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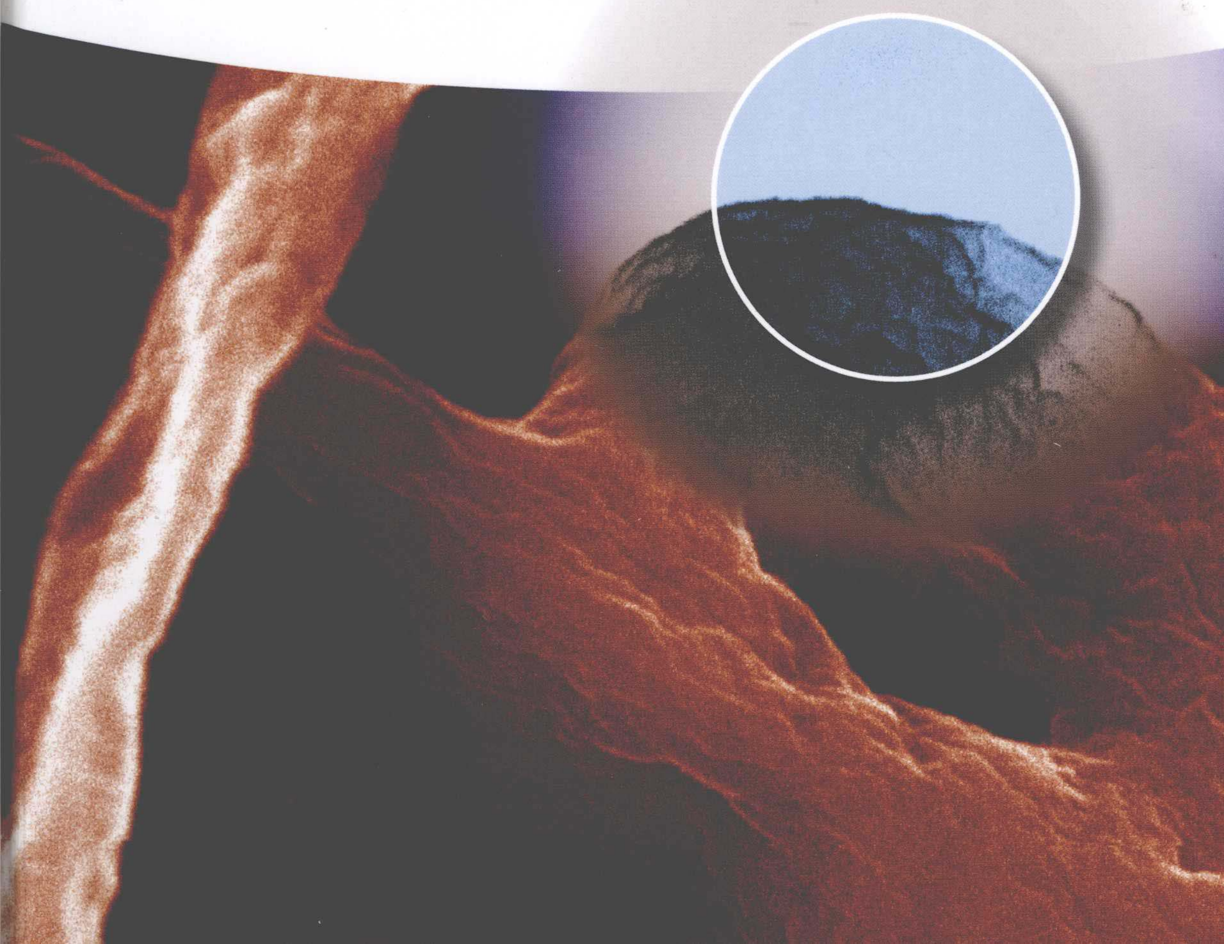
Materials Characterization

Introduction to Microscopic and Spectroscopic Methods

Second Edition



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Contents

1
Light Microscopy

Light or optical microscopy is the primary means for scientists and engineers to examine the microstructure of materials. The history of using a light microscope for microstructural examination of materials can be traced back to the 1880s. Since then, light microscopy has been widely used by metallurgists to examine metallic materials. Light microscopy for metallurgists became a special field named *metallography*. The basic techniques developed in metallography are not only used for examining metals, but also are used for examining ceramics and polymers. In this chapter, light microscopy is introduced as a basic tool for microstructural examination of materials including metals, ceramics, and polymers.

