An improved polarizing microscope. V. The ore-microscope.[1]

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EXAMINATION in reflected polarized light is now widely used in metallography as well as for mineral sections. The recent introduction of graded diamond abrasives[2] has overcome most of the difficulties in polishing that have previously hindered the widespread use of this important method.

The present instrument (fig. 1) has been designed to give the best available control over the conditions of illumination and extinction, and to provide for the complete analysis of the reflected elliptically-polarized beam. A robust stand of normal grade suitable for general research purposes and works control is provided with a stage rack, reflector unit, and the usual polarizing equipment. It may be adapted for transmitted light by the addition of the detachable substage shown on the right of the figure.

Collimation of the plane glass reflector.—The light from a 'cover-glass' reflector is not homogeneous. Rays obliquely incident on the glass surface are somewhat rotated, so that complete extinction occurs along a N.-S. band in the field and similarly at the back of the objective. Fully homogeneous polarization has hitherto been obtained by the use of special prisms, but the restricted conditions of illumination and the injury to definition caused by occulting one-half of the objective opening have led the present authors to abandon prism illumination in favour of a modification of the plane glass illuminator. The new system will be readily understood from fig. 2. Collimating lenses have been inserted above and below the reflector, so that the light from any point within the field iris is rendered parallel over the whole aperture during its

[1] Parts I–IV, Min. Mag., 1946, vol. 27, p. 175; 1947, vol. 28, p. 96; 1948, vol. 28, p. 296; 1950, vol. 29, p. 150.

[2] See H. J. Grenville-Wells, Indust. Diamond Rev., 1949, vol. 9, p. 360.

passage through the reflector, both before reflection from the object and afterwards on its return upwards to the eyepiece.

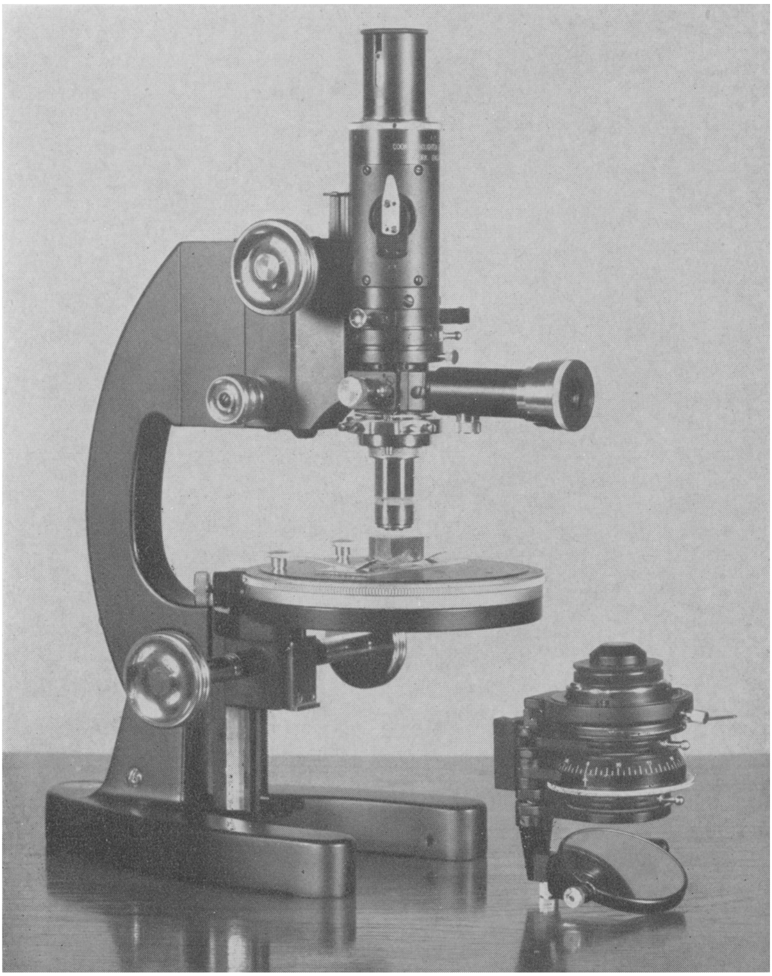

FIG. 1. Improved ore-microscope with detachable substage.

