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Study of residual stresses in A7N01 aluminum alloy with X-ray diffraction Debye ring analysis

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The welding residual stress has different effects on the mechanical properties of aluminum alloy welded joints, such as size stability, fatigue strength and stress corrosion cracking. Therefore, it is very important to evaluate the welding residual stress accurately. In this paper, the residual stress of A7N01 aluminum alloy welded joints was measured by X-ray diffraction. In contrast to the traditional method, the cosα method was used in this paper, the results were compared with those obtained by the conventional $\sin^2\psi$ method. In addition, the influence of oscillation unit on the test results of the cosα method was studied.

Keywords: Residual stress; A7N01 aluminum alloy welded joints; Debye ring; cosα method.

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1. Introduction

At present, the rail transit industry in China is in the stage of rapid development. For the purpose of saving energy, reducing emissions and increasing the speed of operation, it is imperative to lighten the delivery vehicle. Due to the light weight, good tensile properties and good corrosion resistance,[1] aluminum alloy has become the main material of rail vehicle body.

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However, the thermal expansion coefficient of aluminum alloy is higher than that of other metals, and the residual stress will be larger after welding. Tensile residual stress usually results in crack initiation, stress corrosion and reduces the fatigue life of components,[2] therefore, the accurate measurement of residual stress can better evaluate the reliability of rail train body in service.

X-ray diffraction method is commonly used to measure residual stress in engineering practice currently. The traditional $\sin^2\psi$ method has a history of several decades,[3,4] and most of the previous studies of X-ray residual stress testing were based on the $\sin^2\psi$ method. In recent years, a new method to evaluate residual stresses is proposed, which is named as the $\cos\alpha$ method.[5] The $\cos\alpha$ diffraction method is to collect data through single exposure and calculate residual stress by Debye ring while the traditional $\sin^2\psi$ method is to use multiple exposures to fit the diffraction data obtained at different ψ angles, and finally obtain the value of residual stress. By comparison, the test time of the $\cos\alpha$ method is shorter and the diffraction data on Debye ring is more comprehensive.[6] But it is difficult to measure the welding residual stress of aluminum alloy material because of the coarse grain size and the texture.

In this paper, the welding residual stress of aluminum alloy was measured by the $\sin^2\psi$ method and the $\cos\alpha$ method, respectively. In order to improve the accuracy of the $\cos\alpha$ method, an oscillation unit was added in the measuring process and the results of the residual stress were analyzed.[7]

2. Experimental Procedures

2.1. *Samples preparation*

A7N01-T5 aluminum alloy plates (dimensions: 300 mm × 250 mm × 8 mm) were welded by double-pass MIG welding, as shown in Fig. 1(a). The equipment used for welding is KEMPPI KempArc-450 pulse welding machine which is shown in Fig. 1(b), and the welding wire is ER5356. Electropolishing is required before the X-ray residual stress detection, in this paper, 8818-V3 electrolytic polishing instrument was used, as shown in Fig. 1(c).

2.2. *X-ray residual stress measurement*

The residual stress of the welded joints was detected by two methods: the $\sin^2\psi$ method and the $\cos\alpha$ method.

2.2.1. *The* $\sin^2\psi$ *method*

As shown in Fig. 2(a), with the $\sin^2\psi$ method, the residual stress is calculated by the change of the angle ψ. According to the theory of elasticity, strain $\varepsilon^{\phi\psi}$ can be

