Jour. Korean Inst. Mining Geol.
Vol. 18, No.4, p. 343-355, 1985

Physical Properties and Optical Symmetry of Some Bireflecting Ore Mineral Species

Chil-Sup So*, Seong-Jae Doh and Kyeong-Yong Lee***

Abstract: Spectral reflectivity and microhardness were measured quantitatively on polished surfaces of a selection of bireflecting minerals obtained from several well-known metallic deposits. Incremental errors are much higher than decremental errors and errors were found to be lowest in the spectral region close to the green wavelength (544mμ). The characteristics of the spectral profile are significant in their control of white light color. The covellite and graphite have reflectivity profiles similar in shape for each principal direction, showing noticeable difference in magnitude between the profiles: The spectral reflectivity of covellite parallel to the extraordinary vibration is higher ($R\cong10\%$) than that parallel to the ordinary vibration and graphite shows opposite feature. Reflectivity of the enargite and famatinite cut parallel to the cleavage plane is always higher ($R\cong5\%$) than that of the section cut normal. The optical symmetry of 5 bireflecting minerals was determined by noting the variation in reflectivity at 544 mμ. The data indicate that covellite is optically uniaxial positive and graphite is optically uniaxial negative. The Rm values for enargite and famatinite are clearly closer to the minimum value for the mineral (R_1) than to the maximum value (R_2) : the minerals can be recognized as optically biaxial positive. Enargite and famatinite cut parallel to cleavage have much higher hardness values (HV=>200kg/mm^2) than those cut normal to cleavage. Vickers indentations exhibit characteristic features for all the bireflecting mineral species studied. Broad radicle groupings of the mineral species can be made with regard to the reflectivity-microhardness numbers.

INTRODUCTION

In recent years there has been much interest in the quantitative measurement of opaque minerals with the polarizing incident-light microscope. The work of Bowie and Taylor (1958) started a trend towards the use of a combination of reflectivity and microhardness as a basis of a scheme of mineral identification. Unfortunately there are marked variations in the reflectivity and microhardness values of minerals as quoted by previous workers. The principal reasons for the variation seem to be related to differences in instruments, measuring techniques, and preparation of the specimens. The reflection-microhardness study of Korean ore mineral species has been undertaken by So et al. (1980), So and Song (1981), So et al. (1982), So and Jang (1984) and So and Lee (1985).

The purpose of the present study is to determine the character of the spectral profile in relation to optical properties and crystal orientation, and to determine the optical symmetry for some bireflecting ore minerals-covellite; Bor/Yugoslavia, graphite; Kropfmühl/West Germany, lievrite; Elba/Italy, gratonite and jordanite; Wiesloch/Tunisia, enargite; Butte/Montana, U.S.A. and Tsumeb/South-West Africa, and famatinite; Magma/Arizona, U.S.A. The quantitative Vickers microhardness numbers were considered from the point of view of the possibility

---

* Department of Geology, Korea University
** Department of Oceanography, Rhode Island University

of their application to mineral identification, and a broad grouping of the studied minerals was made with respect to the reflectivity-microhardness values. Errors in reflectivity measurements made with a polarizing incident-light microscope are also discussed.

APPARATUS

Photometer

The apparatus for quantitative measurements of reflectivity is a model MPV microphotometer (Leitz), fitted with an Ortholux-Pol ore microscope (Fig. 1). The photoelectric device employed is an RCA type 1 P21 photomultiplier connected to a spot galvanometer (Norma) with an internal resistance of 2k ohms and with a linear scale graduated from 0 to 120. Tests were conducted to check that the photomultiplier response was linear throughout the visible range and at varying galvanometer sensitivities.

A Philips 12-volt 100-watt halogen lamp, operating at a color temperature of about 3400° K, provides the light source. To avoid fluctuations in light intensity, the applied voltage was stabilized by a transistor stabilizer (Knott Electronick).

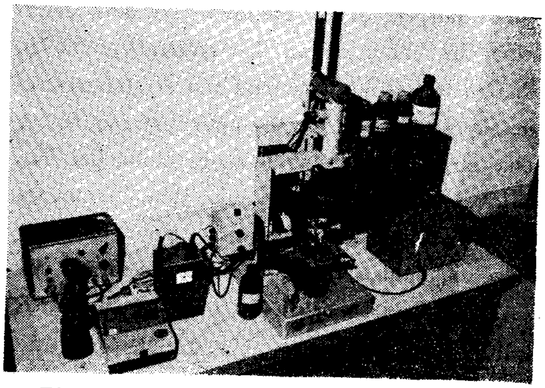


Fig. 1 MPV microscope photometer based on Ortholux-Pol ore microscope.

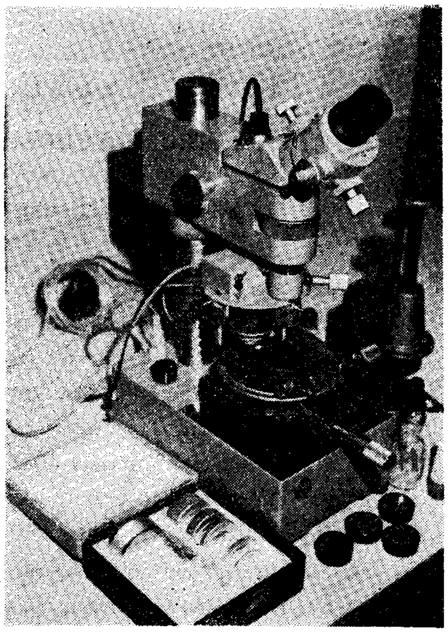


Fig. 2 Miniload hardness tester used.

Monochromatic light was produced by a series of Leitz homogeneous interference filters of effective half-bandwidths around 200Å and of a maximum transmission factor of nearly 60 percent. A neutral gray filter was inserted into the auxiliary system to cut down the light passing through this system. Measurements were performed with a×16 objective having a numerical aperture of 0.40. Larger magnification objectives were not used because these produced a greater amount of unwanted secondary reflections.

Microhardness Tester

Quantitative measurements of microhardness were made with a Miniload hardness tester manufactured by E. Leitz, Ltd. (Fig. 2).

Only the Vickers method was used for the present investigation. The Vickers indenter is a square-based pyramidal diamond with an angle of 136° between opposite faces and the depth of penetration equals one-seventh of the length of the impression diagonal. The descent rate of the indenter is controlled by means of a hydraulic damper.

