# BII-10 Analysis of Pre-existing Flaw of Material by Optical Double Diffraction Method

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## Abstract

Observation of the process of fracture of material was studied by double diffraction method. Experiments were made in two ways, one is based on the frequency modulation of diffraction grating and the other is based on the generalized Schlieren method. As an example of the first method, the elongation in each grain of aluminum macrocrystal was measured and it was found that the elongation in the neighborhood of the grain boundary is constrained. And using the second method, deformation in each stage of the fracture process was shown with the chromatic contour on a screen in the image plane.

## Part I. The Method Based on Frequency Modulation of Diffraction Grating

### 1. Introduction

There are several ways of measuring strain distribution on a specimen. The photoelastic method and X-rays analysis are most widely used for this purpose. In the former case, however, the strain distribution in a specimen are analogized indirectly by a model, which has the same shape and has the same loading condition with the specimen. When photoelastic film method is used, the sensitivity of measurement depends on the thickness of the film. This is inconvenient undoubtedly. In the latter case, to obtain the strain distribution analysis must be done about many points.

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In order to get rid of these disadvantages, the double diffraction method using a diffraction grating has been developed by present authors.(1,2,3) In this method a transparent diffraction grating itself consists of a specimen and two dimensional distribution of the strain induced in the specimen can be measured quantitatively with high sensitivity. Also the strain distribution can be observed intuitively since it corresponds to the intensity distribution of the optical image of the specimen.

## 2. Optical System and Principle

Schematic diagram of the optical double diffraction system is shown in Fig.1. In this figure, S is a monochromatic light source, $C_1$ and $C_2$ are condenser lenses, L is a projection lens and T is a grating (i.e., specimen). When there is no load acting in the specimen, an incident plane wave is diffracted by the grating and will form sharp spectral lines in Fraunhofer diffraction plane M. If the light is monochromatic, the spectra are those of +1st., 0th and -1st. order and so on. Now, when a load is applied to the specimen, the grating which has been regularly ruled changes its shape according to the strain distribution of the specimen. Consequently, each spectral line suffers some disturbaces. Describing the above situation in terms of communication system, it become as follows. When a grating is unevenly strained, the grating has various spatial frequencies. This means in terms of communication system that the grating has been frequency modulated by the signal corresponding to the strain distribution. Here the original regular grating plays a role of carrier wave. If demodulation of the modulated carrier wave is done by a mask (that is, knife edge or amplitude linear wedge) with appropriate transmission put in the Fraunhofer plane M, the signal corresponding to the strain distribution appears as the light intensity distribution in the image plane of the specimen.

## 3. Experimental Results

As an example of this method, we have observed a process of fracture of a plate of aluminum macrocrystal as shown in Fig.2. The photographic emulsion is spread upon the surface of specimen and the rulings of the optical grating is transcribed on it by contact printing. When tensile loads are applied to the specimen on both sides, the process of deformation in the specimen is observed as in following figures. Fig.3 shows 0.8% elongated aluminum. The figure is obtained with an optical wedge placed in Fraunhofer diffraction plane. It is theoretically possible to conclude that the intensity of the image and the amount of strain are proportional, so that, in this figure, central grain elongates mainly and that in the left hand only slightly. Also, it can be seen that in the neighborhood of grain boundaries the elongation is small compared with the other parts, which means that grain boundary plays constraint effect for the deformation. Fig.4 shows the change of the distribution of strain with the increasing amount of tensile load (39.5% elongation) and Fig.5 shows the stage after fracture. It can be seen that fracture never start at grain boundary and the elongation in a grain is not uniform.

As shown in these figures, this method is highly sensitive and the deformation in the specimen can be estimated from the image intensity.

# Part II. The Method Based on Schlieren Effect

## 1. Introduction

In order to measure the optical phase distribution in materials (i.e., thickness, refractive index and surface shape), the interference and the Schlieren methods have been adopted up to the present time. In the former case, the accuracy of measurement was improved remarkably by applying the multiple-beam interference, but the measurement of phase distribution in the region with dense interference fringes is very troublesome and the discrimination between the convex region and the concave one is impossible with single observation of the fringes. On the other hand, it has been known that the Schlieren method has very high sensitivity. But it is very difficult to measure the phase distribution quantitatively and precisely.(4,5)

Recently, as a result of applying the communication theory to optics, the theory of image formation has been much advanced.(6) Present authors have applied these image formation theories to the Schlieren effect as a problem in the optical double diffraction system by the recent image formation theory. Thus, it has become possible to measure the optical phase construction in materials quantitatively.(7) And by the adoption of several new devices the Schlieren method has been generalized.(8) Consequently, the defects in conventional measuring methods have been eliminated and the various new fields of the application have developed.(9,10) In this paper, the deformation of the specimen expressed with chromatic distribution and the process of fracture of material will be shown.

