# THE MICROSCOPE PAST
## 15 YEARS AGO

# Macroscopy with the SEM[1]

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**KEYWORDS**

Scanning electron microscope, macroscopy, photomontage, low magnification, electron channeling pattern, extended working distance, depth of field

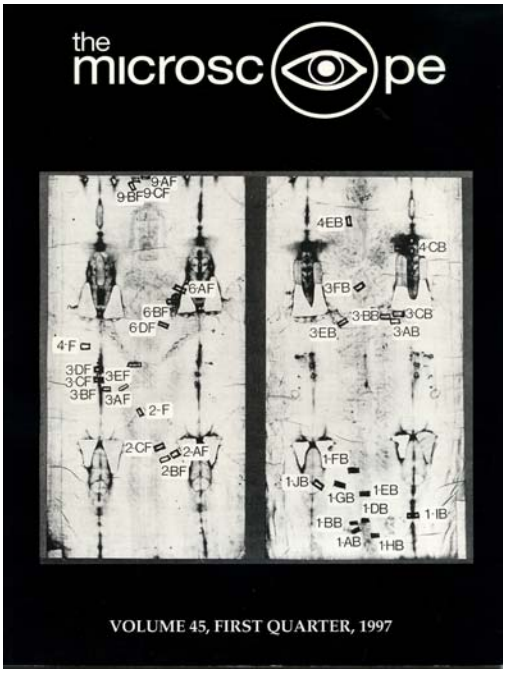
## ABSTRACT

When light is used for imaging, there is no lower limit to magnification. On the other hand, the lowest magnification possible for many SEMs is about x10, which may be too high for some subjects. Several techniques are available that can reduce this figure.

A well known method of reducing magnification with the SEM is by joining adjacent views into a montage and reducing the resulting composite photographically.

Another approach to lower magnification is to extend the working distance in the SEM beyond its normal range.

The lowest magnifications attainable by SEM are achieved by modification of the electron channeling pattern (ECP) mode; magnifications of less than one are feasible.



## INTRODUCTION

An overlooked benefit of imaging with light is that there is really no lower limit to magnification. If the magnification is too high when using a conventional light microscope, one can change to a stereomicroscope; if the magnification remains excessive, a camera with a macro lens can be used, ad infinitum. On the other hand, such flexibility does not exist with a scanning electron microscope (SEM) since there is always a minimum magnification barrier (in the order of x10) that can be too high for some subjects.

An example of such an inadequate lower magnification limit with SEM can be illustrated with a common 1½ inch (3.8 cm) wood screw. The entire length of the screw is covered easily when photographed by a camera with a macro lens as shown in Figure 1. However, if this subject is depicted with an SEM at its minimum magnification (x10) in Figure 2, only a small section of the screw remains visible.

The purpose of this paper is to present a few techniques to decrease the standard minimum magnification limitation and thus make the SEM more versatile

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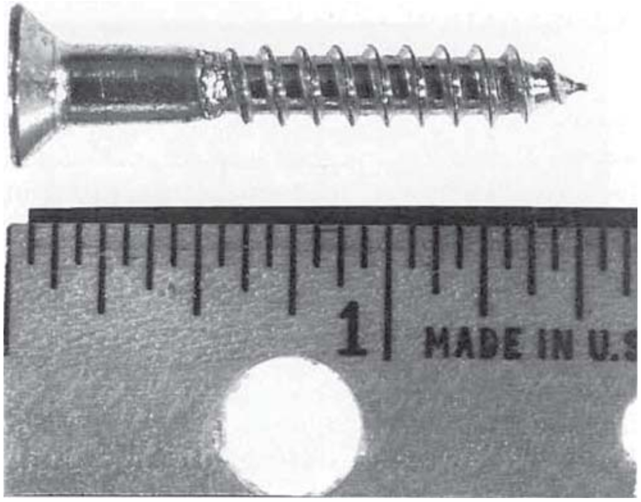

Figure 1. Wood screw photographed using a micro lens — entire length is in view.

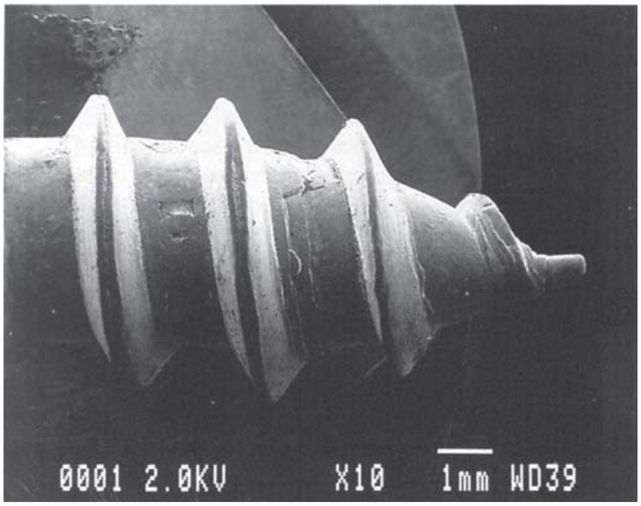

Figure 2. SEM of wood screw at minimum magnification — only a small section is visible.

and useful. Although this work was carried out entirely with a JEOL model 840A, it is believed that the techniques to be shown are generally adaptable to other comparable SEMs as well.