METHOD OF STUDY

Preparation of Specimens

Piller and Gehlen (1964) suggested that an important source of error in reflectivity measurements is the surface condition of the specimen. Whenever possible, the studied minerals were mounted to give as many orientations as possible: enargite and famatinite crystals were cut parallel and normal to the cleavage planes. The embedded specimens were ground and prepolished with $400\sim800$ mesh silicon carbides on various rotating wheels of a H. DEPIEREUX polishing machine. Subsequent stages of polishing were done with 9-1 micron diamond abrasive on a Buehler polishing table, followed by a final polishing with 1/4 micron diamond and lapping oil on napless cloth. Soft minerals tend to become hollowed out when a gentle abrasive on cloth was used to remove scratches. In the case of covellite and graphite, great care was taken to keep this effect to a minimum.

Fig. 3 A studied enargite grain with adjusted measuring iris diaphragm.

Standards

At least two standard reference surfaces of known reflectivity are necessary to check the response linearity of the photomultiplier. Standards should have a surface that is mono-reflecting, not have a high dispersion, and be compact and free from cracks or cleavages, easily reproducible and permanent. The standards used for the present study are artificial substances of black glass(Leitz), silicon carbide 290 (Zeiss), and tungsten titanium carbide 260(Zeiss) which have a reflectivity of about 4%, 20%, and 50% respectively. The reflection powers of these standards in the visible spectrum are given in Table 1.

Measuring Procedure

Measurement of reflectivity

In all the measurements of reflectivity the illuminating diaphragm and the field diaphragm were closed down to about one-tenth of their total diameter to minimize any unwanted secondary reflections. In order to exclude light scattering from the microscope tube the field iris diaphragm was adjusted so as to be 1.2 times larger than the measuring diaphragm. The spectral reflectivities were measured on a mineral area as small as 40 microns (Fig. 3), by direct

Table 1 Spectral reflectivity data of standards.

λ(mμ)	Black Glass	λ(mμ)	SiC290	WTiC 260	λ(mμ)	SiC 290	WTiC 260
	R(%)		R(%)	R(%)		R(%)	R(%)
436	4.40	400	22.8	44.5	560	20.8	48.1
480	4.37	420	22.4	44.8	580	20.7	48.8
546	4.34	440	22.0	45.1	589	20.7	49.1
589	4.27	460	21.7	45.4	600	20.6	49.5
644	4.21	480	21.4	45.8	620	20.5	50.3
		500	21.1	46.3	640	20.4	51.0
		520	21.0	46.8	660	20.3	51.8
		540	20.9	47.4	680	20.3	52.6
		546	20.9	47.6	700	20.2	53.4

Relative standard deviation: ±2%(Black Glass) ±1.5%(SiC290 and WTiC260) photoelectric comparison with standards at wavelengths of 403mμ, 438mμ, 504mμ, 544mμ, 593 mμ, and 615mμ.

A warming up period of 60 minutes was required to obtain a high degree of stability of the instrument. A well polished surface of specimen, cleaned with xylol, was placed on the stage, and was focussed exactly on a scartch-free part of the surface with the aid of minute imperfections outside the 40-micron circle. The section was then set at one of the extinction positions and the reflecting power was measured for this and the other extinction positions. The reflectivity data for the studied anisotropic minerals are based on a mean of measurements on a number of grains.

Cameron (1966) explained that the crystal symmetry of a given mineral can be partly determined from its optical properties, chiefly reflectivity and anisotropism or isotropism. For determination of optical symmetry, specimens containing numerous differently oriented grains of the relevant mineral were chosen, and bireflectance was measured at $\lambda=544\mathrm{m}\mu$ directly by rotating the mineral on the stage until readings for minimum (R_1) and maximum (R_2) reflectivity were obtained.

During the measurement, care was taken to avoid the slightest movement of the microscope when the interference filters or the polarizers or other devices were handled or the microscope stage was rotated. All specimens were immediately measured after polishing was complete to avoid tarnishing effects.

Measurement of microhardness

Microhardness tests for the studied minerals were made at the same portion on which the reflectivity was measured. The descent period of the diamond indenter was set at 15~20 sec. Testing loads from 25 to 300 grams were used and the load was maintained for about 30 sec. before being removed. The length of the impression diagonals was measured with a micrometer ocular at 400× total magnification. Vickers hardness values were calculated using the following formula.

$$\mathrm{HV}(\mathrm{kg/mm^2})=\frac{1854.4\times P}{d^2}$$

P : testing load in grams

d : length of the mean diagonal in microns

Each hardness number is the mean of three replicates per mineral. For precise results the instrument was perfectly leveled by a spirit level of $1:1,000=3'$ accuracy. The relative errors of the Miniload tester against the mean microhardness value of a test plate (Leitz) are ±1.5% at 15 grams and ±1.1% at 100 grams.

All measurements of reflectivity and microhardness were conducted in a vibrationless, clean, and slightly darkened laboratory at about 25°C.

ERRORS

In reflectivity measurements, there are numerous errors caused by the instrument, its operation, and also the specimen. Piller and Gehlen (1964) made a successful attempt to derive the fundamental constants of refraction and absorption from measurements of reflectivity. Leow (1966) has shown that where the specimen is of higher reflectivity than a standard an incremental error is introduced, while a decremental error occurs when a specimen is measured against a standard of higher reflectivity.

In this study, error was determined by comparing the true values of three standards against their measured values and Table 2 presents the tabulated results.

In Figure 4, the curve 1~4 represent the incremental error with respect to the reference diagonal (curve 5) indicating ideal conditions where no incremental error occurs. The incremental error is minimum in the green (544mμ) and increases toward violet, orange, and blue wavelengths. Leow (1966) explained that this

Table 2 Comparison of measured values(Rsp) of three standards with their true values(Rst).

