ON THE MEASUREMENT OF OPTICAL ANISOTROPY BY POLARIZED LIGHT MICROSCOPY OF GRAPHITE AND DEPOSITS OF PYROLYTIC CARBON

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Introduction

Polarized light microscopy (PLM) is a well established technique for the assessment of the degree of preferred orientation of circular-shaped (layer on a fiber) deposits of pyrolytic carbon [1,2]. The corresponding quantification of optical anisotropy is performed by the determination of the analyzer position, denoted as extinction angle, where the coalescence of the dark arms of a Maltese-shaped intensity pattern occurs (Fig.1). The measured extinction angles A_e (Fig.2) for deposits with circular morphology can be as high as 24° [3,4] which is, however, significantly higher than the calculated value of 16.3° reported for graphite [5]. The present contribution aims to explain this contradiction.

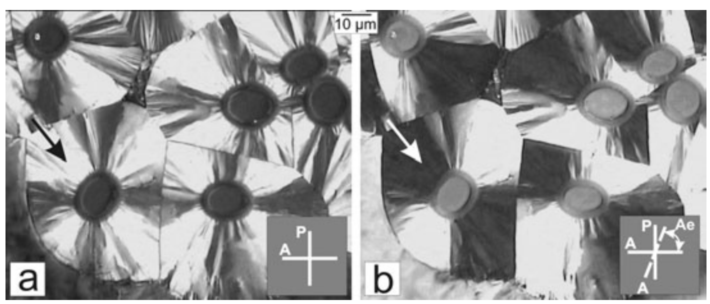

Figure 1. *Light micrographs of a polished section of an infiltrated carbon fiber felt taken under crossed (a) and uncrossed polars (b). The analyzer (A) is rotated with respect to the polarizer (P). A_e value is defined until the darkest image appears within the area marked by arrows.*

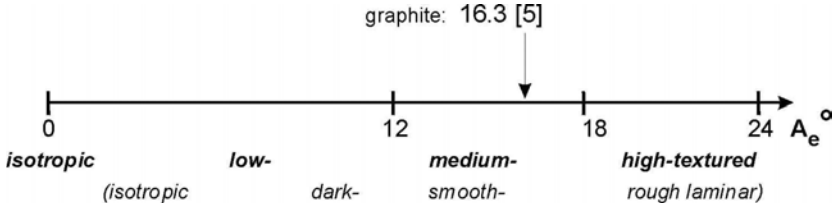

Figure 2. *Values of extinction angle for different types of pyrolytic carbon deposits and for single crystalline graphite. Brackets: terminology used in [5].*

Results and Discussion

The contradiction mentioned above is resolved if two different phenomena in polarized light are distinguished: *extinction* and *coalescence* (Fig.3).