## PHOTOMONTAGE METHODS

The photomontage method as applied to photography is well known. Basically, a series of adjacent views are photographed, the prints lined up and joined into a montage; the magnification of the resulting composite can then be reduced photographically.

An advantage to this procedure is that usually it is adaptable to almost any SEM. First, the axis in the direction of movement of the specimen on the stage must be aligned to an axis of the viewing screen. After taking each exposure, the specimen is moved enough to allow some overlap between the edges of the adjacent views. After matching, the edges of the adjacent prints are trimmed and joined together. A photomontage formed form four adjacent prints incorporates the entire length of the wood screw in Figure 3.

The photomontage method as applied to SEM has several drawbacks. Taking multiple images, matching, trimming and joining the prints, etc. are time-consuming and cumbersome. At times, precisely matching the edges of the adjacent views may be impossible. "Lighting" of the subject can be uneven. The maximum span of the specimen covered by the montage is limited by the displacement of the SEM stage. The presence of a seam between prints can be objectionable. If the individual images are distorted, the montage method is usually unsatisfactory.

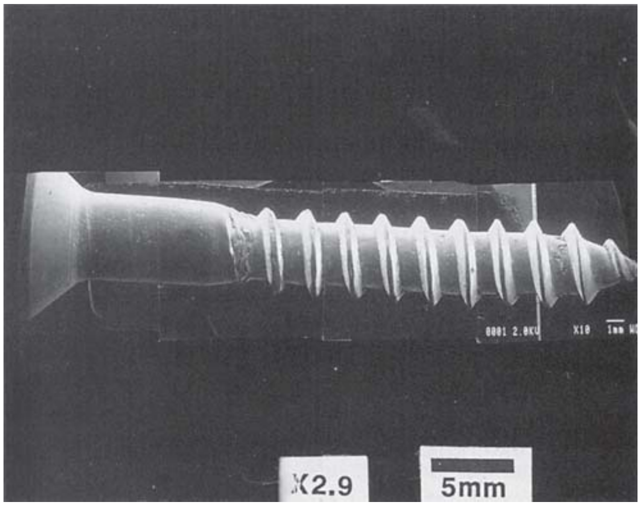

Figure 3. Photomontage of wood screw from four adjacent prints — entire length is in view.

## INCREASING WORKING DISTANCE BEYOND COMPENSATION

A less complex and more practical method to decrease magnification is to increase the length between the subject and the polepiece (the working distance, WD) beyond its normal range, exceeding the limit of SEM compensation.

Consider the movements of an electron probe as it scans the surface of a specimen in Figure 4. At minimum magnification, the angular displacement of the raster scan is at its maximum. As the specimen is lowered, working distance lengthens and the lateral

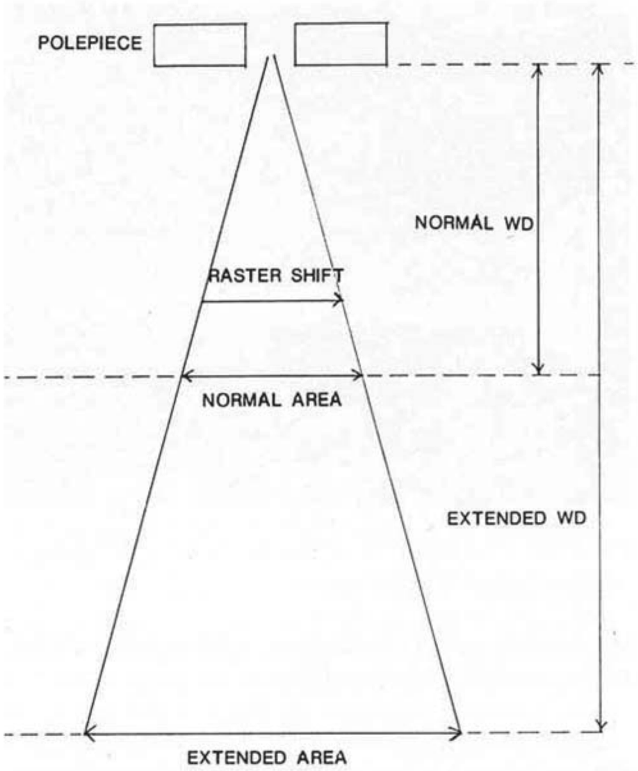

**Figure 4.** Increasing normal working distance beyond compensation increases area rastered and decreases minimum magnification.

linear displacement of the probe over the surface of the specimen increases, resulting in a corresponding extension of scanned area. The greater the area scanned by a raster, the lower the magnification will become.