## 2. Optical System and Principle

The optical system is similar to that shown Fig.1. In this case specimen T is only a phase material and not grating. The Fraunhofer diffraction pattern of the specimen is yielded in the plane M and the image of the specimen is formed in the screen $S_c$. Let the optical phase distribution in material be L(U), than the center of the diffraction pattern caused by the light wave which has passed through the interval $\Delta U_j$ appears at $X=fL'(U_j)$ in Fraunhofer plane. Namely, the real distance from the center of diffraction pattern to optical axis, X, is in proportion to phase gradient. Here f is the focal length of the condenser lens $L_2$.

The diffraction pattern of the phase object can be regarded as the sum of the diffraction image yielded by the light wave which passed through each interval $\Delta U$ on the object plane and the distance from the position of each component of the diffraction pattern to the optical axis is proportional to the phase gradient $L'(U_j)$. When the mask is placed in the diffraction plane, the region on the object plane which has the value of the phase gradient larger than $L'(U)$ corresponding to the position of the mask forms an image on the screen. Since this consideration can be applied to every section, perpendicular to the mask edge, in the object plane, it may be concluded that the contour of the image shows equi-gradient curve of phase distribution. So, measuring the position of mask edge X, the value of phase gradient on the image contour can be calculated.

In order to measure the deformation induced the material, a diffraction system, which has a polychromatic light source, a prism placed in front of the specimen and a slit mask in Fraunhofer plane, was used. When the specimen is deformed by loading, the colored image will be obtained owing to Schlieren effect. From the analogous consideration as in the case of monochromatic light source, it can be proved theoretically that color distribution in the image is equivalent to the distribution of strain gradient in the specimen, and the amount of the strain gradient can be measured quantitatively.

## 3. Experimental Results

As an example, we have observed a process of fracture of a polycarbonate plate with a circular hole by applying tensile loads as shown in Fig.6. The light source in this experiment is ultra high pressure mercury lamp and slit so adjusted as to pass only yellowish green line spectrum (5461Å) on the diffraction plane. In this figure, the color having longer wavelength than yellowish green has a positive gradient in longitudinal direction and that having shorter wavelength has negative gradient. It is easily understood that the absolute value of the gradient become larger, if a spectral color has a larger wavelength difference than that of yellowish green.

Thus, the state of deformation can be obtained from the distribution of color and it was found that pattern shown in Fig.6(a) agrees very well with the one calculated from the theory of elastisity. Fig.6(b) shows state of deformation of specimen with larger tensile loads and is at a transient stage from elastic to plastic deformation. By increasing the amount of tensile loads much beyonds this, Fig.6(c) has been obtained in which the black part corresponds to the region having an extremely high gradient of deformation. Fig.6(d) shows the state of stress release after the fracture. And also, it is possible to analyse the amount of strain quantitatively from these patterns.

Fig.7 shows the process of a polycarbonate plate having V-notches. In these figures, a certain kind of walk of the stress concentration region near the bottoms of notches can be observed.

It is also possible to observe the process of fracture of metals by reflection optical system.(7) As shown in these examples, the observation of process of deformation in material by this method is very sensitive and moreover the measurable range is large, therefore, the process of deformation from small to large deformation can be measured continuously.

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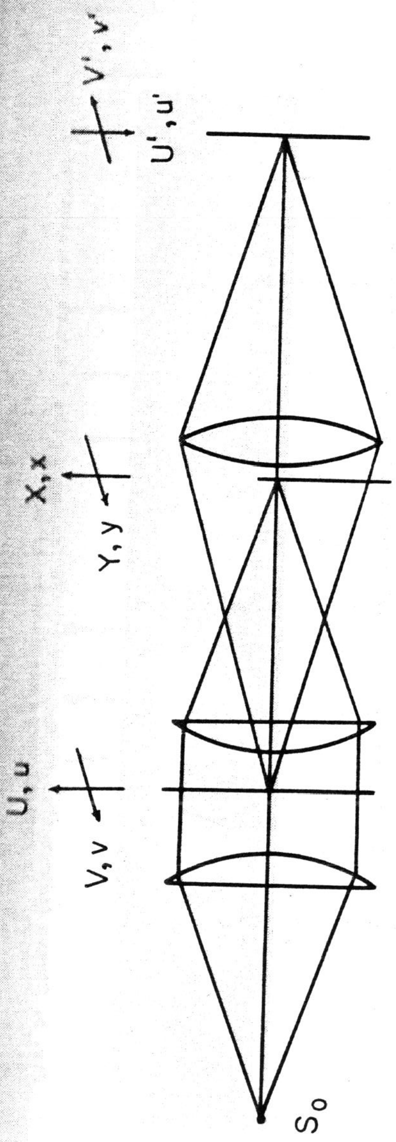


Fig. 1. Arrangement of optical element. $S_0$—Light source; $L_1$, $L_2$—Condenser lenses; T—Test piece; M—Mask; $L_3$—Projection lens; Sc—Screen.