λ(mμ)	Based on black glass as standard				Based on WTiC 260 as standard			
	SiC 290		WTiC 260		Black Glass		SiC 290	
	Rst(%)	Rsp(%)	Rst(%)	Rsp(%)	Rst(%)	Rsp(%)	Rst(%)	Rsp(%)
403	22.8	23.8	44.5	47.3	4.40	4.2	22.8	22.2
438	22.0	22.9	45.1	48.2	4.40	4.2	22.0	21.3
504	21.1	22.3	46.3	49.7	4.37	4.1	21.1	20.8
544	20.9	21.8	47.6	49.9	4.34	4.2	20.9	20.8
593	20.7	21.8	49.1	52.2	4.27	4.1	20.7	20.5
615	20.5	21.6	50.3	53.2	4.27	4.1	20.5	20.3

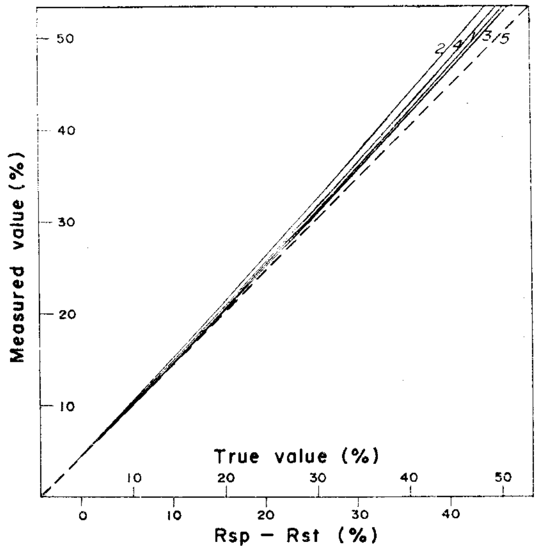


Fig. 4 Comparison of measured values with true values for SiC290 and WTiC260 measured against black glass. A scale for differences in R% between measured values of specimen (Rsp) and true values of standard (Rst) are shown. Curve 1 is the increment for 403mμ; curve 2 is the increment for 504mμ; curve 3 is the increment for 544mμ; curve 4 is the increment for 615mμ; curve 5 is the reference diagonal.

phenomena appears to be due to the antireflection blooming of the lenses being most effective in the middle of the spectrum.

Figure 5 indicates both incremental and decremental errors at different wavelengths against the difference between the true value of the standard and the measured value of the specimen. Decremental errors are considerably smaller than the corresponding incremental errors and both errors decrease toward 504mμ, 615mμ, and

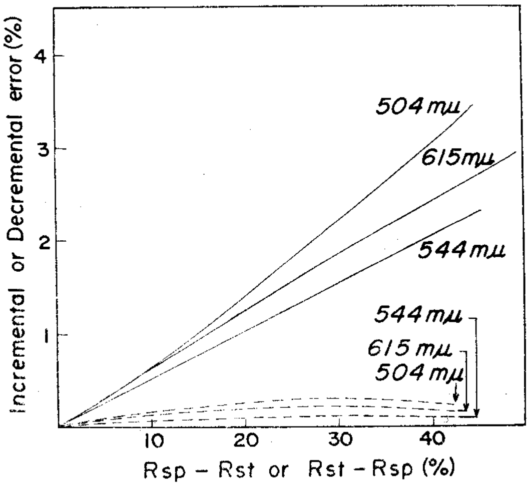


Fig. 5 The relationship between incremental (——) and decremental errors (······).

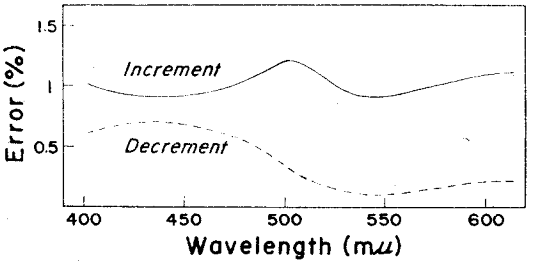


Fig. 6 Experimental curve for incremental and decremental errors in visible spectrum.
—— : incremental error for measuring SiC 290 against black glass
······ : decremental error for measuring SiC 290 against WTiC 260

Table 3 Spectral dispersion(R_1/R_2) of the studied anisotropic minerals in air.

Wavelength(mμ) Mineral	403 (violet)	438 (indigo)	504 (blue)	544 (green)	593 (yellow)	615 (orange)	Locality
Covellite	16.5/23.7	16.3/23.3	12.4/20.0	9.1/16.3	5.1/13.3	4.0/12.6	Bor/Yugoslavia
Graphite	7.0/17.6	7.0/17.5	7.0/18.0	7.1/18.8	7.0/18.6	7.3/19.3	Kropfmühl/W. Germany
Lievrite	9.0/10.3	9.0/10.2	8.3/10.0	8.0/10.0	7.0/9.8	6.7/9.6	Elba/Italy
Gratonite	39.2/40.0	37.6/38.4	36.4/36.9	36.0/36.6	36.5/37.0	35.9/36.4	Wiesloch/Tunesia
Jordanite	40.0/42.0	38.6/40.3	37.8/39.4	37.2/38.5	36.4/37.3	36.0/37.0	Wiesloch/Tunesia
Enargite(//)	32.1/33.0	32.2/33.1	30.5/30.9	29.5/29.9	28.4/28.7	27.7/28.4	Tsumeb/S-W Africa
Enargite(⊥)	27.5/28.2	27.3/28.1	26.2/26.9	25.3/26.1	25.0/26.4	24.9/26.3	Tsumeb/S-W Africa
Enargite(U)	28.3/29.5	27.4/28.5	26.3/27.2	25.8/26.9	25.1/26.8	25.3/27.3	Butte/Montana, U.S.A.
Famatinite(//)	31.0/33.3	29.9/32.3	28.4/31.0	27.6/30.0	26.9/29.5	26.7/29.0	Magma/Arizona, U.S.A.
Famatinite(⊥)	27.0/29.2	26.1/28.1	26.0/27.4	25.3/26.8	25.1/26.8	25.0/26.7	Magma/Arizona, U.S.A.

// : parallel to cleavage ⊥ : normal to cleavage U : unoriented section

544mμ.

Figure 6 shows similar results.

The results are in good agreement with those of Leow (1966). Consequently, use of a standard of higher rather than lower reflectivity with respect to the specimen is desirable in reflectivity measurement.

DEPENDENCE OF WHITE LIGHT COLOR ON SPECTRAL PROFILES

The spectral reflectivities of oriented and unoriented anisotropic minerals studied are given in Table 3.

