CHAPTER 2.1

Fundamentals of Electron Microscopy

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1. Introduction

It would be impossible to review adequately within one chapter the basics of electron microscopy and the reader is urged to consult the bibliography at the end for more details on the topics discussed here. It will be shown in this chapter what kind of information can be gained by using electron microscopy techniques which have become standard in metals research. The principles of these techniques will be reviewed and they will be illustrated with examples drawn from current research on ceramics and minerals in our laboratory. Wherever minerals and ceramics may present a problem because of their more complex structure, this will be indicated. Some examples of what are often called “non-conventional techniques” will also be presented.

2. Preliminaries

The information that is obtained by electron microscope methods is derived from the scattering processes that take place when the electron beam travels through the specimen. There are two main types of scattering (a) elastic—the interaction of the electrons with the effective potential field of the nuclei—involving no energy losses and which can be coherent or incoherent (poor phase relationships) (b) inelastic—the interaction of the electrons and the electrons in the specimen involving energy losses i.e. absorption. It is the elastic scattering that produces a diffraction pattern; and if the scattering centers in the specimen are arrayed in an orderly, regular manner such as in crystals, the scattering is coherent and results in spot patterns, Kikuchi patterns and, if the sample is a fine-grained polycrystal, ring patterns.

The basic reason for the utilization of the electron microscope is its superior resolution resulting from the very small wavelengths of electrons compared to other forms of radiation for which an optical system can be constructed. The resolution is given by the Rayleigh formula which is derived from considering the maximum angle of electron scattering (α) which can pass through the objective lens. This formula is:

\[ R = \frac{0.61 \lambda}{\alpha} \]  

(1)
where $R$ is the size of the resolved object, $\lambda$ is wavelength, and $\alpha$ is identical to the effective aperture of the objective lens.

In the electron microscope, the effective aperture is limited chiefly by spherical aberration. The spherical aberration error is:

$$\Delta S = C_s \alpha^3$$  \hfill (2)

where $C_s$ is the coefficient of spherical aberration of the objective lens ($\propto$ focal length e.g. 3 mm).

Thus $R$ increases with decreasing $\alpha$; whereas $\Delta S$ decreases with decreasing $\alpha$. As a result, in electron optics one arrives at an optimum aperture and minimum resolution given by:

$$\alpha_{\text{opt}} = A(\lambda^{1/4}) C_s^{-1/4}$$  \hfill (3)

$$\Delta R_{\text{min}} = B(\lambda^{3/4}) C_s^{1/4}$$  \hfill (4)

where $A, B$ are constants of order 1.

The relativistic wavelength of electrons depends on the accelerating voltage and is given by the modified De Broglie wavelength:

$$\lambda = \frac{h}{\left[2m_0eE \left(1 + \frac{eE}{2m_0c^2}\right)\right]^{1/2}}$$  \hfill (5)

$$\lambda = \frac{12.26}{E^{1/2} (1 + 0.9788 \times 10^{-6} E)^{1/2}} \text{ (Å)}$$  \hfill (6)

where $h$ = Planck’s constant, $m_0$ is rest mass and $e$ the charge of the electron, $E$ is the accelerating potential (volts), $c$ is the velocity of light, $v$ is the electron velocity, and thus decreases with energy $E$. Some values pertinent to electron microscopy are given below in Table 1.

<table>
<thead>
<tr>
<th>$E$ (volts)</th>
<th>$\lambda$ (Å)</th>
<th>$\lambda^{-1}$ (Å$^{-1}$)</th>
<th>$(v/c)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kV</td>
<td>0.037</td>
<td>27.02</td>
<td>0.3005</td>
</tr>
<tr>
<td>500 kV</td>
<td>0.0142</td>
<td>70.36</td>
<td>0.7445</td>
</tr>
<tr>
<td>1 MeV</td>
<td>0.0087</td>
<td>114.7</td>
<td>0.8856</td>
</tr>
<tr>
<td>10 MeV</td>
<td>0.0012</td>
<td>846.8</td>
<td>0.9976</td>
</tr>
</tbody>
</table>

Another advantage of the small wavelength of electrons is that the depth of field and depth of focus are very large in electron microscopes.

At 100 kV $\alpha_{\text{opt}} \approx 6 \times 10^{-3}$ rad. and $\Delta R_{\text{min}} \approx 6.5$ Å for $C_s = 3.3$ mm. Other factors which affect resolution are astigmatism and chromatic aberration of the imaging system, and chromatic aberration resulting from energy losses in the specimen. These errors produce poor resolution for non-axial illumination.