly[4]. The main nondestructive testing method of residual stress is X-ray diffraction. This method mainly aims at isotropic fine-grained materials, and it is unable to measure anisotropic materials with strong texture[5],while some material can form texture[6]. The other methods (Ultrasonic method, magnetic method) get accurate residual stress[7]. So the residual stress cannot measure accurately in rolling aluminium alloys.

In X-ray method, the $\sin^2 \psi$ method is commonly used. This method based on Hooke's law of isotropic materials. As shown in Figure 1. when the material is anisotropic in the X-ray irradiation region, the $\sin^2 \psi-2\theta$ of the material is nonlinear[8].
Figure 1. The $\sin^2 \psi - 2\theta$ curve in textural material

If the linear fitting method is used to calculate the residual stress, there will be a large error. There are three representative views on the reason why $\sin^2 \psi$ and $2\theta$ is nonlinear. 1) Inhomogeneous plastic deformation inside the material. 2) Elastic anisotropy of texture materials. 3) Micro inhomogeneous stress caused by the interaction between grains\cite{9,10}. He Jiawen made a deep theoretical analysis on this issue\cite{11}. He analyzed the residual stress of LY12 aluminum alloy, 60-40 copper alloy and industrial pure iron after rolling. The experimental results show that the $\sin^2 \psi - 2\theta$ curves of (311) and (211) crystal faces oscillate. In aluminum alloy and industrial pure iron, the H-plane does not lose linearity. In rolling brass, it is found that (222) crystal surface fluctuates in the test results of gradually peeling layer from surface to sub surface. This is due to the lower multiplicity factor of H-plane and the fewer grains involved in diffraction.

In this paper, the orientation distribution function of materials and the interaction model between grains are studied to calculate the elastic constants of strong texture materials at various $\psi$ angles. The residual stress on the surface of 2A97 Al Li alloy rolled plate was obtained. The results are verified with the results of blind-hole method. The theory and method of X-ray residual stress test for strong texture materials are enriched and improved.

2. Experimental method

2.1. Experimental materials

The chemical composition of 2A97 aluminum lithium alloy meets Table 1. The heat treatment process is mainly solution + aging. In order to obtain higher performance, the aging process usually adopts two-stage aging treatment. Large residual stress may be produced in solution treatment engineering, which may lead to deformation and cracking of material in subsequent aging treatment. In this paper, 2A97 aluminum lithium alloy rolled plate in solution state is taken as the research object. The ingot is uniformly heat treated (520 °C), heated to 490 °C before rolling and air cooled after three passes of hot rolling (400mm → 80mm). After rolling, heat the rolling plate to 520 °C and keep it warm for 30 ~ 50min for water cooling. The metallographic structure of the material is shown in Figure 2. The grains on the rd-td plane are equiaxed, and the grains on the RD-ND plane are fibrous. There are a small amount of Al2CuLi phase at the grain boundary.

Table 1. Chemical composition of 2A97 aluminum lithium alloy (mass fraction/%)

| Element | Si  | Fe  | Cu   | Mn  | Mg  | Zn  | Ti  | Zr  | Be  | Li  | Al  |
|---------|-----|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|
|         | 0.15| 0.15| 2.0– | 0.20–| 0.25–| 0.17–| 0.001| 0.08–| 0.001| 0.8–2.| Bal |
|         |     |     | 3.2  | 0.6  | 0.5  | 1.0  | -0.1 | 0.2  | -0.10 | 3    |      |
2.2. X-ray diffraction analysis

The X-ray diffraction analysis uses Bruker D8 advance diffractometer. The radiation parameter is Cu target, $\lambda = 1.5418$ Å. Tube voltage is 40kV. Tube current is 40mA.

1) X-ray texture analysis

The polar figures of $\alpha$-Al $\{200\}$, $\{220\}$, and $\{111\}$ crystal surfaces were measured by X-ray texture analysis. During the test, the $\chi$ angle test range is 0° to 70°, the $\phi$ angle test range is 0° to 360°, and the test interval is 5°.

2) X-ray stress analysis

In the X-ray stress analysis, the (311) crystal surface is used. In the conventional X-ray $\sin^2 \psi$ method, $\psi$ angle is 0°, 18°, 17°, 33°, 39°, 45°. In the residual stress analysis of texture materials, due to the fact that Bragg diffraction law cannot be strictly satisfied at high $\psi$ angle, the $\psi$ angle test range is 0 ~ 50° and the test interval is 2°.

2.3. Residual stress analysis of blind-hole method

Blind-hole method stress analysis adopts Sigma blind-hole method stress instrument. As shown in Figure 3, strain flowers were pasted on the surface of the material.