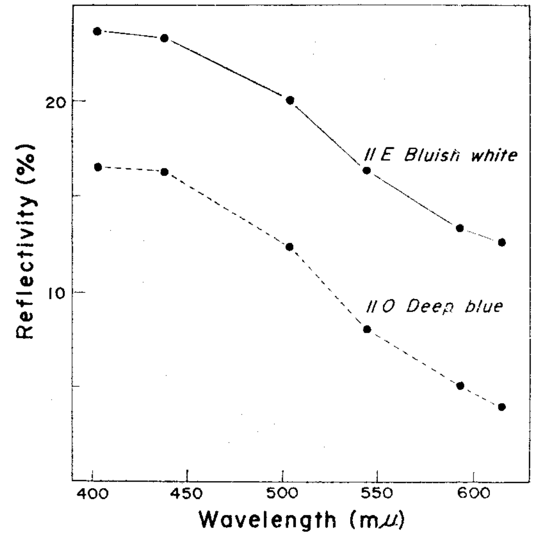


Fig. 7 Spectral profiles for covellite from Bor/Yugoslavia.

Lower symmetry minerals are bireflecting except for sections at 90° to the optic axis(uniaxial minerals) or rotation axes(biaxial minerals). These minerals show a range of reflectivity defined by two spectral profiles. When each principal direction of an anisotropic species is parallel to the vibration of the incident light, the white light color of the mineral depends on the magnitude and shape of the spectral profile while the reflection pleochroism obtained when the section is rotated depends on the differences in magnitude and shape of the two profiles (Gray and Millman, 1962). The covellite and graphite crystals studied have reflectivity profiles similar in shape for each principal direction, showing noticeable difference in magnitude between the profiles. The resulting colors in reflected light for each principal direction are similar in tint, though different in intensity. The spectral reflectivity of covellite parallel to the extraordinary vibration is higher than that parallel to the ordinary vibration and shows a progressive decrease towards orange wavelengths. Under the microscope the O-vibration appears deep blue while the E-vibration looks bluish white (Fig. 7). On the other hand, graphite shows flat pro-

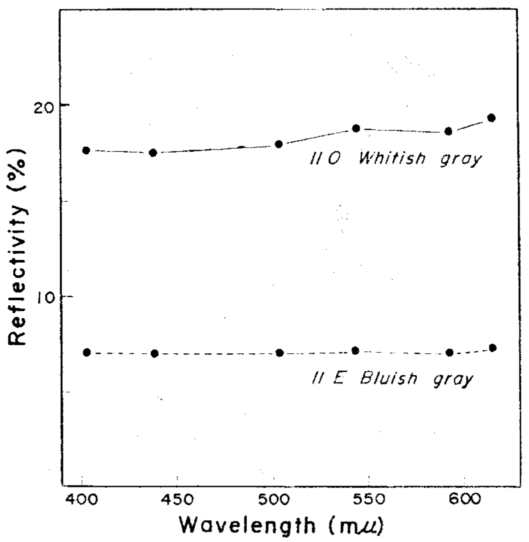


Fig. 8 Spectral profiles for graphite from Kropfmühl/West Germany.

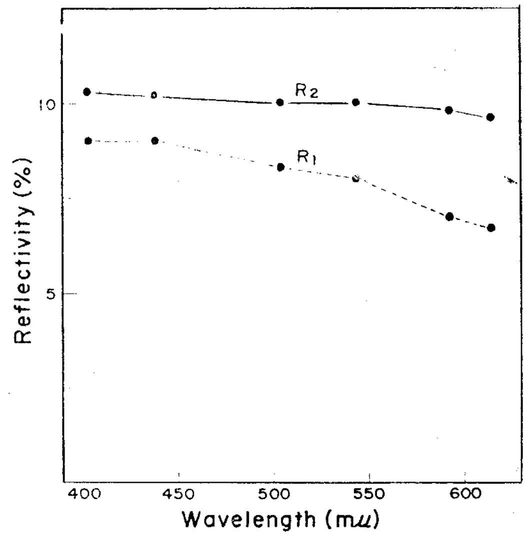


Fig. 9 Spectral profiles for lievrite from Elba/Italy.
R_1: minimum spectral dispersion
R_2: maximum spectral dispersion

files, colored whitish gray parallel to O-ray and bluish gray parallel to E-ray (Fig. 8).

Lievrite, with relatively flat profiles, appears pinkish gray (R_2) to bluish gray (R_1) in white light illumination and indicates a higher bireflectance in the yellow-orange wavelengths (Fig. 9).

The reflection behavior of jordanite is similar to that of gratonite. The studied jordanite and gratonite, white with grayish-tint and white with yellowish-tint under the microscope, decrease in reflectivity towards orange wavelengths. Jordanite has slightly higher reflectivity than gratonite (Fig. 10).

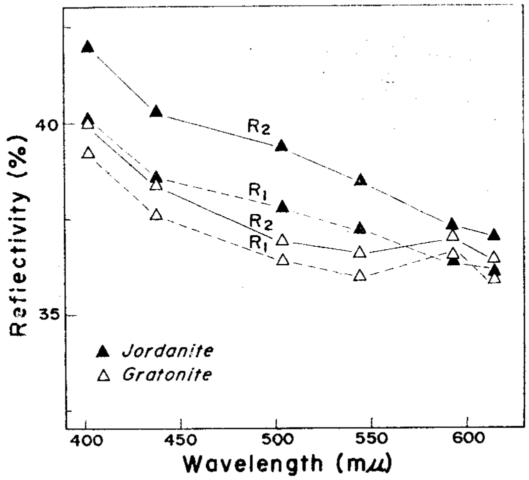


Fig. 10 Spectral porfiles for jordanite and gratonite from Wiesloch/Tunisia.
R_1: minimum spectral dispersion
R_2: maximum spectral dispersion

Distinguishing the minerals enargite and famatinite entails very appreciable difficulties, because these minerals are almost always associated and paramorphically transformed into one another, and isomorphic mixtures are possible under certain conditions of formation (Ramdohr, 1969). There are marked variations in the reflectivity values quoted for enargite and famatinite by different workers (Folinsbee, 1949; Gray and Millman, 1962; Cameron, 1963 and 1966). In the studied enargite and famatinite, it can be seen that reflectivity of the section cut parallel to the cleavage plane is always higher than that of the section cut normal. The spectral reflectivity obtained from an unoriented section of enargite is intermediate between the values for the sections cut ⊥ and // to the cleavage plane. Both enargite and famatinite, each colored grayish white and brown to gray in white