In the orthoscopic field, light coming from points on the E. or W. sides is still subject to small rotations so that a dark extinction band[1] is still visible in the field; with a $\times 10$ eyepiece, however, the area of

[1] Utilized by L. Capdecomme and J. Orcel, Rev. d'optique théor. et instr. 1941, vol. 20, p. 47.

field is sufficiently large to obviate inconvenience from this cause. When light from the central area of the field has been isolated in the usual way by an eyepiece diaphragm, the illumination of the whole objective opening is homogeneous; with the Nakamura plate it can be shown that the extinction is uniform within about 0·1 degree over the whole area. The extinction obtainable is now so complete that it is necessary to give special attention to the question of 'parasitic' anomalies and of dye-transmission in the polarizing filters.

The objective changer.—As is well known, few objectives are perfectly free from anomaly, and even selected lenses may vary somewhat through pressure on the mounts.[1] There remains in any case a certain anomaly arising from the rest of the optical system; selection of objectives is not, therefore, a complete remedy for this difficulty. There are also mechanical deficiencies in the majority of changers of the collar type. The objective changer used in the present instrument has therefore been completely redesigned.[2] A flanged inner collar with a small locking head permits the objective to be rotated about the axis of the microscope. Since the anomaly is in all cases well below 1/10 λ the objective will act as an elliptic compensator, and is so used. It should in fact have an anomaly somewhat greater than that of the rest of the system. It can then be rotated till it neutralizes the rest of the optical anomalies. A bright isotropic surface is placed in the field and the extinction is checked with the Nakamura plate. On rotating the objective, the field will darken and complete extinction may be verified by means of the conoscopic image; or the absence of ellipticity may be tested in the orthoscopic field with a Koenigsberger plate. There are usually four extinction positions for the objective, but they are in pairs, not mutually perpendicular. When

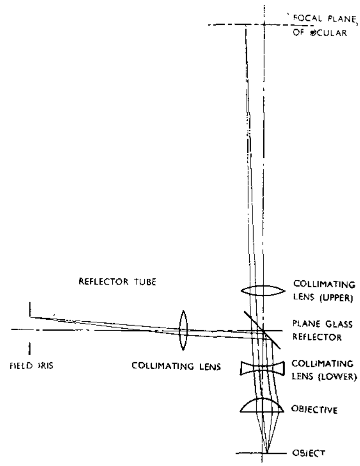

FIG. 2. Plane glass reflector with additional collimating lenses to give homogeneous aperture.

[1] B. W. Mott, H. R. Haines, and J. Woodrow, Atomic Energy Research Establishment, Report M/R856, 1952, Harwell.

[2] A. F. Hallimond, Brit. Pat. 638334/1950. Property of the National Research Development Corporation.

the object causes rotation of the plane of polarization the objective compensation will have a slightly different value for the returning light, but for the small angles usually met with this is negligible. For the highest accuracy in measuring it would probably be rather better to use a completely isotropic objective and allow for the small zero value representing the anomaly of the remainder of the system, but complete extinction is better for ordinary visual work.

Dye-transmission of the polarizing filters.—If a sufficiently strong light is used there will always be a certain transmission of light at 'extinction'. Part of this light is due to ellipticity in the glass mounts, and part to transmission of the absorbed vibration by the dye. Anomaly due to the mounts is now compensated by rotation of the objective, but there remains a bluish tint in the extinction. For most purposes this is negligible and may even be a useful indication that the ellipticity has been compensated. The dye-transmitted light vibrates at right angles to the transmission direction of the polarizing filter, and can be eliminated by introducing a second filter parallel with the first on the side distant from the object. This filter need not be so intensely dyed as the principal filter; a sheet of 'sun-glass' polaroid in front of the lamp is often useful, without doubling the analyser.

Adjustment of the reflector to the symmetry position.—Since the glass plate causes rotation it must be situated exactly at right angles to the principal plane of the polarizer. The most accurate setting is made by transmitted light. The extinction is first verified with the plate horizontal; the plate is then set at its normal inclination, in which position it resembles a birefringent object. The reflector unit must be rotated about the axis of the microscope till complete extinction is obtained, preferably indicated by the Nakamura plate. The illuminator should be locked at this azimuth and need not be again disturbed.

Measurement of rotation and ellipticity.—In most crystal sections the path-difference between the components along the principal directions is very small. The rotation angle can therefore be measured with considerable accuracy without compensating the ellipticity. Even this incomplete determination is of considerable interest, and rotating analysers have been fitted for this purpose though not always with means of accurate measurement. The special ocular shown in fig. 3 has graduated rotation, reading by vernier to 0·1 degree and to 0·05 by estimation. It is provided with slots that permit the use of rotary compensators for path-differences below $1/10\ \lambda$ and of quartz-wedge types for larger values.