1.1
Optical Principles

1.1.1
Image Formation

Reviewing the optical principles of microscopes should be the first step to understanding light microscopy. The optical principles of microscopes include image formation, magnification, and resolution. Image formation can be illustrated by the behavior of a light path in a compound light microscope as shown in Figure 1.1. A specimen (*object*) is placed at position A where it is between one and two focal lengths from an *objective lens*. Light rays from the object first converge at the objective lens and are then focused at position B to form a magnified inverted image. The light rays from the image are further converged by the second lens (*projector lens*) to form a final magnified image of an object at C.

The light path shown in Figure 1.1 generates the real image at C on a screen or camera film, which is not what we see with our eyes. Only a real image can be formed on a screen and photographed. When we examine microstructure with our eyes, the light path in a microscope goes through an *eyepiece* instead of projector lens to form a *virtual image* on the human eye retina, as shown in Figure 1.2. The virtual image is inverted with respect to the object. The virtual image is often adjusted to be located as the minimum distance of eye focus, which is conventionally taken

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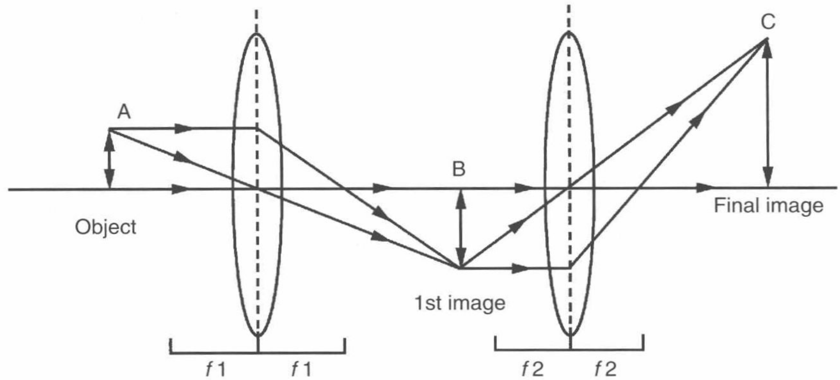

Figure 1.1 Principles of magnification in a microscope.

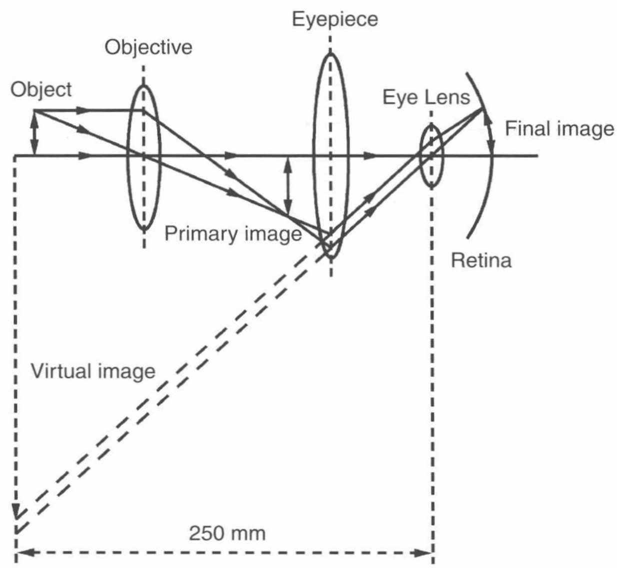

Figure 1.2 Schematic path of light in a microscope with an eyepiece. The virtual image is reviewed by a human eye composed of the eye lens and retina.

as 250 mm from the eyepiece. A modern microscope is commonly equipped with a device to switch from eyepiece to projector lens for either recording images on photographic film or sending images to a computer screen.

Advanced microscopes made since 1980 have a more complicated optical arrangement called "*infinity-corrected*" optics. The objective lens of these microscopes generates parallel beams from a point on the object. A tube lens is added between the objective and eyepiece to focus the parallel beams to form an image on a plane, which is further viewed and enlarged by the eyepiece.

The magnification of a microscope can be calculated by linear optics, which tells us the magnification of a convergent lens, M:

$$M = \frac{\nu - f}{f} \tag{1.1}$$

where f is the focal length of the lens and ν is the distance between the image and lens. A higher magnification lens has a shorter focal length, as indicated by Eq. (1.1). The total magnification of a compound microscope as shown in Figure 1.1 should be the magnification of the objective lens multiplied by that of the projector lens.

$$M = M_1 M_2 \frac{(\nu_1 - f_1)(\nu_2 - f_2)}{f_1 f_2} \tag{1.2}$$

When an eyepiece is used, the total magnification should be the objective lens magnification multiplied by the eyepiece magnification.