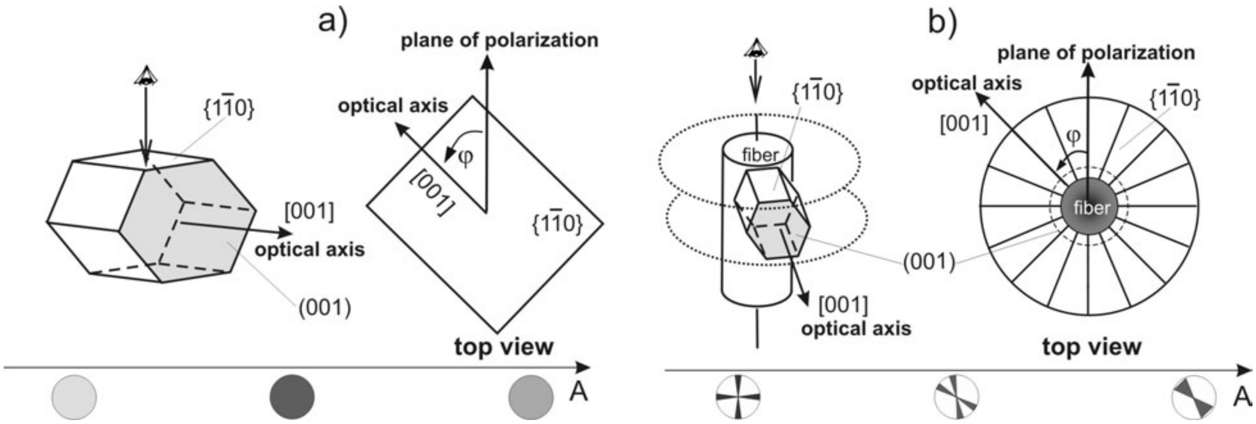

Figure 3. *Optical models of a single crystal (a) and circular deposit (b) in relation to the light normally incident on prismatic planes. The relative changes in PLM image in the dependence on the analyzer position (A) is shown schematically at the bottom.*

In the case of the prismatic {110} plane of graphite (Fig.3a), the optical axis forms an angle φ with the plane of polarization of the normally incident light (top view). This angle is constant for the whole sample surface, as it is fixed by the direction of the optical axis. The brightness of the reflected light observed through an analyzer is uniform and can be changed by rotation of the crystal or the analyzer (Fig.3, bottom). The extinction angle Ae measured in this case is the angle of analyzer uncrossing to the position of the minimal observed brightness and according to [6] can be expressed as following:

$$\cot 2(A_e + \varphi) = \frac{(R_o/R_e)\sin^2\varphi - \cos^2\varphi}{\sqrt{R_o/R_e}\,\cos\Delta\sin 2\varphi} \qquad (1)$$

where Ro and Re are intensity reflection coefficients for ordinary and extraordinary rays, respectively; Δ is the phase shift between Fresnel (amplitude) reflection coefficients [6,7]. Taking Δ=26.7^0 for graphite calculated from optical constansts[8], the minimal observed brightness, i.e. the light extinction occurs at A_e=17.9^0. This value corresponds to the sample setting with its optical axis inclined by the angle φ = –45^0 to the plane of polarization of the incident light.

For the case of circular shaped objects (Fig.1 and Fig.3b) the brightness around the fiber is a periodical function of the angle φ (Fig.3, top view) and depends only on the analyzer position. Correspondingly, the completely another expression should be used

[6,7] for the calculation of the *coalescence* angle Ac corresponding to the analyzer uncrossing at which two minima coalescence (Fig.1b and Fig.3, bottom):

$$\sin Ac = \pm \frac{R_o - 2\sqrt{R_o R_e}\cos\Delta + R_e}{R_o - R_e} \qquad (2)$$

The calculated coalescence angle Ac=27.4°. This value is consistent with the measured values for circular-shaped deposits of pyrolytic graphite [4] and pyrolytic carbon [3,5,9,10] exhibiting the highest optical anisotropy.
The presented considerations demonstrate that different morphologies of the same graphite-like material demand different analytical expressions for calculation of light changes observed by PLM. In spite of the common name "extinction angle", the obtained values of such angles cannot be compared directly. Therefore, a correlation between Ac and Ae should be taking into account as it schematically shown in Fig. 4.