Analysis of the reflected beam (A. F. H.).

Berek[1] has described very clearly the conditions for the use of the elliptic compensator. Briefly, the section is brought to one of the 45° azimuths and the ocular is turned so as to restore 'extinction'. The elliptic compensator is then adjusted to give complete extinction, and the extinction condition is again checked until both rotation and compensation are giving the maximum extinction. The rotation can be

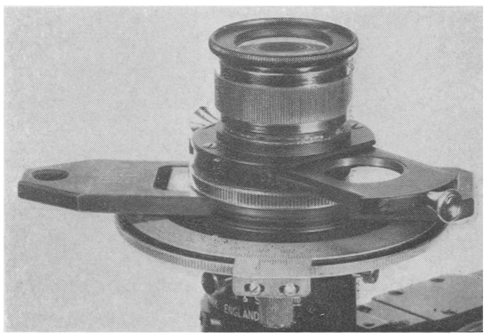

FIG. 3. Graduated rotating slotted ocular and analyser.

checked conoscopically by the Nakamura plate and the compensation by the Koenigsberger plate. The section is then turned on the stage through 90° and the setting is repeated. The difference between the analyser readings is twice the rotation angle, and the difference between the compensator readings is twice the angle θ. If Γ_0 is the constant for the compensator plate, the path-difference Γ is $\Gamma_0 \sin 2\theta$. If the compensator is in the ocular slots it rotates by the same angle as the ellipse and the path-difference is simply that required to compensate the ellipse along its 45° azimuth. The compensator can also be used in the tube slots, in which case its readings must be increased or diminished by the rotation angle in order to obtain the correct value.

For values larger than $1/10\ \lambda$ it is necessary to use a different kind of compensator, of which the quartz-wedge may be taken as the type. If the quartz-wedge is inserted at 45° to the axis of an elliptically polarized beam (e.g. the beam from a birefringent object in the familiar procedure with transmitted light) a black compensation band appears at the angular phase-difference $\phi = 2 \tan^{-1} b/a$, where b and a are the axes of the ellipse. If the wedge is not exactly at 45° azimuth the extinction of the band will be impaired.

[1] M. Berek, Fortsch. Min. Krist. Petr., 1937, vol. 22, p. 1. [M.A. 7-250.]

By means of the rotating slotted ocular the same arrangement can be used to analyse the rotated beam in the ore-microscope. The quartz-wedge must first be *accurately* set at 45° with the vibration-direction of the analyser. It is best to use a special carrier for the final adjustment since the slots are not usually exactly at 45° with the analyser. The analyser is rotated by exactly 45° from its normal position; this brings the direction of the wedge nearly to extinction (tested with a loose filter

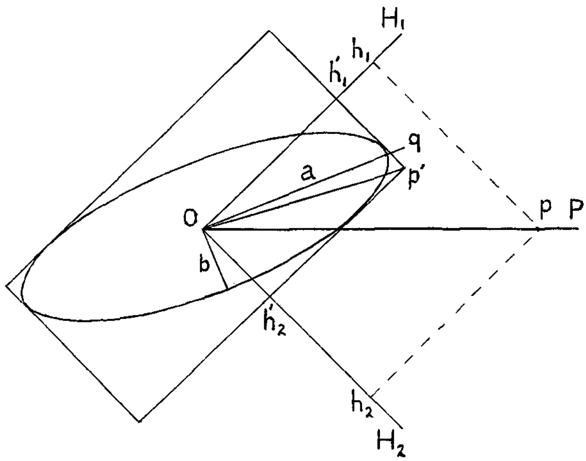

FIG. 4. Formation of elliptically polarized light by reflection from a polished surface at normal incidence.

instead of the usual analyser) and the final adjustment to extinction can be completed. When a crystal section has been brought into place at its 45° position, the ordinary analyser is brought in and the ocular is rotated, carrying the wedge round with it, until the extinction band is found and is brought to maximum extinction. The position of the band then gives the phase-difference, and the rotation angle of the analyser gives the azimuth of the reflected ellipse.

The accuracy so attainable for azimuth is not very good, but full accuracy could no doubt be obtained if the quartz-wedge was replaced by a Soleil compensator, with Nakamura and Koenigsberger plates used conoscopically.