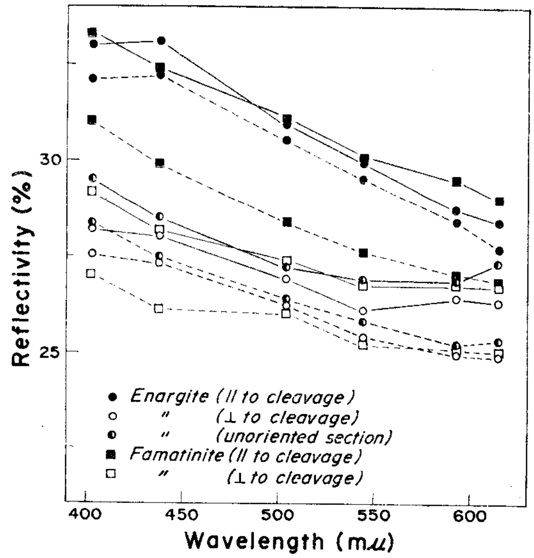


Fig. 11 Spectral profiles of enargite from Tsumeb/South-West Africa and Butte/Montana, U.S.A., and famatinite from Magma/Arizona, U.S.A.
—— : maximum spectral dispersion
…… : minimum spectral dispersion

light illumination, show progressively decreasing profiles towards the orange wavelength. The bireflectance of famatinite is greater than that of the enargite (Fig. 11).

DETERMINATION OF OPTICAL SYMMETRY FROM REFLECTIVITY MEASUREMENTS

The optical symmetry of 5 bireflecting minerals was determined by noting the variation in reflectivity at 544mμ. A determination procedure similar to that described by Cameron (1963) was adopted.

Uniaxial minerals

Random sections of a uniaxial mineral always give one constant value of reflectivity parallel to O(Rω, containing the a axes), and one variable value corresponding to E or E′(Re or Re′); basal sections give a single constant value. The sign is also apparent according to whether the constant reflectivity value, Rω (⊥c), is greater or less than the other values Re or Re′ parallel to or at intermediate angles with the c axis trace; when Rω>Re′, the mineral is optically negative, and vice versa.

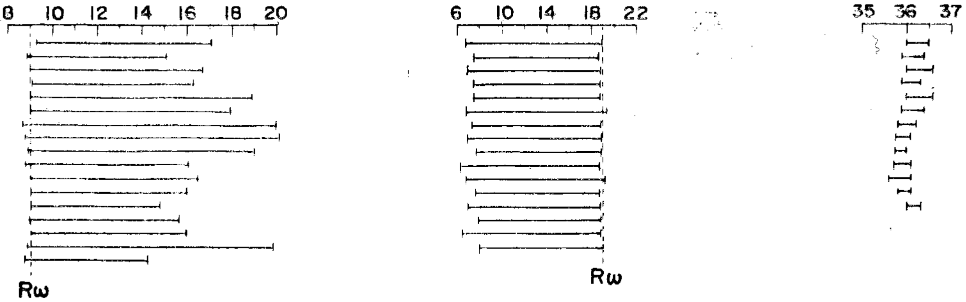
Table 4 Reflectivity measurements of the studied covellite and graphite at 544mμ.

Grain No.	Covellite		Graphite	
	Re′	Rω	Re′	Rω
1	17.1	9.2	6.9	19.0
2	15.1	8.6	7.5	18.7
3	16.7	9.0	7.0	18.8
4	16.3	9.1	7.2	18.9
5	18.9	9.0	7.6	18.9
6	18.0	9.0	6.8	19.3
7	20.0	9.0	7.0	19.0
8	20.1	8.8	6.5	19.0
9	19.0	8.9	7.7	19.0
10	16.1	8.8	6.3	18.9
11	16.5	9.0	6.8	19.1
12	16.0	9.0	7.5	18.9
13	15.7	9.0	7.1	18.9
14	14.8	9.1	7.8	18.8
15	17.0	9.0	6.4	18.8
16	19.9	8.9	7.9	18.9
17	14.2	8.8		
Mean Rω	9.0		18.9	
Mean deviation Rω	0.08		0.09	
Range Re′	14.2~20.1		6.3~7.9	
Optic sign	(+)		(−)	

Rω: reflectivity for O ray
Re′: reflectivity for E ray

Data (in percent) for 17 covellite grains studied are Rω=8.8−9.2; mean Rω=9.0; mean deviation of Rω=0.08; Re′=14.2−20.1. Corresponding data for 16 graphite grains are Rω=18.7−19.3; mean Rω=18.9; mean deviation of Rω=0.09; Re′=6.3−7.9. The data indicate that covellite is optically positive and graphite is optically negative (Table 4 and Fig. 12).

This method can not be applied to minerals of extremely low bireflectance such as gratonite represented in Figure 12c.



(a) Covellite (b) Graphite (c) Gratonite

Fig. 12 Reflectivities of diversely oriented grains of covellite, graphite, and gratonite. Scales give reflectivities in percent.

Table 5 Vickers hardness values for the studied anisotropic minerals.