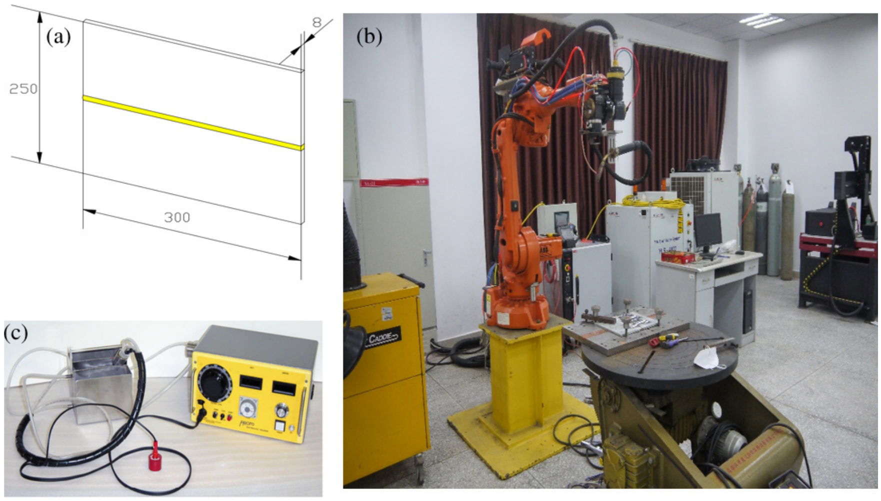

Fig. 1. (Color online) Sample preparation stage: (a) Aluminum alloy test plate size. (b) KempArc-450 pulse welding machine. (c) 8818-V3 electrolytic polishing instrument.

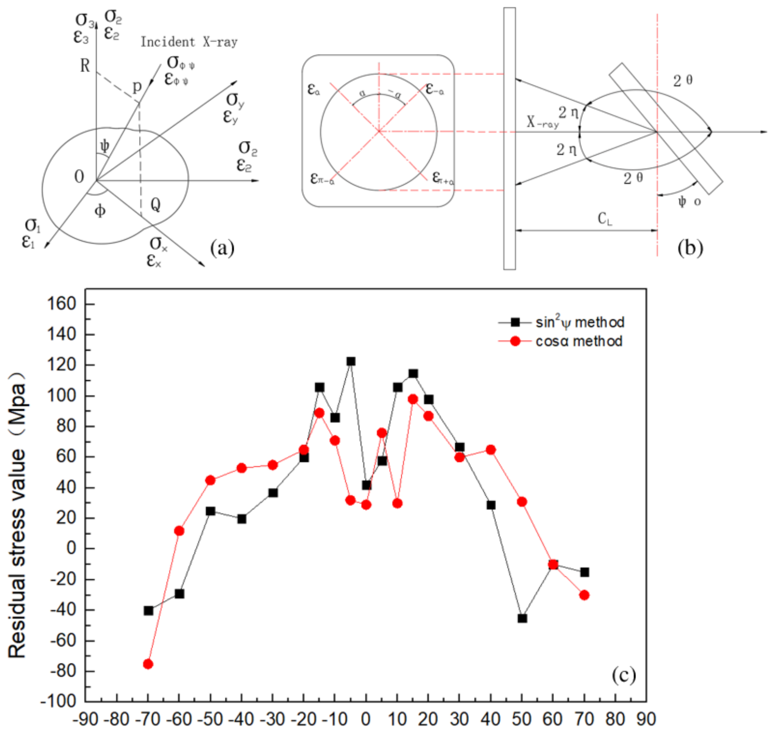

Fig. 2. (Color online) The $\sin^2\psi$ method and the $\cos\alpha$ method: (a) Schematic diagram of the $\sin^2\psi$ method. (b) Schematic diagram of the $\cos\alpha$ method; (c) Longitudinal residual stress measured by two methods.

expressed as

$$\varepsilon^{\phi\psi} = \frac{1+\nu}{E}(\sigma_x \cos^2\Phi + \tau_{xy}\sin 2\Phi + \sigma_y \sin^2\Phi - \sigma_z)\sin^2\psi + \frac{1+\nu}{E}(\tau_{xz}\cos\Phi + \tau_{yz}\sin\Phi)\sin^2\psi + \frac{1+\nu}{E}\sigma_z - \frac{\nu}{E}(\sigma_x + \sigma_y + \sigma_z), \quad (1)$$

where σ_1 and σ_2 denote the maximum and minimum stresses in the plane, respectively, Φ and ψ are the two azimuth angles of OP in any direction of space, ψ is the angle between OP and the normal line of the surface of the sample, Φ is the angle between the projection of OP on the plane of the sample and the X axis, and $\varepsilon^{\Phi\psi}$ is the elastic strain of materials along the OP direction. In the formula, E is the elastic modulus of the material and ν is the Poisson's ratio. This formula is the relation between macroscopic stress and strain.

