

Internal Residual Stress Measurement of Aluminum Alloy Castings Using Neutron Diffraction

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ABSTRACT

When designing engine parts of motor vehicles, it is important to evaluate internal residual stresses that cause crack growth and influence the strength of parts. Internal stresses can be measured nondestructively by the neutron diffraction method. However, it is difficult to apply this method to aluminum alloy castings because they consist of coarse crystal grains. As for cylinder heads, the grain size ranges up to approximately 400 μm and there are few grains contributing to intensity of diffraction in each gauge volume. In the case of X-ray diffraction, "the oscillation method" has been employed for materials with coarse grains.

In this study, the applicability of the oscillation method to aluminum alloy castings was investigated with the aim of establishing a method of measuring internal stresses and strains. A related objective was to determine the accuracy of stresses. For the purpose of the study, specimens made of an aluminum alloy casting and measuring 20×20×140 mm in size were prepared and subjected to a bending load. A neutron diffraction experiment with oscillations was conducted, and the strain values were compared with the results measured with strain gauges. The experimental results show that an oscillation range of ± 15 degrees provides enough intensity of diffraction to read peak positions. Under this measurement condition, the differences between the strain values obtained by neutron diffraction and with strain gauges were less than 250×10^{-6} and the accuracy of the stresses was within 20-25 MPa. We also applied this method to an actual cylinder head. As a result, sufficient intensity of diffraction was observed with oscillations of ± 15 degrees. It was found that there were internal tensile residual stresses. We verified the efficacy of the neutron diffraction method with oscillations for aluminum alloy castings.

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INTRODUCTION

Residual stresses generated in heat treatments and machining processes should be observed when evaluating durability of engine parts because such stresses can reduce fatigue and tensile strength. Since tensile residual stresses inside parts often contribute to extension of cracks, these stresses need to be controlled in addition to surface stresses. In recent years, vehicle manufacturers everywhere have been striving for vehicle weight reductions. It has thus become more important to evaluate internal residual stresses in order to minimize declines in strength resulting from adoptions of thinner parts.

Although in-plane residual stresses of surfaces can be measured with strain gauges and by X-ray diffraction, these

methods cannot be applied to inner regions. In contrast, neutron beam can reach deeper regions than X-ray and the only way to measure the three-dimensional stresses inside large objects such as engines nondestructively is by neutron diffraction, which has been applied to products made of steel [1, 2]. However, aluminum alloy castings, which usually consist of coarse crystal grains, cannot be measured by the original diffraction method because of a lack of sufficient grains contributing to diffraction in a gauge volume (see Fig. 4). The oscillation method of X-ray diffraction has been applied in such cases because it can magnify the number of grains contributing to diffraction [1]. A study has been reported in which the oscillation method was applied to wrought Al alloys in a neutron diffraction experiment [3]. For the purpose of establishing a method of measuring internal

residual stresses in Al alloy castings such as cylinder heads, we researched the best oscillation conditions for this material in neutron diffraction experiments and investigated the accuracy of measured stress or strain levels [4]. The applicability of the oscillation method to actual engine parts was also examined.

1. RESEARCH ON MEASUREMENT CONDITIONS AND ACCURACY TEST

1-1. SPECIMENS

Specimens measuring 20×20×140 mm in size were cut from an JIS AC2A aluminum alloy casting block and prepared for use in research on the measurement conditions and in the accuracy test. Observation under a microscope showed that the mean grain diameter in the Al phase was about 400 μm. Specimens were subjected to a 4-point bending stress, which was induced by inputting 2.94-kN loads from two lines on the bottom, to generate internal strain fields. Strain gauges were attached to the top, bottom and side surfaces as shown in Fig. 1. The results of FEM calculations were also used to confirm the accuracy of measured strain values.

Strains in the Y-direction at six points inside a cross section were measured by neutron diffraction and at seven points on the surfaces, located on the perimeter of the section, by strain gauges. The cross section was located at the midpoint of the longitudinal direction of the specimen. Accuracy was examined by comparing the values at points located at the same Z-positions because the FEM calculation results showed that they were all equal theoretically regardless whether they were on the surfaces or not. We do not have to take into account the gauge length differences between neutron diffraction and strain gauges because the strain values near the midsection do not depend on their Y-positions under a 4-point bending load.

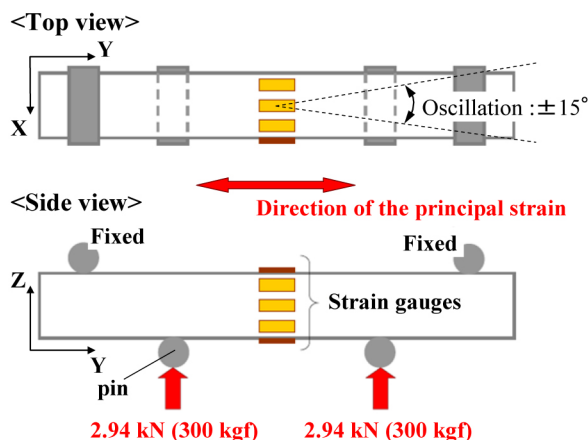


Figure 1. The structure of the bending test. The X, Y, and Z directions correspond to Fig. 2.

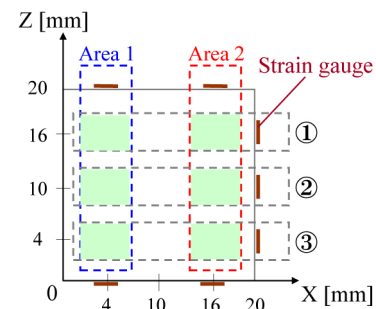


Figure 2. The section of the specimen measured in this experiment. indicates the areas measured by neutron diffraction.

1-2. NEUTRON DIFFRACTION

The experiment was carried out using the RESA-2 diffractometer of the JRR-3 reactor at the Japan Atomic Energy Agency. Strain ε inside a specimen was evaluated by the shift in the lattice plane distance d of the Al phase, which was calculated using an angle of 2θ between the incident beam and the diffracted beam.

$$d = \frac{\lambda}{2 \sin \theta} \quad (1)$$

$$\varepsilon = \frac{d - d_0}{d_0} \quad (2)$$

Equation (1) expresses Bragg's law. When the path difference shown in Fig.3 is equal to the wavelength, the intensity of the scattered beam peaks. In this experiment, the wavelength of the neutron beam, λ , was set to 0.22 nm. The strain-free lattice plane distance d_0 was defined as the observed distance when no load was input to a specimen. Hook's equation was used to convert measured strain values to stresses as shown in the equation (3).

$$\sigma_i = \frac{E}{1 + \nu} \left\{ \varepsilon_i + \frac{\nu}{1 - 2\nu} (\varepsilon_i + \varepsilon_j + \varepsilon_k) \right\} \quad (3)$$

The tensors i , j and k represent the three orthogonal directions. The notations E and ν are Young's modulus and Poisson's ratio, respectively.