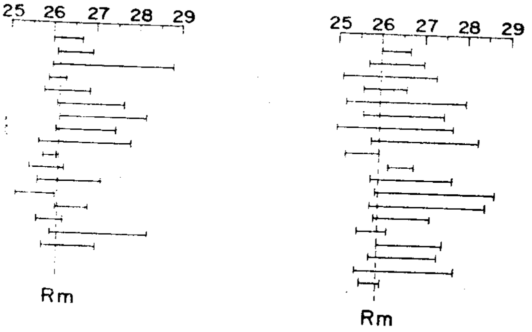
Mineral		Weights applied in grams					Mean (HV)	Locality
		25	50	100	200	300		
Covellite	m	20.7	31.8	42.3	74.2	86.8		Bor/Yugoslavia
	HV	108.2	91.7	103.6	67.4	73.8	88.9	
Graphite	m	37.0	62.6	93.5	138.6	182.5		Kropfmühl/W.Germany
	HV	33.9	23.7	21.2	19.3	16.7	23.0	
Lievrite	m	7.3	10.5	15.9	23.0	28.2		Elba/Italy
	HV	870.0	841.0	733.5	701.1	699.6	769.0	
Gratonite	m	16.7	25.2	36.1	52.0	66.6		Wiesloch/Tunesia
	HV	166.2	146.0	142.3	137.2	125.4	143.4	
Jordanite	m	15.9	22.4	31.6	45.8	56.9		〃
	HV	183.4	184.8	185.7	176.8	171.8	180.5	
Enargite(//)	m	12.4	17.4	24.8	37.1	45.9		Tsumeb/S-W Africa
	HV	301.5	306.2	301.5	269.5	264.1	288.6	
〃 (⊥)	m	21.0	29.2	40.6	61.7	78.0		〃
	HV	105.1	108.7	112.5	97.4	91.4	103.0	
〃 (U)	m	12.8	18.0	25.0	38.1	46.8		Butte/Montana, U.S.A.
	HV	283.0	286.2	296.7	255.5	254.0	266.1	
Famatinite(//)	m	11.1	15.3	23.6	33.8	43.3		Magma/Arizona, U.S.A.
	HV	376.3	396.1	333.0	324.6	296.7	345.3	
〃 (⊥)	m	19.3	25.6	37.9	58.9	69.9		〃
	HV	124.5	141.5	129.1	106.9	113.9	123.2	

m=length of Vickers diagonal in microns
//=parallel to cleavage
U=unoriented section

HV=Vickers hardness in kg/mm^2
⊥=normal to cleavage

Minerals of lower symmetry

In Figure 13, the individual line gives the reflectivity value of R_1 and R_2 for the each grain of enargite and famatinite, and the measurements indicate that for both of the minerals R_1 or R_2 are not constant. Enargite (17 grains) indicates that they give of non-uniaxial character and shows a value of R_1 that is equal to or less than 26. 2±0. 1 and a value of R_2 that is either equal to or greater than 26. 2±0. 1. Famatinite (19 grains) shows a value of $R_1 \leqq 26.0 \pm 0.2$, and $R_2 \geqq 26.0 \pm 0.2$. These values were taken as the Rm value. The Rm values for enargite and famatinite are clearly closer to the minimum value for the mineral(R_1) than to the maximum value (R_2): the minerals can be indicated as optically positive.



(a) Enargite (b) Famatinite

Fig. 13 Reflectivities of diversely oriented grains of enargite and famatinite.
Scales give reflectivities in percent.

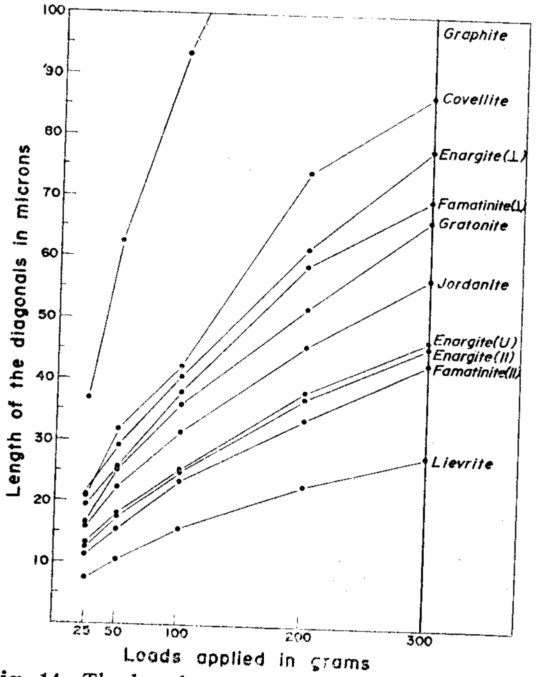


Fig. 14 The length variation of the diagonals from Vickers indentation on the studied minerals with various test loads.
//: parallel to cleavage
⊥: normal to cleavage
U: unoriented section

MICROHARDNESS AND ITS RELATIONSHIP TO REFLECTIVITY

The Vickers hardness of seven different mineral species was determined by applying various testing loads ranging from 25 to 300 grams. The data obtained are presented in Table 5, and graphically shown in Figure 14 and 15.

Figure 14 shows the relation between the length of the diagonals of Vickers indentations,

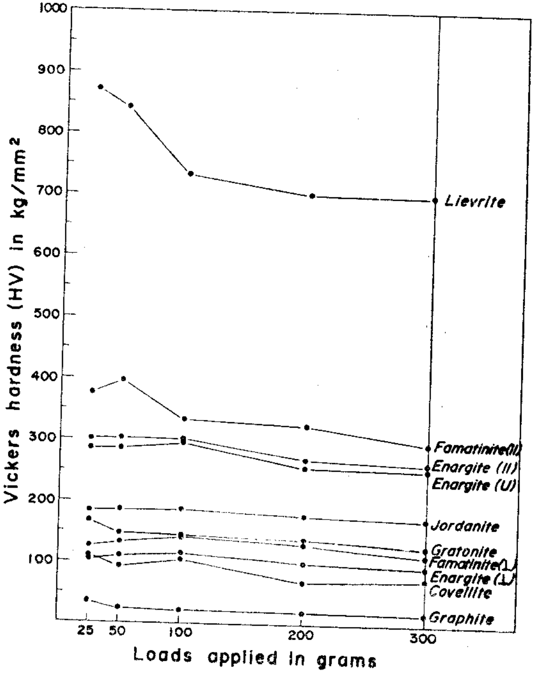


Fig. 15 Variation of Vickers hardness for the studied minerals in relation to the testing loads.
//: parallel to cleavage
⊥: normal to cleavage
U: unoriented section

measured in microns, and the various testing loads applied in grams. The gradients of the lines increase progressively from the hardest lievrite to the softest graphite.

Figure 15 illustrates the relation between Vickers hardness (kg/mm²) of the studied minerals in relation to the test load. The hardness numbers of the mineral are more variable at applying loads of 25 and 50 grams than heavier weights. Harder minerals show more irregular profiles than soft minerals.