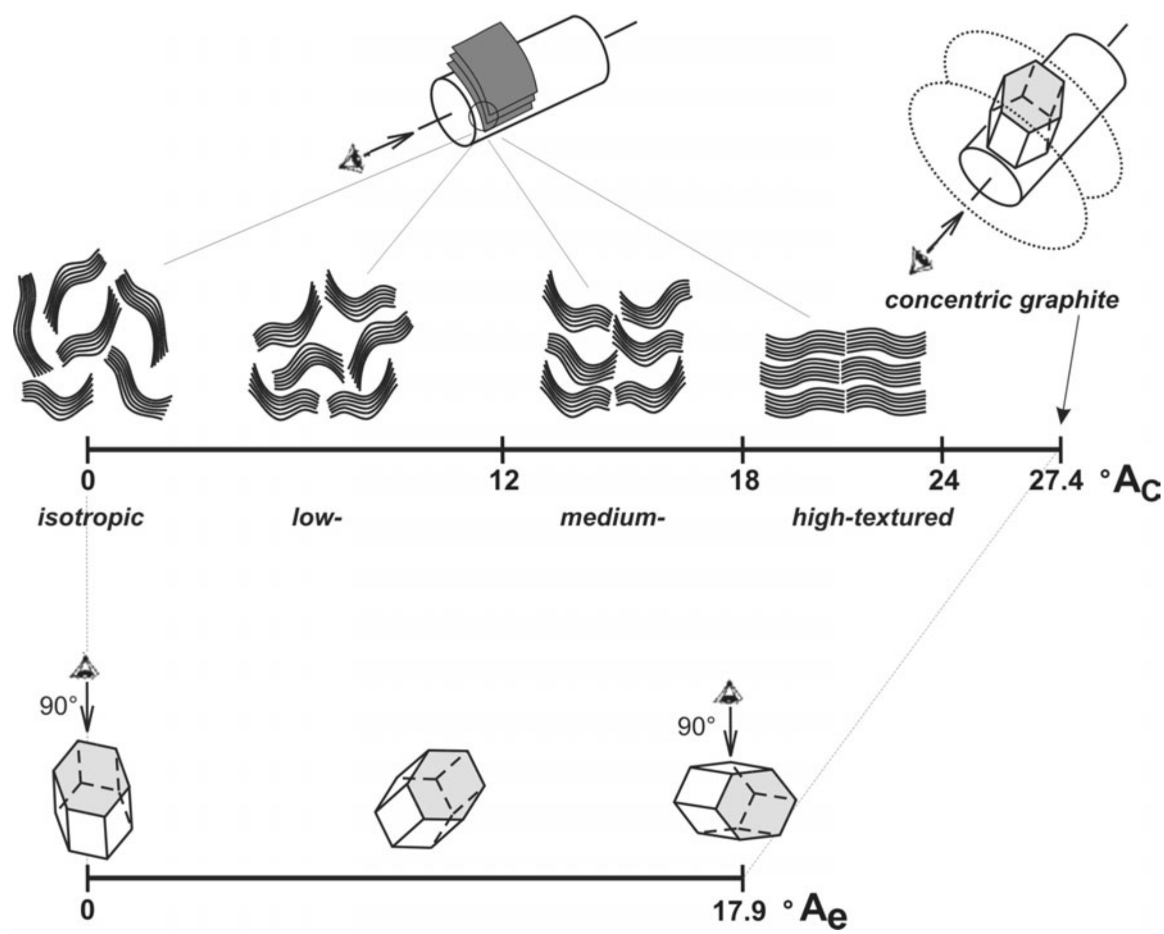

Figure 4. Correlation between the *coalescence* angle A_c measured for circular deposits (top) and *extinction* angle A_e measured for single crystalline graphite (bottom).

Conclusions

1. The discrepancy between values of optical anisotropy of crystalline graphite and pyrolytic carbon deposits is clarified.

2. Two different types of light changes are proposed to distinguished: *extinction* and *coalescence*, giving A_e values for planar and Ac values for circular deposits, respectively. Correspondingly, expressions describing light intensity transmitted through an analyzer for different shapes of pyrolytic carbon deposits are obtained.

3. The calculated *extinction* angle A_e value for graphite with optical constants [8] is A_e = 17.9°.

4. The calculated *coalescence* angle Ac value for circular shaped deposits is Ac = 27.4°. This maximal value hypothetically anticipates a crystalline graphite wrapped around a fiber-like core with radially oriented prismatic planes.

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ACKNOWLEDGEMENTS

The present study was performed in the Center of Excellence 551 in Research on "Carbon from the gas phase: elementary reactions, structures, materials". The financial support of the German Research Foundation (DFG) is gratefully acknowledged.