1.1.2 Resolution

We naturally ask whether there is any limitation for magnification in light microscopes because Eq. (1.2) suggests there is no limitation. However, meaningful magnification of a light microscope is limited by its *resolution*. Resolution refers to the minimum distance between two points at which they can be visibly distinguished as two points. The resolution of a microscope is theoretically controlled by the diffraction of light.

Light diffraction controlling the resolution of microscope can be illustrated with the images of two self-luminous point objects. When the point object is magnified, its image is a central spot (the *Airy disk*) surrounded by a series of diffraction rings (Figure 1.3), not a single spot. To distinguish between two such point objects separated by a short distance, the Airy disks should not severely overlap each other. Thus, controlling the size of the Airy disk is the key to controlling resolution. The size of the Airy disk (d) is related to the wavelength of light (λ) and the angle of light coming into the lens. The *resolution of a microscope* (R) is defined as the minimum distance between two Airy disks that can be distinguished (Figure 1.4). Resolution is a function of microscope parameters as shown in the following equation:

$$R = \frac{d}{2} = \frac{0.61\lambda}{\mu \sin\alpha} \tag{1.3}$$

where μ is the refractive index of the medium between the object and objective lens and α is the half-angle of the cone of light entering the objective lens (Figure 1.5). The product, $\mu \sin\alpha$, is called the *numerical aperture* (NA).

According to Eq. (1.3), to achieve higher resolution we should use shorter-wavelength light and larger NA. The shortest wavelength of visible light is about 400 nm, while the NA of the lens depends on α and the medium between the

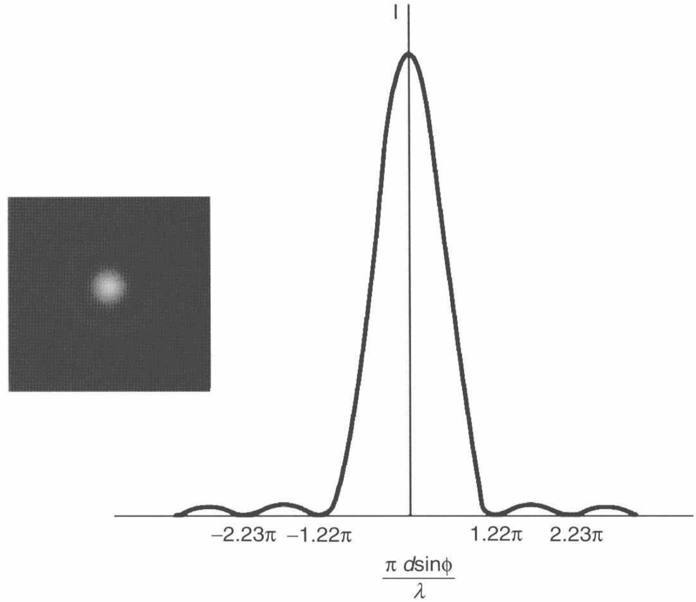

Figure 1.3 A self-luminous point object and the light-intensity distribution along a line passing through its center.

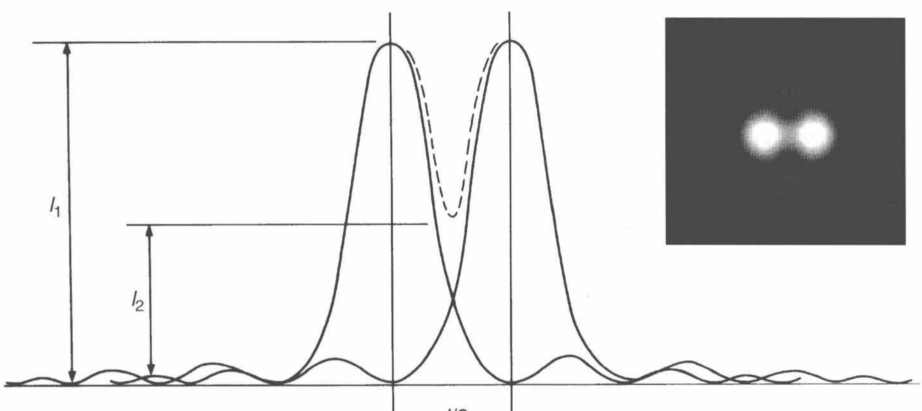

Figure 1.4 Intensity distribution of two airy disks with a distance $d/2$. I_1 indicates the maximum intensity of each point and I_2 represents the overlap intensity.

lens and object. Two media between object and objective lens are commonly used: either air for which $\mu = 1$, or oil for which $\mu \approx 1.5$. Thus, the maximum value of NA is about 1.5. We estimate the best resolution of a light microscope from Eq. (1.3) as about 0.2 μm.