3. Results and discussion

3.1. X-ray $\sin^2 \psi$ stress analysis

In the X-ray analysis, in order to avoid the influence of KaII radiation on the peak finding results, the KαII diffraction peak is first removed by mathematical method. Taking $\psi = 0^\circ$ in rolling direction as an example, the experimental data are shown in Figure 3. The original diffraction data of each crystal surface is the black data point in the figure. The peak shapes of diffraction peaks are similar, and they are all in incomplete symmetry (the right side is slightly wider than the left side), which is caused by the superposition of diffraction effects produced by KαI and KαII rays. In order to peel off these two peaks accurately, the intensity ratio of the two peaks is set as 2:1 according to the radiation intensity of KαI and KαII, and the original data is processed by Pearson VII peak function. See Figure 4 for the diffraction data of each crystal surface after stripping. The red data point is the diffraction peak caused by KαI radiation, and the blue data point is the diffraction peak caused by KαII radiation. The two sub peaks are completely symmetrical.
Figure 3. The (311) crystal plane diffraction spectrum

In the rolling direction, X-ray sin²ψ method is used for residual stress test, and the test results are shown in Figure 4. The sin²ψ-2θ has a nonlinear distribution. The residual stress is -40.6 MPa and the correlation coefficient of linear fitting is 0.398. This material does not satisfy the assumption of sin²ψ method, and there are a lot of errors in the results.

Figure 4. The result of X-ray sin²ψ method

3.2. X-ray texture analysis

Figure 5 is the pole figure of 2A97 Al Li alloy in solid solution state. In this state, the polar density distribution of {200}, {220}, {111} crystal surface in some directions is up to six. The orientation distribution function of materials is calculated by Bunge function. There are strong brass texture and copper type texture in the material. The traditional sin²ψ method is not suitable for the residual stress test of this kind of strong texture material. It is necessary to establish a set of X-ray residual stress analysis method for strong texture materials.
3.3. Residual stress analysis of texture materials

In calculating the residual stress of texture materials, the relationship among the sample coordinate system, diffraction coordinate system and crystal coordinate system of the material should be clarified, and the relationship between the sample coordinate system (S) and diffraction coordinate system (L) is shown in Figure 7.

Figure 7. Coordinate system description

First, the elastic constants of materials in all directions should be calculated. The macroscopic elastic constants of texture materials can be obtained by the analysis of grain interaction model and single crystal elastic constants, among which Voigt, Ruess and Neerfeld Hill models are commonly used in block materials. Voigt model assumes that the strain distribution in the specimen is uniform and the stress distribution is discontinuous\cite{12}. The Ruess model assumes that the stress distribution in
the specimen is uniform and the strain distribution is discontinuous[13]. Voigt and Ruess models are extreme grain interaction models. Boas and Schmid have successively proved that the elastic constants defined by Voigt model and Reuss model are the upper and lower limits of the elastic constants in real materials. Neerfeld and hill have proposed that the weighted average results of Voigt model and Ruess model are in good agreement with the experimental data[14]. The elastic constants of Voigt, Ruess and Neerfeld Hill models are given in formula (1).

\[
\{C^S_{\text{Voigt}}(hkl, \lambda, \phi, \psi)\}_{ijkl} = \frac{\int_0^{2\pi} \int_0^{\pi} a^S_{im} a^S_{jn} a^S_{ko} a^S_{lp} S^S_{\text{avop}}(hkl, \lambda, \phi, \psi) d\lambda d\phi}{\int_0^{2\pi} \int_0^{\pi} f^S(hkl, \lambda, \phi, \psi) d\lambda d\phi}
\]

\[
\{S^S_{\text{Reuss}}(hkl, \lambda, \phi, \psi)\}_{ijkl} = \frac{\int_0^{2\pi} \int_0^{\pi} a^S_{im} a^S_{jn} a^S_{ko} a^S_{lp} S^S_{\text{avop}}(hkl, \lambda, \phi, \psi) d\lambda d\phi}{\int_0^{2\pi} \int_0^{\pi} f^S(hkl, \lambda, \phi, \psi) d\lambda d\phi}
\]

\[
\{S^S_{\text{Neerfeld-Hill}}(hkl, \lambda, \phi, \psi)\} = \left(\{S^S_{\text{Reuss}}(hkl, \lambda, \phi, \psi)\}_{ijkl} + \{C^S_{\text{Voigt}}(hkl, \lambda, \phi, \psi)\}_{ijkl}\right)/2
\]

In the formula:

\(C^S_{\text{Voigt}}(hkl, \lambda, \phi, \psi)\) —— Stiffness coefficient of material under Voigt model;

\(\{S^S_{\text{Reuss}}(hkl, \lambda, \phi, \psi)\}_{ijkl}\) —— The flexibility coefficient of materials under the Ruess model;

\(\{S^S_{\text{Neerfeld-Hill}}(hkl, \lambda, \phi, \psi)\}\) —— The flexibility coefficient of materials in Neerfeld Hill model;

\(a^S_{im}, a^S_{jn}, a^S_{ko}, a^S_{lp}\) —— Transformation matrix from crystal coordinate system to sample coordinate system;

\(f^S(hkl, \lambda, \phi, \psi)\) —— Orientation distribution function of materials;

\(\lambda, \phi, \psi\) —— Angle in sample coordinate system and crystal coordinate system;

\(S^C_{\text{avop}}\) —— Single crystal elastic constants of materials.

