Stress measurements of coarse-grained materials and welded parts by double exposure method with high-energy monochromatic X-rays

In this article, we report the double exposure method (DEM) that was developed at SPring-8 **BL14B1**. The DEM with synchrotron monochromatic X-rays has made it possible to measure residual stresses of coarse-grained materials and welded parts.

Knowledge of the residual stress is indispensable for estimating strength and reliability. Only an X-ray method can nondestructively measure the residual stress of the actual object. In the X-ray method, the change in lattice spacing, Δd, is obtained from the change in diffraction angle, $\Delta\theta$, based on Bragg's law. The residual stress is calculated from the elastic strain $\varepsilon = \Delta d/d_0$, where d_0 is the strain-free lattice spacing. Elastic strain measurements require an accuracy of 5–6 orders of magnitude. For powder diffraction, the residual stress can be measured with sufficient accuracy using a diffractometer.

However, diffraction from the coarse-grained material becomes spotty rather than a continuous ring. This is especially notable in the synchrotron X-ray beam, which is a microbeam with excellent directivity. Therefore, the diffractometer (point detector) cannot be used for coarse-grained materials and an area detector should be used. In the angle measured using the area detector, a center of diffraction, O, is assumed as shown in Fig. 1, and the diffraction angle 2θ is calculated from $\tan^{-1}(r_1/L_0)$. If the sample is small and fined-grained, it is possible to measure the diffraction angle 2θ by this method.

A new problem arises when measuring stress in bulk samples using the strong penetrating power of high-energy synchrotron X-rays. The diffraction from the bulk sample with coarse grains is shown in Fig. 1. The diffraction points differ in accordance with the positions of the grains on the transmitted X-ray beam, as shown in Fig. 1. For example, the diffraction angle, which is calculated using the diffraction center, becomes large for the upstream grain and small for the downstream grain. With this method, the angular variation is too large to measure the elastic strain.

To solve the above problem, we must find a new angle measurement method that does not use the diffraction center. The DEM is proposed as a countermeasure. As shown in Fig. 1, the diffraction spots are measured using the area detector at P1 and P2, and diffraction radii r_1 and r_2 are obtained. The true diffraction radius r is calculated as $r = r_2 - r_1$ and L is the length between P1 and P2. The angle determined from $2\theta = \tan^{-1}(r/L)$ gives the correct diffraction angle regardless of the grain position. This is the principle of the DEM and no diffraction center is required. Also, the diffraction angle and position can be determined from the relationship between the straight lines of the diffracted and incident beams [1].

The nonuniformity of the diffraction ring, which is indicated by the arrow in the images at P1 of Fig. 1, is due to the grain position. The same discrepancy can also be seen in the image at P2 (arrow). The DEM is able to cancel the error due to the grain position. Figure 2 demonstrates the canceling mechanism in the DEM. The fluctuations in the diffraction radii r_1 and r_2 are very large, as shown in Fig. 2, but the fluctuations in both r_1 and r_2 are synchronous. As a result, $r = r_2 - r_1$ gives the accurate diffraction radius.

On the other hand, there is an excellent method called three-dimensional X-ray diffraction microscopy (3DXRD) [2]. It is based on two principles: the use of highly penetrating hard X-rays from a synchrotron source and the application of 'tomographic' reconstruction algorithms for the analysis of the diffraction data.

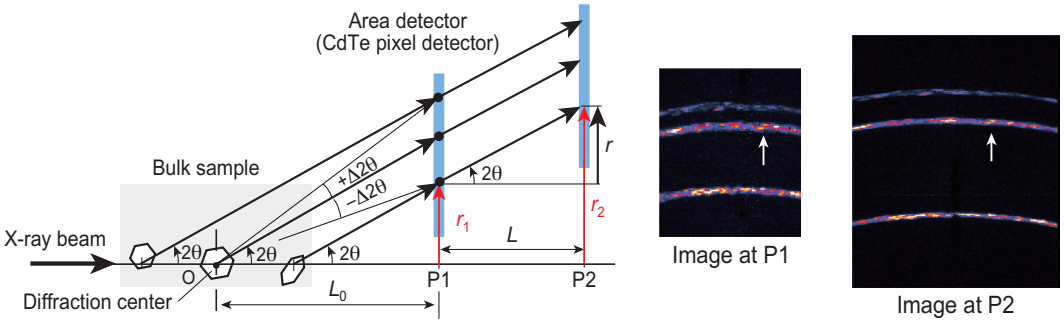

Fig. 1. Diffraction from coarse grains. The difference in the position of coarse grains causes the errors of diffraction angle $\Delta 2\theta$. Using the double exposure method (DEM), angular errors can be canceled.