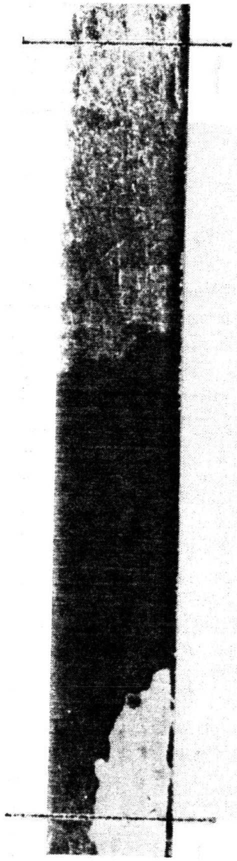


Fig. 2. Crystal grains of aluminum before transcribing a grating.

Fig. 3. Strain distribution in the case of 0.8% extension. A knife edge was used to detect.

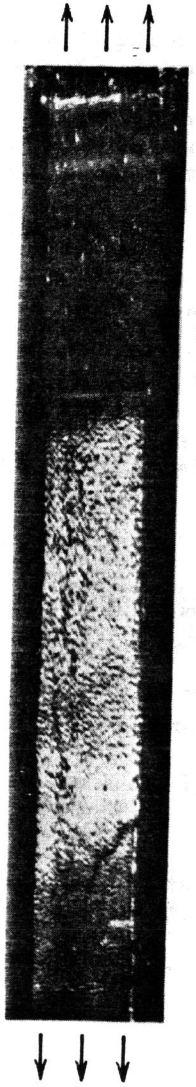


Fig. 4. Strain distribution in the case of 39.5% extension. An optical wedge was used to detect.

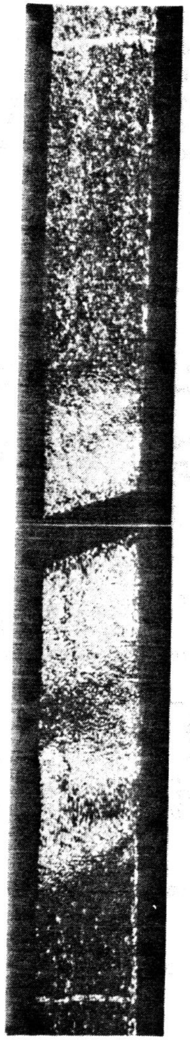


Fig. 5. Strain distribution in the case of the fracture. The fracture was occurred at 46.5% extension. An optical wedge was used to detect.