Under normal conditions, the magnification marker on the print or that indicated on the SEM panel is correct since the magnification is compensated automatically for changes in working distance by focus control. However, such compensation is effective only if a specimen is located within the normal working distance range. If the working distance exceeds this range, compensation for working distance will no longer be operative; consequently, the indicated magnification on the panel and on the print will no longer be correct.

One can take advantage of this effect to lower the normal minimum magnification of an SEM. As working distance increases in a region beyond compensation, the area covered by the raster will continue to expand; therefore, true magnification will keep on decreasing, regardless of the indicated now-invalid magnification on the marker or on the panel; the decrease in magnification is dependent on the extension of

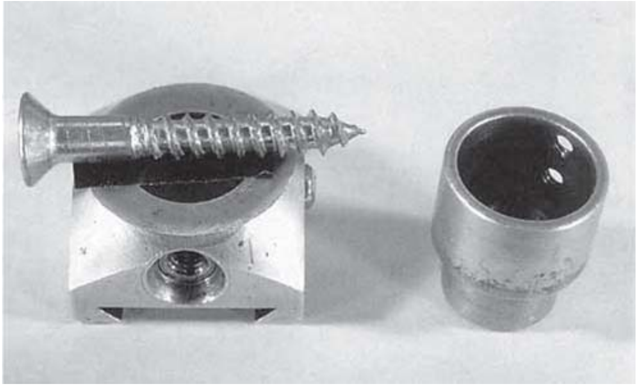

**Figure 5.** Increasing working distance slightly by mounting the wood screw directly on the dovetail.

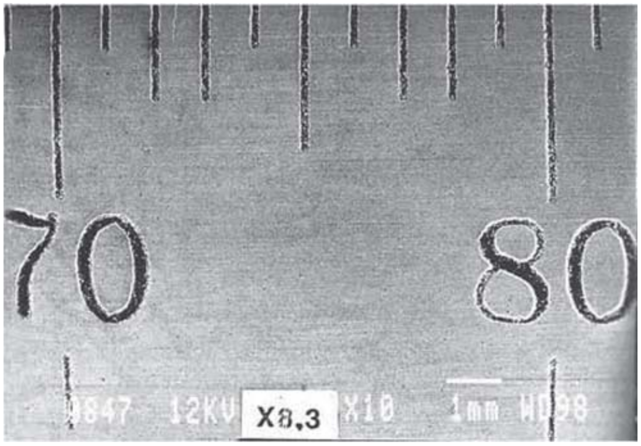

**Figure 6.** Metric scale mounted directly on dovetail. The magnification indicated on the scale does not agree with that of the markers on the print.