The X-ray penetration ability is so weak that the residual stress on the surface of the material can only be measured. The stress on the surface of the material can be regarded as a two-dimensional stress, and the normal direction stress is 0. The azimuth Φ is set to 0°, 90° and 45° respectively, and the partial derivation of $\sin^2\psi$ is obtained as

$$\sigma = K\frac{\partial 2\theta}{\partial \sin^2\psi}, \quad (2)$$

$$K = -\frac{E}{2(1+\nu)} \cdot \cot\theta \cdot \frac{\pi}{180}, \quad (3)$$

where K is defined as the X-ray stress constant and $\frac{\partial 2\theta}{\partial \sin^2\Psi}$ is measured experimentally. This formula is the basic formula for the detection of the $\sin^2\psi$ method.

2.3. *The cosα method*

The residual stress will lead to the distortion of Debye ring, where the radius at different angle α is not the same, as shown in Fig. 2(b). In the cosα method, the strain ε_α can be used to estimate the residual stress,

$$\varepsilon_\alpha = \frac{1}{2}[(\varepsilon_\alpha - \varepsilon_{\pi+\alpha}) + (\varepsilon_{-\alpha} - \varepsilon_{\pi-\alpha})], \quad (4)$$

$$\sigma_x = -\frac{E}{1+\nu} \cdot \frac{1}{\sin 2\eta \sin 2\psi_0} \cdot \left(\frac{\partial \varepsilon_\alpha}{\partial \cos\alpha}\right), \quad (5)$$

where η is the mutual complementary angle of diffraction angle θ, ψ is the angle between the normal line of the sample surface and the angle of incidence of X-ray, and σ_x is the longitudinal stress.

3. Results and Discussion

3.1. *Residual stress measured by two methods*

It can be seen from Fig. 2(c) that the longitudinal stress distribution obtained with both the methods is of obvious regularity, and both show the shape of double peaks of residual stress distribution in aluminum alloy welding. In addition, the magnitude of stress value is close to each other. The tensile stress is mostly near the center of weld and heat affected zone, and the peak value of tensile stress is about 100 Mpa, the stress value in the center of weld is smaller than that of the heat affected zone on both sides of weld. In the base metal zone, the residual stress decreases with the distance getting further from the center of the weld. The compressive stress appears at the distance from the weld 50 mm, and the maximum compressive stress value is about 50 Mpa.

By comparing the data measured by the $\sin^2\psi$ method and the $\cos\alpha$ method, it can be seen that the value of residual stress in base metal position obtained by the $\sin^2\psi$ method is smaller than that achieved by $\cos\alpha$ method, while the residual stress value in heat affected zone and weld seam measured by $\sin^2\psi$ method is larger than that of $\cos\alpha$ method. The trend of data measured by $\cos\alpha$ method is more obvious than $\sin^2\psi$ method.

3.2. *Adding the oscillation unit to the* $\cos\alpha$ *method*

As shown in Fig. 3(a), the stress measuring instrument using $\cos\alpha$ method integrates X-ray tube and detector in a single shell. The oscillation unit is attached to the shell of the equipment. With the oscillation of the oscillating unit, the incidence angle of X-ray can be increased.