Enargite and famatinite cut parallel to clevage

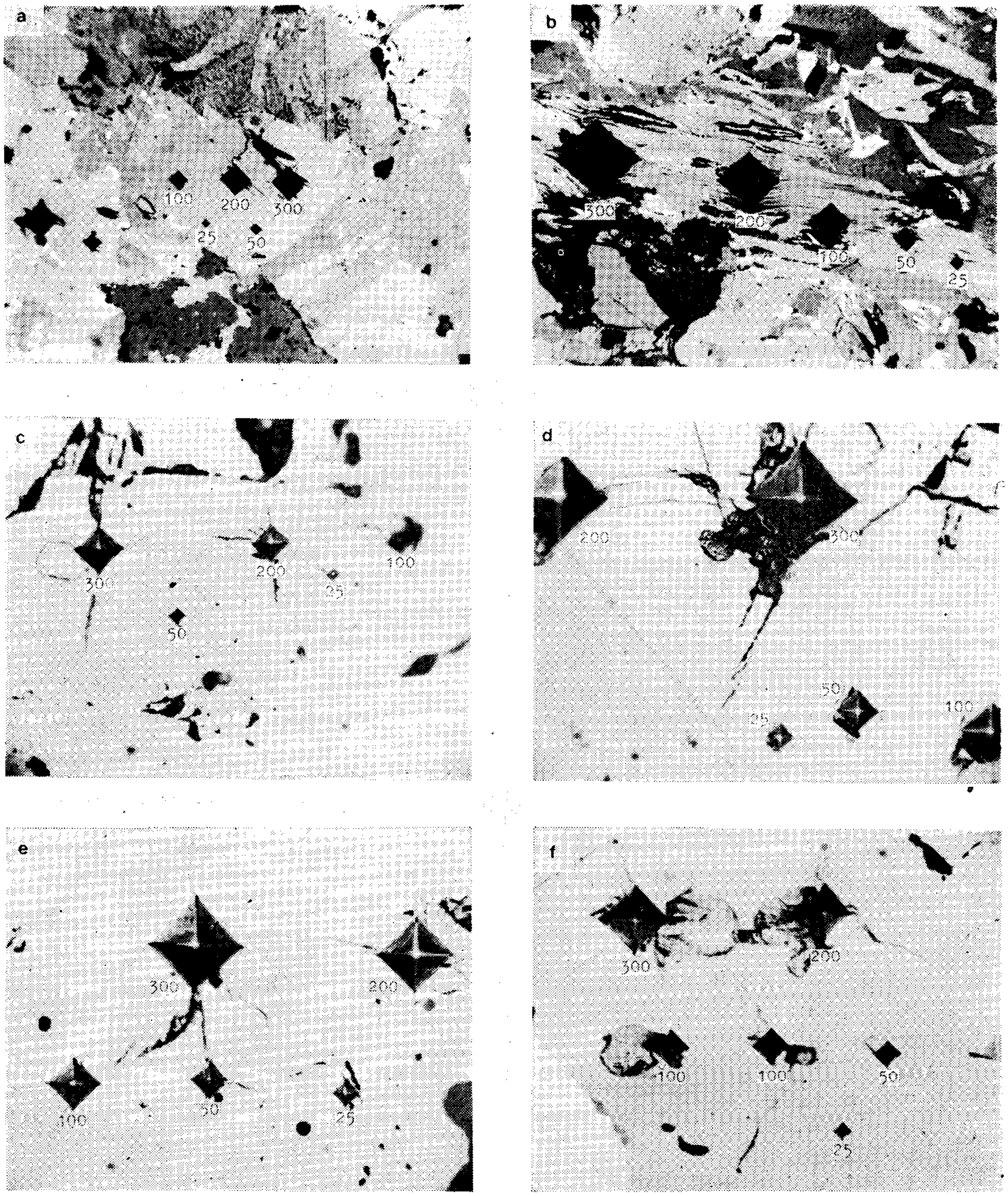


Fig. 16 Vicker's indentations made on the studied mineral species and cracks of varying form around them,
(a) Covellite(×95) (b) Graphite(×95) (c) Lievrite(×380)
(d) Gratonite(×380) (e) Jordanite(×380) (f) Enargite(×380)

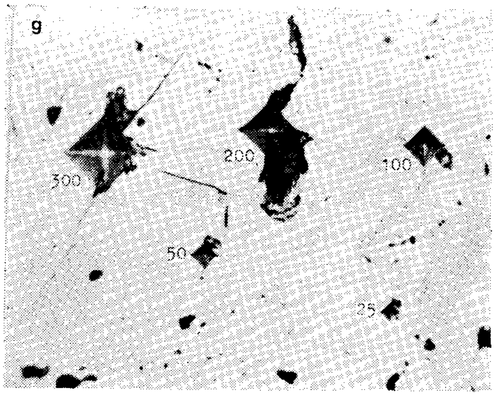


Fig. 16 Continued. (g) Famatinite(×380)

have much higher hardness values than those cut normal to cleavage. Robertson and Van Meter (1951) suggested that anisotropic minerals show marked differences in hardness with respect to the orientation of the indentation with the crystallographic axes.

Figure 16 shows the Vickers indentation made on the polished sections with variable testing weights. Hard minerals, gratonite, enargite, and famatinite produced large, shell-shaped cracks on applying loads of 100, 200, and 300 grams (Fig. 16d, f, and g).

Fine cracks resulted in lievrite and jordanite from all the test weights (Fig. 16c and e). Graphite tends to flow along the cleavage planes and partially obliterate the limits of the indentations (Fig. 16b). The Vickers hardness numbers for all the studied anisotropic minerals may be of diagnostic value on applying loads ranging from 100 to 300 grams.

The broader aspects of reflection phenomena in the studied bireflecting minerals are represented in the form of a reflectivity-microhardness plot after Gray and Millman (1962). The tested sulphide, oxides, sulphosalts, and silicates were clearly plotted in the corresponding area respectively except graphite (Fig. 17).

In Figure 18, 615mμ reflectivity ranges were plotted against the mean microhardness values, and were with the exception of covellite, gratonite, and famatinite, in good agreement to the results outlined by Gray and Millman (1962).

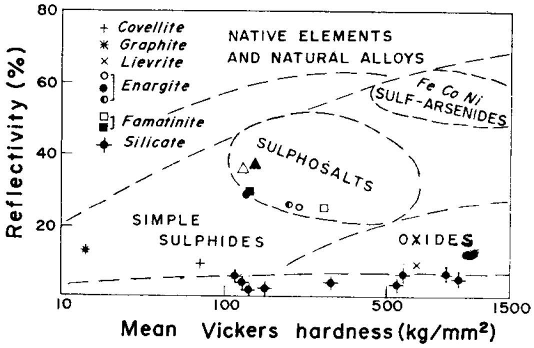


Fig. 17 Reflectivity-microhardness values of the studied minerals plotted on the grouping areas after Gray and Millman (1962).