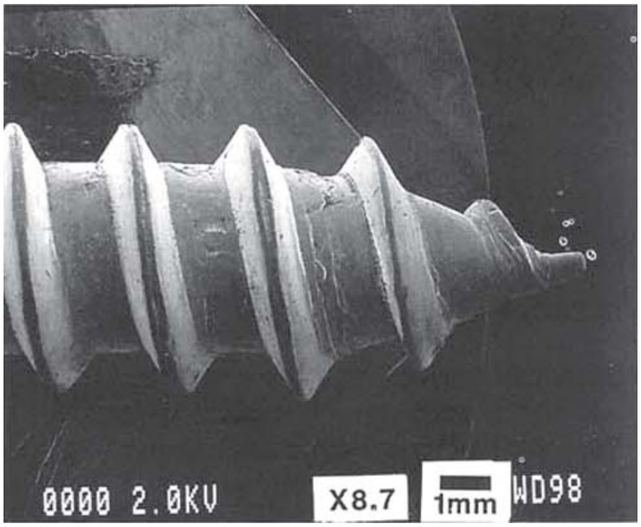

**Figure 7.** Wood screw mounted on dovetail — magnification is lower than that in Figure 2.

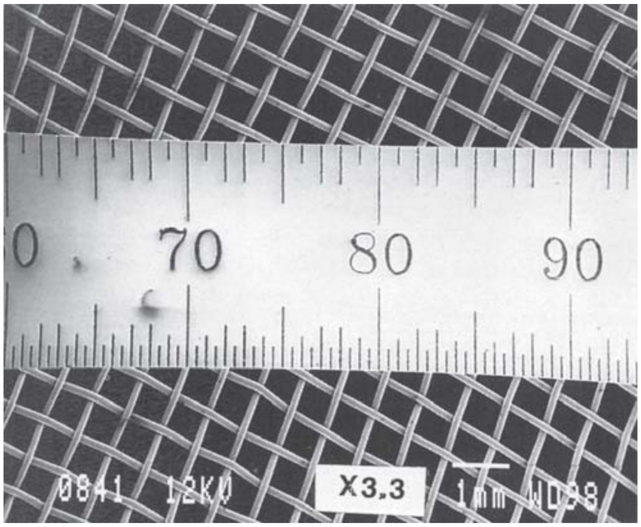

**Figure 8.** Metric scale on base of SEM chamber.

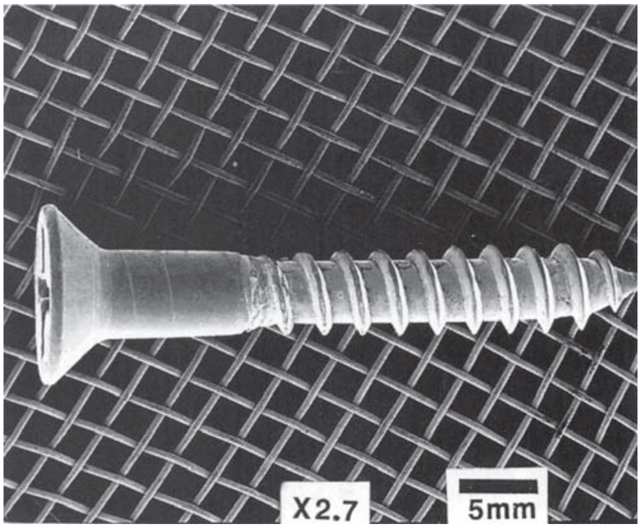

**Figure 9.** Wood screw on screen below base of chamber — entire length is in view.

working distance beyond the compensation limit.

For slight reductions in magnification, the working distance can be extended a small amount beyond compensation by lowering the stage as much as possible and shortening the height of the specimen holder. The specimen holder can be shortened as shown in Figure 5. The specimen holder illustrated consists of a cup fitting into a dovetail assembly. By removing the cup and mounting the specimen directly onto the dovetail, an increase in working distance of about 12 mm results. An advantage of this arrangement is that movement of the specimen by the stage is unrestricted.

A metric scale mounted directly over the dovetail assembly described above (Figure 6) demonstrates the inconsistency that will occur with such methods. Because working distance exceeds the compensation limit, true magnification as indicated by divisions on the scale does not correspond with the magnification markers on the print. Therefore, one should disable the magnification marking system in these situations. By mounting the wood screw directly on the dovetail as above, the normal working distance is exceeded somewhat, resulting in a slightly lower magnification (Figure 7) than that in Figure 2.

For further decreases in magnification, the working distance is increased substantially beyond the limit of compensation. The normal maximum working distance as measured between the polepiece and the specimen is about 48 mm. Very large increases in working distance can be made by moving the stage aside so as to be out of view, and placing and observing the specimen on the bottom of the chamber; the resulting working distance between polepiece and the bottom of the chamber measures about 240 mm. A wire screen positioned on the bottom of the chamber sags below it; the plane at the maximum depth of sag adds an additional 20–30 mm. With a specimen placed directly on this screen, the enormous working distance (about 270 mm) results in a corresponding major decrease in magnification.

A metric scale placed on the base of the SEM chamber in Figure 8 exhibits a magnification of almost x3.3 on a Polaroid™ print.

When the screw is lowered below the base of the SEM chamber by placement directly on the wire screen in Figure 9, its entire length comes in view with a magnification of about x2.7 on the Polaroid™ print. Unfortunately, inserting and repositioning a specimen on the base of the chamber or on the wire screen is awkward since neither the airlock nor the stage can be used. Since the wood screw lies immobile on the screen in Figure 9 rather than on a moveable stage, it cannot be moved dynamically. Movement of the screw would have to be manual, requiring the vacuum to be broken in order to open the chamber, followed by repositioning the specimen; re-evacuation of the chamber takes about 10 minutes. Even more bothersome, it may be necessary to repeat these steps several times to place the specimen at the exact position desired! Repositioning would not be required if the wire screen or similar subject were to be imaged. Since the screen is uniform, large and homogeneous, any area that happens to fall in view would be about the same as any other.

Though electronic image shift controls are incorporated in SEMs, the maximum image movement possible by using them is almost insignificant at these extremely low magnifications.