Calculation of the reflectivity ratio R_2/R_1 *and path-difference* Δ *for the principal directions of the crystal section.*—With the notation of fig. 4 the relations for the ellipse inscribed within the rectangle $h'_1p'h'_2$, &c., are given by a well-known set of equations[1] of which the following two give the desired values:

(1) $\cos 2 \tan^{-1} b/a \cos 2\, H_1Oq = \cos 2\, H_1Op' = \cos 2 \tan^{-1} \sqrt{(R_2/R_1)}$ (when $H_1OP = 45°$).

(2) $\tan 2 \tan^{-1} b/a / \sin 2\, H_1Oq = \tan \Delta$.

OP is the vibration-direction of light coming from the polarizer and OH_1 OH_2 the principal directions of the crystal section. Δ is the angular phase-difference. If Δ is in circular measure, $2\pi/\Delta = n$ where $\lambda \times 1/n$ is the path-difference.

For the present purpose graphical solution is hardly needed, but reference may be made to the method due to H. Poincaré.[2] Since the above-mentioned equations are formally analogous with the familiar 'Napierian' set of equations for solving right-angled spherical triangles, the values concerned can be set off as a right angled triangle on the stereographic projection, and solved with the Wulff net. A brief summary of some of the literature is given by C. Burri.[3]

For large values ϕ and Δ will not be the same. When the path-difference is less than $1/10\ \lambda$ the axis *Oq* nearly coincides with *Op'*.

For small values of b/a,

from (1) $\cos 2 \tan^{-1} b/a = 1$ and $H_1Oq = H_1Op' = \tan^{-1} \sqrt{(R_2/R_1)}$

from (2) if the rotation angle *POp'* is small, $\sin 2H_1Oq = 1$ and $2 \tan^{-1} b/a = \Delta$.

But the compensator gives $2 \tan^{-1} b/a = \Gamma$ (expressed as the phase-angle ϕ). The elliptic compensator therefore gives directly the approximate path-difference for the principal directions of the crystal, provided that the rotation angle is small. $\tan (45° - POq) = \sqrt{(R_2/R_1)}$.

Determination of the rotation (and ellipticity) due to return of the light through the inclined plane glass reflector.—With transmitted light the polarizer is removed and a polarizing filter is laid on the stage. After the extinction reading has been noted, the stage is set to positions at 2, 4, 6, &c., degrees on either side of extinction and the corresponding extinction positions of the analyser are read on the analyser scale. The analyser readings are larger than the stage readings, which give the true rotation of the light, on account of the further rotation produced by skew incidence on the inclined glass plate. Up to 20° the two series are strictly proportional, and the ratio can be ascertained, e.g. 5:4. Measurements made with the plane glass reflector must be reduced in this

[1] A. Schuster and J. W. Nicholson, Theory of optics. 3rd edit., 1924, p. 14.

[2] H. Poincaré, Théorie mathématique de la lumière, II. 1892, p. 275.

[3] C. Burri, Das Polarisationsmikroskop. Basel, 1950, p. 31. [M.A. **11**–181.]

proportion. It has been assumed throughout the preceding notes that this has been done.

In the same way, the ellipticity can be measured with the elliptic compensator. The values found were very small, a rotation of 20° giving only one degree difference in the compensator reading. Even this value is doubtfully due to the inclined plate, for the change in azimuth toward the objective might cause this small variation. With ordinary rotation angles of 5° or less this effect seems negligible. One degree on the compensator used represents about 0·0025 λ Na.

In considering the corrections required for the return of light through the glass plate the usual procedure will be to resolve into components along and at right angles to *OP* (fig. 4). Owing to the greater transmission of vibrations in the plane of incidence, the components at right angles will undergo a relative extension in the ratio that has already been determined above by observations on rotation angles up to 20°. Although the glass plate itself produces a negligible path-difference, any existing ellipse will undergo a small distortion. If the observed ellipse is plotted as in fig. 4, it should be corrected by reducing the vertical scale in this ratio. For the small ellipticities (up to 1/10 λ) and rotation angles (up to 20°) usually met with in work on ores and metals, the correction will amount simply to reducing both the ellipticity and the rotation angle by the known ratio. Example: stibnite cleavage; measured rotation 2·4°, path-difference 0·0071 λ Na. Constant for the inclined glass plate 6/5. Corrected values; rotation 2·0°, path-difference 0·0060.

Photometry is not here dealt with, but attention should be drawn to the great advantage of using the central beam given by a plane glass reflector in comparison with the restricted oblique aperture required for the Berek prism. There is also a full aperture for the conoscopic polarization figures.