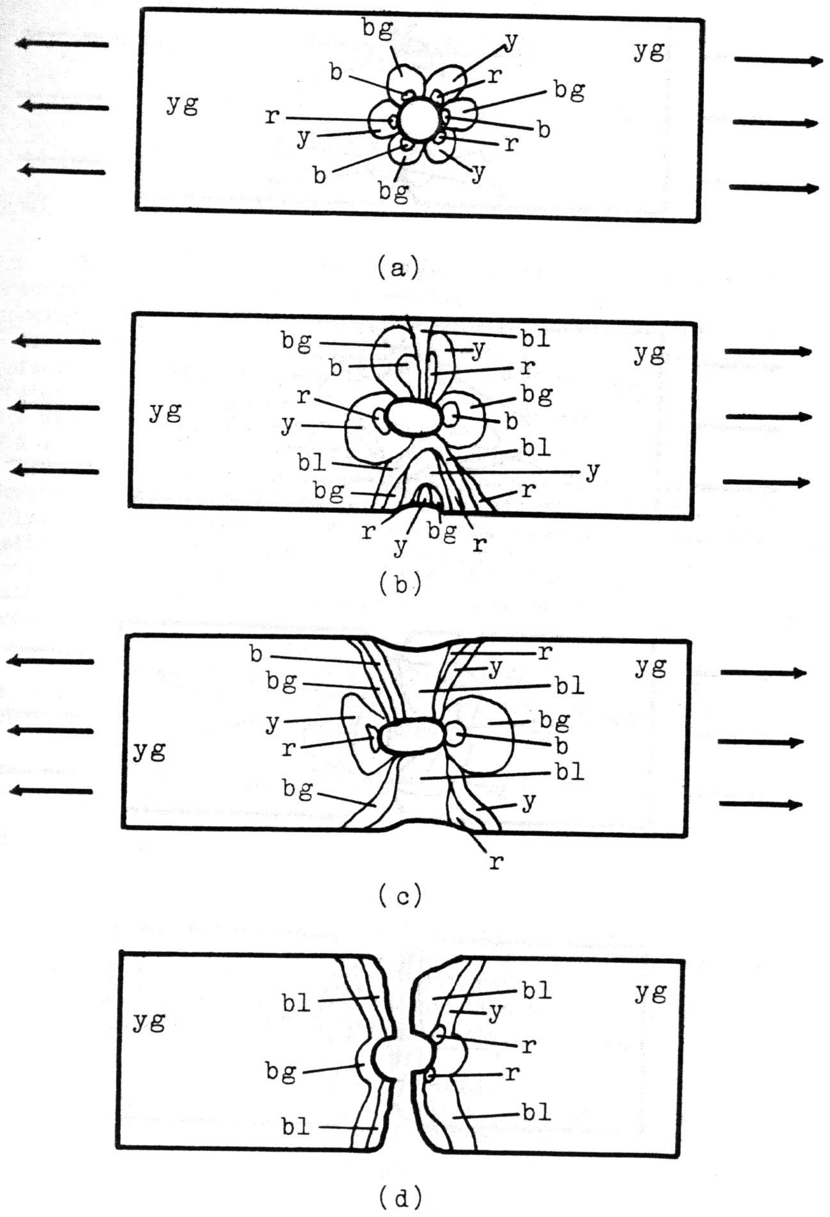
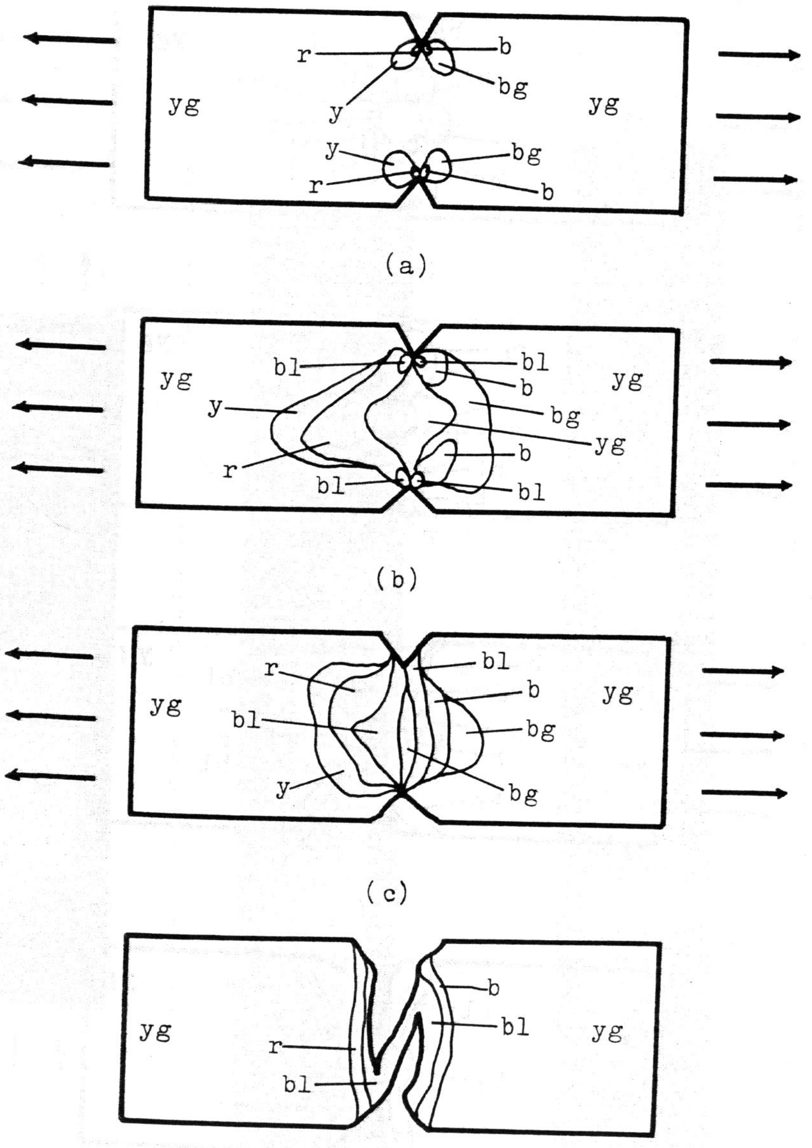


Fig. 6. Gradient distribution obtained by color differences in a strained rectangular plate having a circular hole. b—blue; bg—bluish green; yg—yellowish green; y—yellow; r—red; bl—black.



(a)

(b)

(c)

(d)

Fig. 7. Gradient distribution obtained by color differences in a strained rectangular plate having notches. The letters indicated are the same in Fig. 6.