## IMAGING WITH THE ELECTRON CHANNELING PATTERN (ECP) MODE

For moderate decreases in magnification, the above method based on increasing working distance beyond compensation is effective, simple, and adaptable to many SEMs. For further decreases in magnification, a very clever and unconventional tactic was devised by Vernon E. Robinson (1). The normal electron channeling pattern (ECP) mode, usually restricted to crystallization studies, can be modified for imaging.

In order to understand ECP imaging, a rather simplistic explanation of the normal ECP mode as applied to crystallographic studies will first be made.

In Figure 10, electron beams are seen approaching a lattice structure of a specimen at two specific angles. As seen on the left side of this diagram (A), if the angle of approach of the incoming beam is coincident or close to the line of sight for a plane corresponding to a gap or channel in the lattice, the beam will tend to "sandwich" between the walls of the channel and penetrate deeply below the surface before contact is made with atoms on the lattice walls. The efficiency of escape of backscatter electrons resulting from such contact for a region buried deeply within the structure will tend to be low, with a resulting weak signal. On the other hand, as seen in the right side (B) of Figure 10, if the angle of approach of the incoming beam is not coincident with the line of sight for a plane of the gap or channel in the lattice structure, the beam will penetrate less deeply before colliding with atoms on the walls of the channel close to the surface. With a shorter distance to the surface, the efficiency of escape of the backscatter electrons will tend to be higher, resulting in a stronger signal.

In Figure 10, the electron beam was shown approaching the surface of the specimen at two specific angles. In fact, in the ECP mode, rather than the electron beam remaining static and approaching at only a specific angle over a small spot on the surface, the angle of approach of the probe is continually changing, rocking back and forth over the contact spot which acts as a pivot point. The resulting backscatter electron signal is synchronized to the angle change of the beam and is displayed on the screen. This integrated variable signal forms the electron channeling pattern

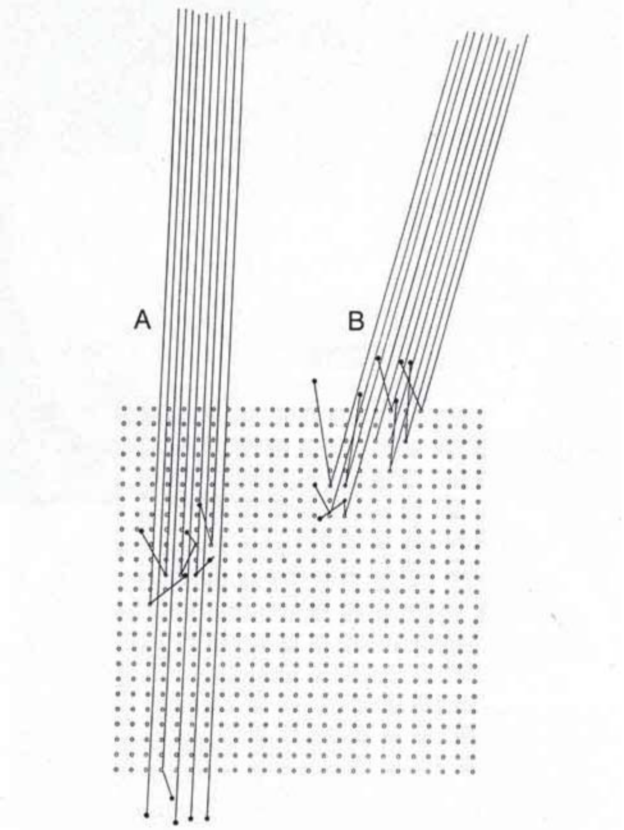

**Figure 10.** Deep penetration of probe into lattice structure yields a weak backscatter signal (A). Shallow penetration of probe into lattice structure yields a stronger backscatter signal (B).