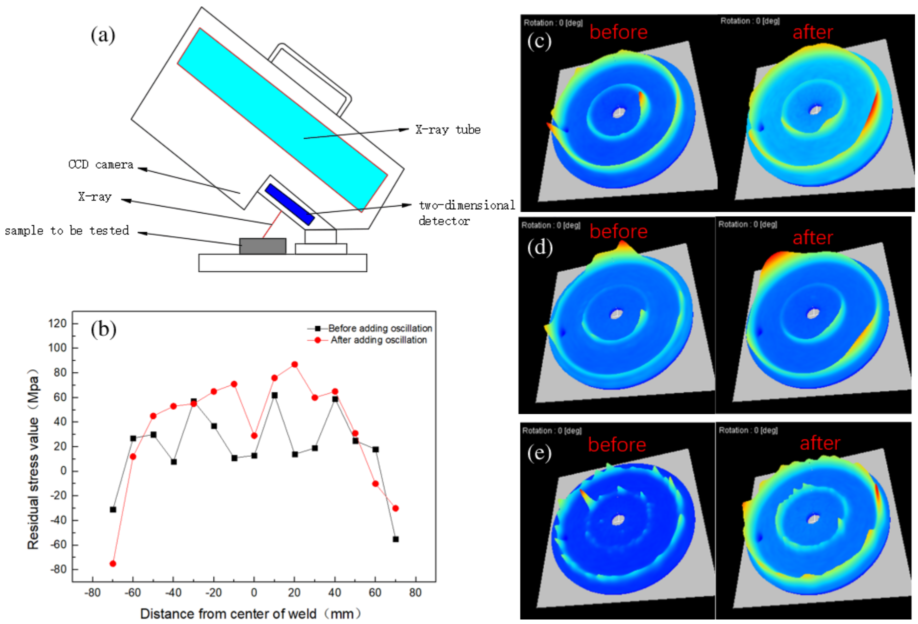

Fig. 3. (Color online) The influence of oscillation on the residual stress and Debye ring: (a) the stress measuring instrument using $\cos\alpha$ method. (b) The residual stress before and after adding oscillation. (c) Debye ring of the base metal with oscillation and without oscillation. (d) Debye ring of the heat affected zone with oscillation and without oscillation. (e) Debye ring of the weld seam with oscillation and without oscillation.

The measured results of residual stress before and after adding oscillation are shown in Fig. 3(b). Compared with those without oscillation, the fluctuation of the measured results by oscillating method is obviously reduced, and shows a bimodal trend, which is consistent with the theoretical trend of welding residual stress of aluminum alloy. With the addition of oscillation, the value of residual stress increases slightly. There is no obvious difference of the stress values in the base metal region, and the residual stresses near the weld seam and in the heat-affected zone are quite different, which is due to the fact that less grains participate in X-ray diffraction and the numerical deviation is larger when oscillation is not added. After oscillating, the number of grains participating in diffraction increased and the measured stress values were more reliable.

The depth of color on the Debye ring corresponds to the intensity of the diffraction peak at a certain angle, so if there is texture in the material, it will reduce the diffraction intensity of some angles, and cause the color on the Debye ring to be different in depth. In the detection of large grain samples, few number of grains involved in diffraction will lead to the absence of diffraction information at a certain angle, that is, the grain size can be estimated from the integrity of Debye ring.

Figure 3(c) shows Debye rings of the base metal with and without oscillation. By comparing the continuity of the two, it can be found that the shape of the Debye ring is more complete after the addition of oscillation, and there is not much difference in the overall diffraction intensity between them. Figure 3(d) shows Debye rings of the heat affected zone with and without oscillation. It can be seen that the continuity of the Debye ring detected without oscillation is poor and the diffraction intensity is low. After adding the oscillation, the integrity and strength are better than that without oscillation. The diffraction pattern of the weld zone is distributed in a dot shape when oscillation is not applied, and the diffraction intensity is uneven, as shown in Fig. 3(d). With the oscillation, the diffraction intensity is obviously improved and the vacancy between the intermittent points becomes a continuous figure. Besides, the diffraction intensity is strengthened to a certain extent. This shows that the grains involved in the diffraction are obviously increased.

4. Conclusions

The $\cos\alpha$ method is a new method to evaluate the residual stress through the Debye ring. In this paper, the welding residual stress of aluminum alloy was measured by both $\sin^2\psi$ and $\cos\alpha$ methods. It is found that residual stress achieved by both methods are consistent. Applying oscillation to the $\cos\alpha$ method improved the accuracy of the residual stress measured in the aluminum alloy welded joints.

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