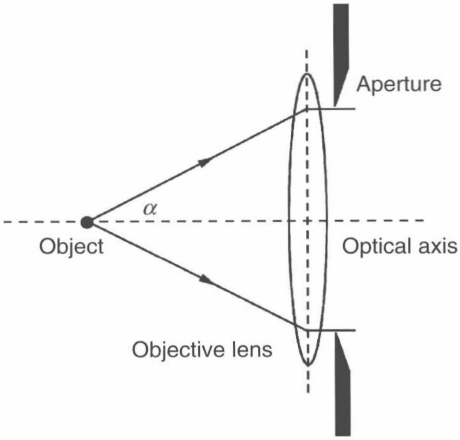

Figure 1.5 The cone of light entering an objective lens showing α is the half-angle.

1.1.2.1 **Effective Magnification**

Magnification is meaningful only in so far as the human eye can see the features resolved by the microscope. Meaningful magnification is the magnification that is sufficient to allow the eyes to see the microscopic features resolved by the microscope. A microscope should enlarge features to about 0.2 mm, the resolution level of the human eye. This means that the microscope resolution multiplying the effective magnification should be equal to the eye resolution. Thus, the *effective magnification* of a light microscope should approximately be $M_{eff} = 0.2 \div 0.2 \times 10^3 = 1.0 \times 10^3$.

A higher magnification than the effective magnification only makes the image bigger, may make eyes more comfortable during observation, but does not provide more detail in an image.

1.1.2.2 **Brightness and Contrast**

To make a microscale object in a material specimen visible, high magnification is not sufficient. A microscope should also generate sufficient *brightness* and *contrast* of light from the object. Brightness refers to the intensity of light. In a transmission light microscope the brightness is related to the numerical aperture (NA) and magnification (M).

$$\text{Brightness} = \frac{(\text{NA})^2}{M^2} \tag{1.4}$$

In a reflected-light microscope the brightness is more highly dependent on NA.

$$\text{Brightness} = \frac{(\text{NA})^4}{M^2} \tag{1.5}$$

These relationships indicate that the brightness decreases rapidly with increasing magnification, and controlling NA is not only important for resolution but also for brightness, particularly in a reflected-light microscope.

Contrast is defined as the relative change in light intensity (I) between an object and its background.

$$\text{Contrast} = \frac{I_{\text{object}} - I_{\text{background}}}{I_{\text{background}}} \tag{1.6}$$

Visibility requires that the contrast of an object exceeds a critical value called the *contrast threshold*. The contrast threshold of an object is not constant for all images but varies with image brightness. In bright light, the threshold can be as low as about 3%, while in dim light the threshold is greater than 200%.

1.1.3 Depth of Field

Depth of field is an important concept when photographing an image. It refers to the range of position for an object in which image sharpness does not change. As illustrated in Figure 1.6, an object image is only accurately in focus when the object lies in a plane within a certain distance from the objective lens. The image is out of focus when the object lies either closer to or farther from the lens. Since the diffraction effect limits the resolution R, it does not make any difference to the sharpness of the image if the object is within the range of D_f shown in Figure 1.6. Thus, the depth of field can be calculated.

$$D_f = \frac{d}{\tan\alpha} = \frac{2R}{\tan\alpha} = \frac{1.22\lambda}{\mu \sin\alpha \tan\alpha} \tag{1.7}$$

Equation (1.7) indicates that a large depth of field and high resolution cannot be obtained simultaneously; thus, a larger D_f means a larger R and worse resolution.

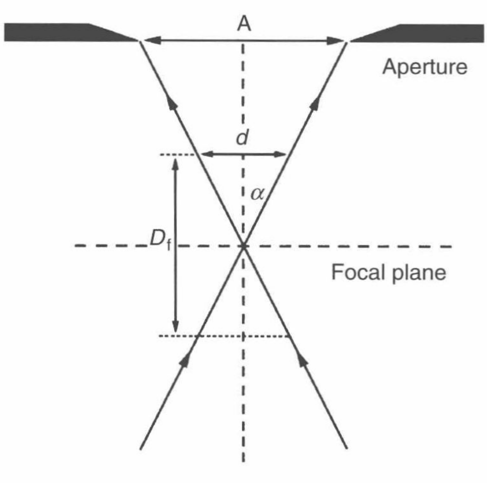

Figure 1.6 Geometric relation among the depth of field (D_f), the half-angle entering the objective lens (α), and the size of the Airy disk (d).