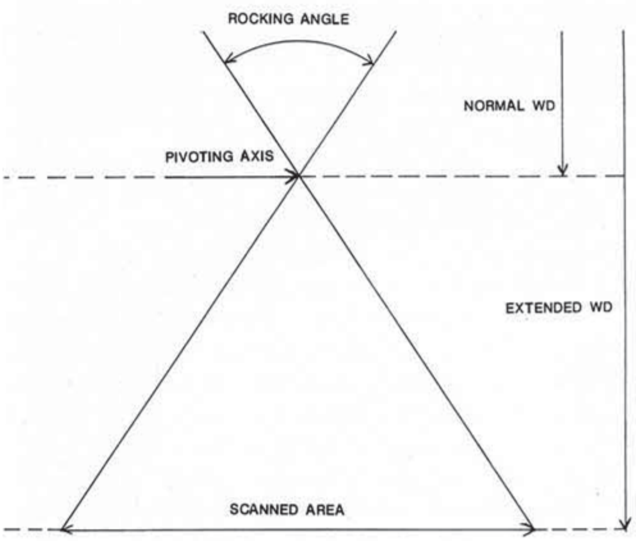

**Figure 11.** Lowering the subject below the crossover-apex in the ECP results in raster scanning of the surface.

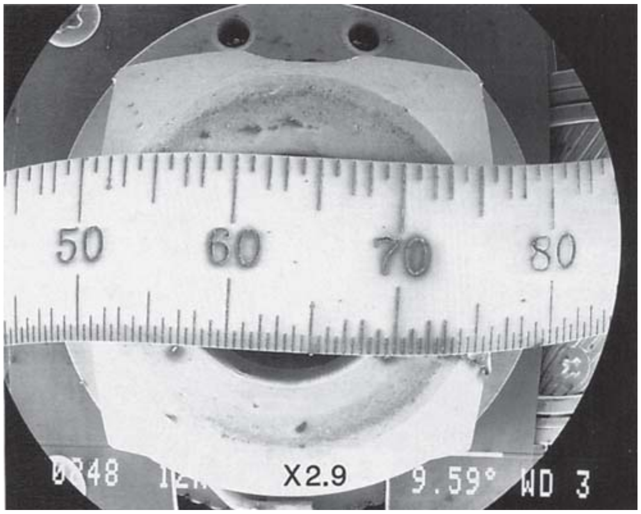

Figure 12. Metric scale on dovetail in the ECP mode.

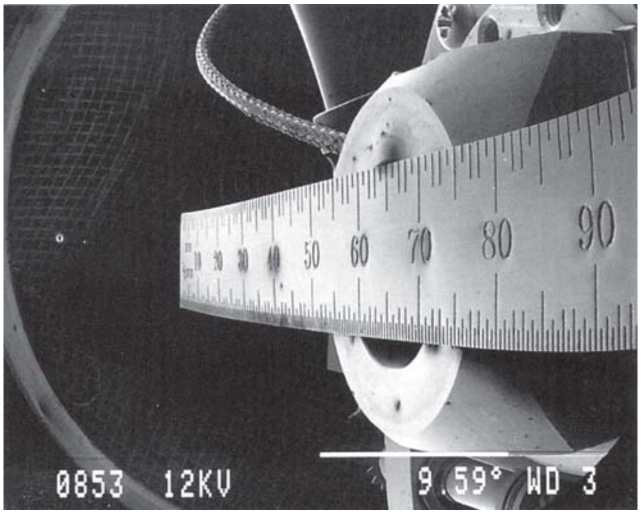

Figure 13. Tilted metric scale on dovetail in the ECP mode showing enhanced depth of field.

(somewhat similar to an X-ray diffraction pattern), which is related to the lattice structure.

The ECP mode as normally applied to crystallography can be modified for imaging at low magnifications in the following manner. In the conventional ECP mode at normal working distance, a probe rocks and pivots over a single spot on the surface of a specimen, as seen in the upper part of Figure 11. If the specimen is now lowered below this convergence point of the probe, the pivoting beam will cross through its apex to the opposite side, reaching toward and scanning along the surface of the specimen as if it were in the normal raster mode. In this way, an ECP rocking beam pivoting over a point has been transformed into a scanning beam to produce a linear raster along a surface. The farther away the surface is from the crossover apex, the longer the linear scan of the probe on the surface will be, with a corresponding expanded area. As the area covered by the raster increases, magnification will decrease accordingly. In addition, the maximum angular spread of the scan in the ECP rocking mode is wider than that from a conventional raster mode, tending to enlarge the scanned area further. With the surface sufficiently far away from the crossover-apex point, the scanned area can become so large that a magnification of less than one is attainable.

An added bonus of ECP imaging is a depth of field much deeper than that possible with conventional SEM methods. The increase is due largely to the shape of the scanning probe. To optimize resolution in conventional SEM, it is essential to minimize the spot size of the probe in contact with the surface. In order to produce such a small spot size, it is necessary to focus the electron beam in the form of a cone over the contact spot on the surface; the wider the cone angle, the smaller the spot size that can be focused. Unfortunately, the wide cone angle necessary for minimum spot size comes at the expense of a reduction in the depth of field.

In the ECP mode, the shape of the probe is unlike that of conventional SEM. Rather than the beam being conical and focused to a tiny spot as in the conventional mode, with ECP the electrons in the probe are collimated in the form of a uniform, parallel column. An analogy is that of a searchlight where a light beam is also collimated rather than being focused to a spot and thus remains parallel indefinitely; as such an example, an aircraft searchlight beam is capable of illuminating a target over several kilometers. Applying this principle to the ECP mode, because the probe is essentially collimated, it will sustain a constant diameter indefinitely, regardless of working distance; consequently, the size of the scanned spot projected on the specimen surface will stay almost constant at any position, no matter at what height it might be. The outcome of imaging with a collimated scanning probe is a nearly infinite depth of field.