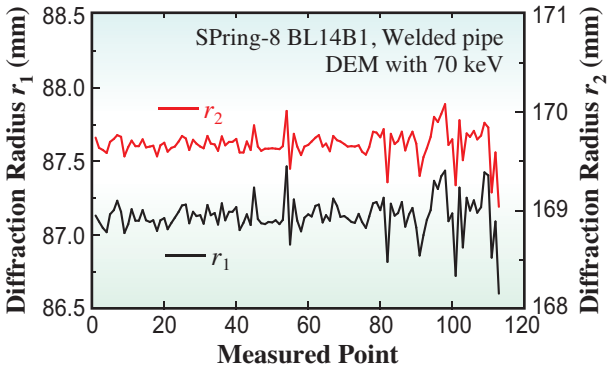

Fig. 2. Fluctuations of the diffraction radii r_1 and r_2 synchronize with each other and cancel the diffraction radius error due to the grain position.

Using 3DXRD, not only the position, morphology and crystallographic orientation but also the elastic strain can be obtained. However, this method cannot be applied to bulk samples. The features of the DEM make it the stress measurement method suitable for bulk materials.

By the DEM, the stress map of coarse-grained materials and welded parts can be obtained; however, a plane stress is estimated without an out-of-plane stress in the DEM. This problem can be solved by combining neutron stress measurement with the DEM, as shown in Fig. 3. For example, the rough hoop stress map is obtained by neutron stress measurement under the triaxial stress state. Combining the out-of-plane stress distribution obtained by neutrons and the detailed two-dimensional stress map obtained by the DEM, a detailed residual stress map of the triaxial stress state can be obtained. The method of analyzing actual stress by using neutrons and the DEM in a complementary manner is called a hybrid actual stress analysis. The maps on the right side in Fig. 3 show the residual stresses of the butt-welded pipe obtained by the hybrid actual stress analysis [3].

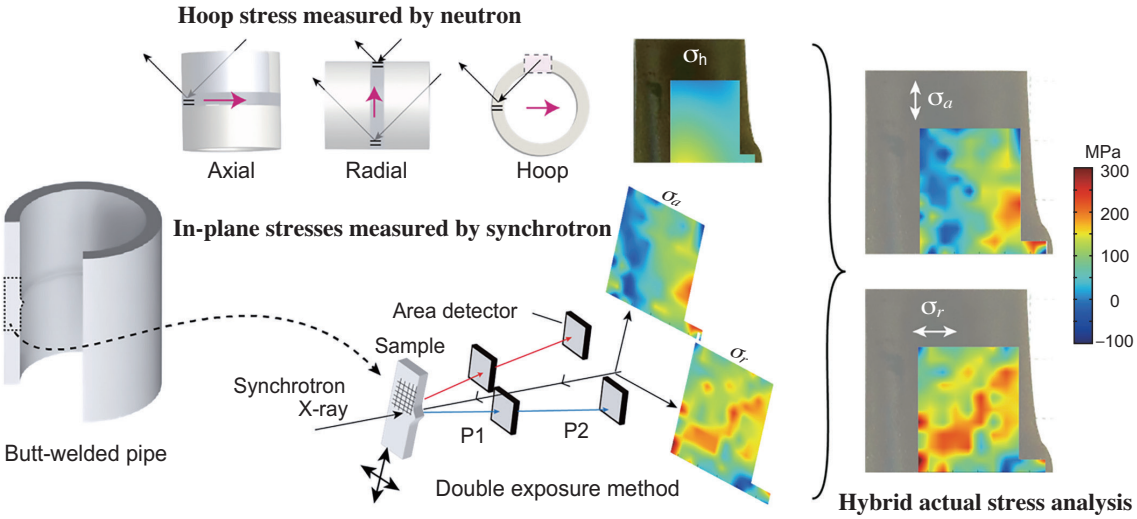

Fig. 3. Hybrid actual stress analysis using hard synchrotron X-rays and neutrons.

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References

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