In the calculation of residual stress of texture material, the theoretical elastic constants of materials under different model conditions can be obtained by using single crystal elastic constants, orientation distribution functions and different interaction models. The elastic constants of aluminium single crystal used in the calculation are shown in Table 2.

| Table 2. Elastic constants of Aluminium single crystal |
|---------------------------------|---------|-----------------|
| Stiffness coefficient (×10^10 Pa) | Flexibility coefficient (×10^10 Pa) |
| \(C_{1111}\) | 10.82 | \(S_{1111}\) | 0.157 |
| \(C_{1122}\) | 6.13 | \(S_{1122}\) | -0.057 |
| \(C_{2323}\) | 2.83 | \(S_{2323}\) | 0.351 |

According to formula (1), the elastic constants of materials at different \(\psi\) angles are obtained, and the X-ray stress factors of materials are obtained.

\[F_{\text{Voigt},ij}(hkl, \phi, \psi) = m_i^S \{C^S(hkl, \phi, \psi)\}_{ijkl}^{-1} m_j^S\]

\[F_{\text{Reuss},ij}(hkl, \phi, \psi) = m_i^S \{S^S(hkl, \phi, \psi)\}_{ijkl}^{-1} m_j^S\]

\[F_{\text{Neerfeld-Hill},ij}(hkl, \phi, \psi) = \left(\{F_{\text{Reuss},ij}(hkl, \phi, \psi) + F_{\text{Voigt},ij}(hkl, \phi, \psi)\}\right)/2\]

The X-ray stress factors of each model are calculated as shown in Figure 9.
After obtaining the X-ray stress factor of the sample, the residual stress of the material surface can be obtained according to formula (3).

\[
\sigma_S = \frac{\int_{0}^{\pi/2} \varepsilon_{hkl}^{5,bb} F_{hkl}^{bb} (\psi) d\psi}{\int_{0}^{\pi/2} F_{hkl}^{bb} (\psi) d\psi} = \frac{\int_{0}^{\pi/2} \left( \varepsilon_{hkl}^{5,bb} / F_{hkl}^{bb} \right) F_{hkl}^{bb} (\psi) d\psi}{\int_{0}^{\pi/2} F_{hkl}^{bb} (\psi) d\psi}
\]

In the formula:
- \(\sigma_S\) — Macro stress of sample surface;
- \(\varepsilon_{hkl}^{5,bb}\) — Diffraction strain at different \(\psi\) angle;
- \(F_{hkl}^{bb}\) — X-ray stress factor;
- \(F_{hkl}^{bb} (\psi)\) — orientation distribution function at different \(\psi\) angles.

In calculating the residual stress of the actual sample, X-ray diffraction test should be carried out at different \(\psi\) angles. In calculating the residual stress of the actual sample, X-ray diffraction test should be carried out at different \(\psi\) angles. The \(F_{hkl}^{bb} (\psi)\) is the orientation distribution function of the material, that is, the relative diffraction intensity of the sample (the ratio of the actual diffraction intensity to the diffraction intensity of the standard sample). Therefore, it is necessary to use 300 to 350 mesh powder samples as the zero stress, non-oriented standard samples. The test results were shown in figure 9. The calculation result of residual stress are shown in table 3.

(a) Diffraction intensity of no preferred powder sample

(b) The actual sample diffraction intensity
Figure 9. The results of X-ray diffraction

(c) The relative diffraction intensity
(d) The relationship between $\psi$ and $2\theta$

Table 3. The results of Residual stress / MPa

|                      | Ruess model | Voigt model | Neerfeld-Hill model |
|----------------------|-------------|-------------|---------------------|
| Residual stress      | -17.3       | 294.1       | -115.3              |

3.4. Stress analysis of Blind-hole method

The residual stress test results of blind-hole method is $\sigma_1=-155.5$MPa, $\sigma_2=-110.6$MPa, $\varphi=71.2^\circ$. According to the theory of stress Mohr circle, the normal stress in RD direction is $-125.6$MPa.

4. Conclusions

1) The sin$^2\psi$ method cannot used to measure residual stress in 2A97 Al-Li rolling plate;
2) There are differences between the results of sin$^2\psi$ method and blind-hole method;
3) Neerfeld-Hill mode can be used to measure residual stress in 2A97 Al-Li rolling plate

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