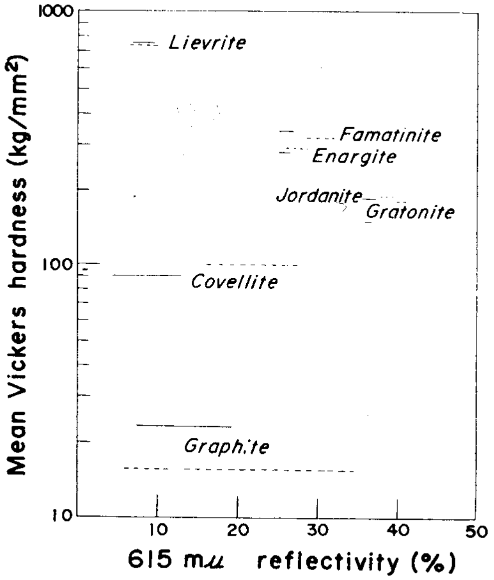


Fig. 18 Plot of mean microhardness values and 615 mμ reflectivity ranges.
—— : present study
······ : data after Gray and Millman (1962)

ACKNOWLEDGEMENTS

The research for this paper was financially supported by 1984 program of Asan Foundation.

REFERENCES

Bowie S.H.U. and Henry N.F.M. (1964) Quantitative Measurements with the Reflecting Polarizing Microscope. Trans. Inst. Mining & Metall., v. 73, p.

467-478.

Cameron E.N. (1963) Optical Symmetry from Reflectivity Measurements. Am. Mineral., v. 48, p.1070-1079.

Cameron E.N. (1966) Ore Microscopy. John Wiley & Sons Inc., New York, p. 293.

Folinsbee R.E. (1949) Determination of Reflectivity of the Ore Minerals. Econ. Geol., v. 44, p.425-436.

Gray I.M. and Millman A.P. (1962) Reflection Characteristics of Ore Minerals. Econ. Geol., v. 57, p. 325-349.

Leow J.H. (1966) Reflectivity Measurements on Molybdenite. Econ. Geol., v. 61, p.598-612.

Piller H. and Gehlen K.V. (1964) On Errors of Reflectivity Measurements and of Calculation of Refractive Index n and Absorption Coefficient k. Am. Mineral., v. 49, p.867-882.

Ramdohr, P. (1969) Die Erzmineralien und ihre Verwachsungen. XV+1089S., 688 Abb., Berin (Akademie-Verlag).

Robertson F. and Van Meter W.J. (1951) The Kentron Microhardness Tester, A Quantitative Tool in Opaque Mineral Identification. Econ. Geol., v. 46, p.541-550.

So, C.S., Kim, I.K. and Kim, D.H. (1980) Spectral Reflectivity and Microhardness of Some Anisotropic Ore Minerals from Sulfide and Iron Deposits, Korea. Jour. Geol. Soc. Korea, v. 16, p.16-31.

So, C.S. and Song S.H. (1981) Physical Properties of Korean Ore Sulfide Species. Jour. Geol. Soc. Korea, v. 17, o. 1, p.1-14.

So, C.S., Lee S.M. and Doh S.J. (1982) Reflection-Microhardness Characteristics and Optical Symmetry of Some Ore Minerals. Jour. Geol. Soc. Korea, v. 18, p.55-66.

So, C.S. and Jang, Y.N. (1984) Reflection-Microhardness Characteristics and Geneses of Sphalerites from Pb-Zn Deposits in Korea. Jour. Geol. Soc. Korea, v. 20, p.28-40.

So, C.S. and Lee, H.S. (1985) Spectral Reflection, and Its Relationship to Microhardness, Composition and Geneses of Magnetites from Iron Deposits in Korea. Jour. Geol. Soc. Korea, v. 21, No. 2, p. 109-124.

異方性 資源鑛物의 物性 및 光學的 對稱性 硏究

蘇七燮*·都城宰**·李慶鎔*

요약 : 본 논문에서는 세계적으로 유명한 대규모의 黃化鑛床에서 산출되는 7종의 異方性 鑛石鑛物을 대상으로 物理的 特性을 실험 연구하고, 鑛物 고유의 他光學性, 結晶方向과의 상관 관계를 밝히며, 금속자원 광물의 鑑定을 위한 자료를 제시하고자 시도되었다.

연구대상 異方性 鑛物(covellite, graphite)은 광물상호간의 white light color의 차이 뿐아니라 同種鑛物내부의 두 偏光(常光線, 異常光線)의 방향에 따라 동일한 형태이나 큰 정량적 차이(R=약 10%)를 보여주는 spectral profile을 갖는다. 結晶方向에 따라 고찰된 異方性 鑛物(enargite, famatinite)의 反射力은 벽개면에 평행한 면에서 항상 높은 값(R=약 5%)을 갖는다. 측정 反射力을 이용하여 규명된 연구 광물종의 光學的 對稱性은 covellite가 一軸性(+), graphite는 一軸性(—)이고, enargite와 famatinite는 二軸性(+)이며, 複反射力이 낮은 gratonite의 경우는 결정이 불가능하였다. 표준하중별로 실시된 微硬度실험에서 異方性鑛物(enargite, famatinite)의 결정방향은 큰 영향을 미치는데, 즉 벽개면에 평행한 면에서 항상 높은 (HV=>200kg/mm^2) 微硬度값을 보여준다. 모든 실험광물이 각각 특정적인 indentation의 형태를 갖음은 微硬度와 함께 鑛物鑑定에 유용할 것이다. 실험광물이 최소하중에서 항상 불규칙한 微硬度값을 갖는 것은 관찰에서 기인되는 측정오차로 사료된다. 微硬度—反射力의 상관 관계를 이용한 시험광물의 분류는 Gray-Millman(1962)의 실험결과와 일치된다. 한편 反射度의 파장별 측정오차와 그의 제거 방안이 논의되었다.

---

* 高麗大學校 地質學科

** Rhode Island大學校 海洋學科