Employing a collimated probe presents a problem. Since the probe is not focused to an extremely small spot in the ECP mode, contact area on the specimen will be relatively wide, resulting in limited resolution. Nevertheless, resolution will usually still be adequate if the magnification is low enough and if the width of a collimated probe is minimized.

Another problem of ECP imaging is that it is diffi-

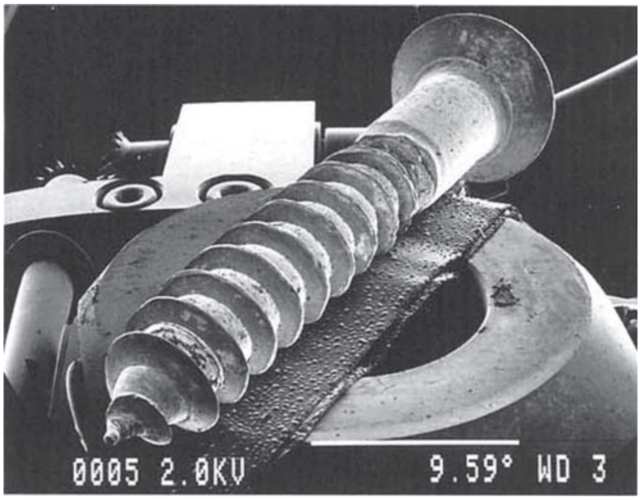

**Figure 14.** Tilted wood screw on dovetail in the ECP mode showing enhanced depth of field.

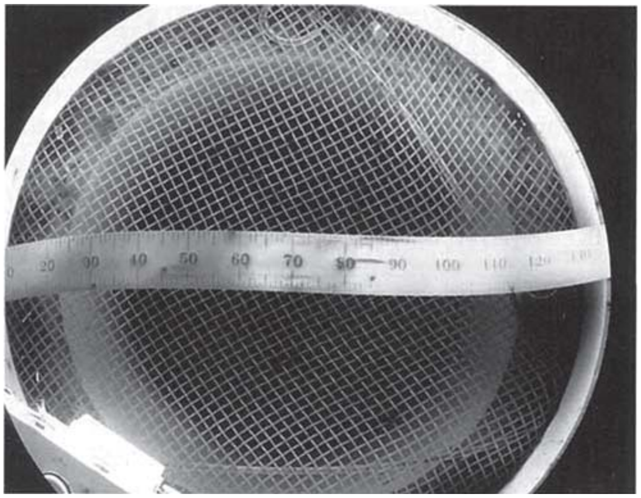

**Figure 15.** Metric scale on base of chamber in the ECP mode.

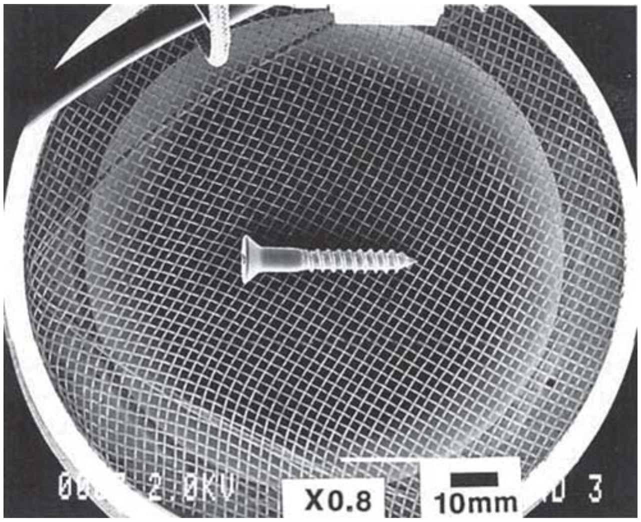

**Figure 16.** Wood screw on screen below base of chamber in the ECP mode.

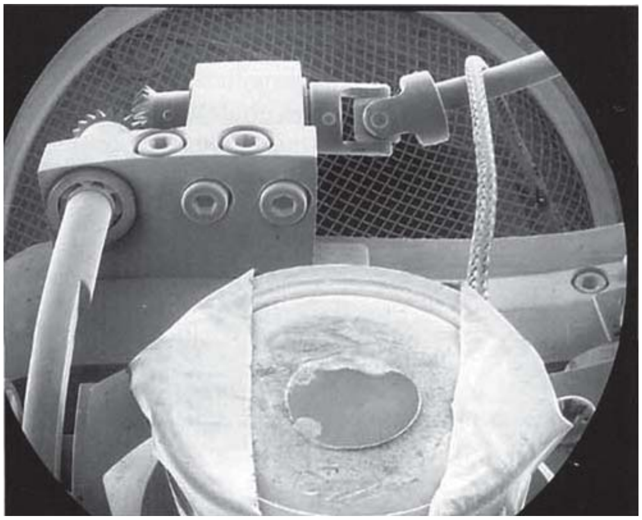

**Figure 17.** View of components in the SEM chamber in the ECP mode covering depth of field over 200 mm.

cult to operate. In order for a collimated electron beam to rock and pivot over a small spot as opposed to sweeping along the surface as in a conventional raster, the entire lens system in the SEM must be altered considerably. Due to such changes, it follows that the normal SEM controls will also change drastically. Consequently, operating in the ECP imaging mode can be most confusing, but with practice, eventually one can become accustomed to it. Some of the control changes in ECP imaging are: 1) the normal focus controls now influence magnification; 2) the normal probe current controls now influence focus; 3) the fine probe knob also affects brightness; and 4) the normal magnification controls still influence magnification, but in addition, alter the rocking angle. Previously, it had been shown that the image shifting knobs had an insignificant effect on movement at lowest magnification; however, the ECP centering knobs are capable of shifting the image significantly.

As with the extended working distance method, the location of the specimen also influences magnification in the ECP mode.

Some examples of photomicrographs utilizing the ECP imaging mode will be given. A metric scale mounted directly on the dovetail assembly is shown in the ECP mode (Figure 12). In this position at a short working distance, full functionality of the stage is maintained. A magnification of about x2.9 results on the Polaroid™ print. Unfortunately, there is distortion present at the ends of the scale which points out a problem inherent to ECP imaging that is especially critical at short working distances.

The metric scale, being mounted on the stage as show in Figure 12, is moveable and was tilted 70° in Figure 13. The differential focus control on the SEM was not used. The entire visible length of the ruler (100 mm) appears in acceptable focus. This points out the great depth of field achievable with ECP imaging.

The wood screw was mounted directly onto the dovetail on the stage as above and was tilted 65° (Figure 14). This again points out the enhanced depth of field possible with ECP imaging.

Magnification can be decreased considerably by extending the working distance. The metric scale placed on the bottom of the chamber with a WD of about 24 mm (Figure 15) results in a magnification of about x0.9 on a Polaroid™ print. Distortion is apparent on the ends of the scale.

The wood screw placed on the wire screen below the base of the chamber (WD of about 270 mm) yields magnification on the Polaroid™ print of about x0.75 (Figure 16). As was pointed out previously in the extended working distance mode with the subject placed in this location, the airlock and the stage cannot be used. Fortunately, in the ECP imaging mode the viewed area can be shifted significantly using the ECP centering knobs.

Figure 17 illustrates some capabilities unique to the ECP imaging mode. On the lower section of this figure a tilted stub is seen with a 5 mm disc attached on it, which equates to a magnification of about x4 on the Polaroid™ print. On the upper portion of this figure, the wire screen is seen below the base of the SEM chamber. The openings in the screen are 2 mm, which equates to about x0.75 on the Polaroid™ print. Some of the mechanisms of the stage are seen in the middle portion of the figure (universal joint, gear, ball bearing, etc.) All the planes are in acceptable focus. A satisfactory depth of field over a range greater than 200 mm in an SEM is quite remarkable.

## CONCLUSIONS

The three techniques presented in this work to overcome the lower magnification barrier of SEM can be summarized as follows.

The photomontage method is adaptable to almost any SEM if there is only minimal distortion present; however, the procedure is cumbersome, time-consuming and not always successful. Extending the working distance beyond the compensation limit is effective for moderate decreases in magnification, especially if the stage can be displaced to allow the specimen to be viewed near the base of the chamber. The ECP imaging method produces the greatest decrease in magnification possible; unfortunately, there is distortion present. Operating in the ECP imaging mode is difficult, and many SEMs do not have ECP capabilities.

Choosing which technique to employ depends to a large part on the magnification required. Generally, for low to moderate decreases in magnification, extending the working distance is preferred. For greater decreases in magnification, especially if a very large depth of field is required, the ECP imaging mode is usually best.

By means of these magnification-lowering techniques, the range of the SEM has been extended well into the macro domain, and thus it has become a more versatile and useful instrument.

## REFERENCES

1. Robinson, Vernon E. "The Scanning Electron MACROscope"; *Microscopy Today*, 1995, Issue 95-10, 16.