Understanding Transmission Electron Microscope Alignment: A Tutorial

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BIOGRAPHY

John Rodenburg has worked on many aspects of electron microscopy technique over the last twenty years (previously at the University of Cambridge and Sheffield Hallam University), as well as a wide range of materials applications including sol-gel and PVD hard coatings, steel and semiconductors. He has recently moved to Sheffield University, where he is a senior lecturer in the Department of Electronic and Electrical Engineering and working on diffractive imaging.

ABSTRACT

Now that most transmission electron microscopes are computerised, there are a growing number of users who have amazingly little understanding of what actually goes on inside an electron column. For most purposes, doing what the computer and the instruction manual tell you to do is sufficient to get reasonable results. But just a little understanding of alignment strategies can make the whole process much more effective (and, perhaps, a little less boring!). This article is an elementary tutorial in the main elements of beam alignment.

KEYWORDS

transmission electron microscopy, alignment, lenses, deflection coils, tutorial

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AN INTRODUCTION TO SHIFT AND TILT

The optical elements of an electron microscope have to be aligned with one another in order to minimize image distortion and loss of resolution due to aberrations and chromatic spread. Mechanical alignment can be achieved approximately by physically shifting lenses by screw-thread adjustment. However, most day-to-day TEM (and SEM) alignments rely on steering the electron beam by double-deflection coils. The term 'double' refers to the fact that we cannot introduce a purely lateral shift into a beam without first deflecting it off its original axis, and then deflecting it back again, so that it is parallel to its original direction, as shown in Fig 1a. A single set of deflection coils introduces a 'tilt' into the beam (a change in the angle of flight of the electrons), but then only at the plane of the coils. Double deflection coils can achieve a pure sideways shift and also have the advantage of being able to tilt the beam in a plane some distance from the coils themselves, as illustrated in Fig 1b, where a tilt-angle has been introduced around the circle, which is called a 'pivot point'. The only difference between 'shift' and 'tilt', as far as the double deflection coils are concerned, is that the ratio of the excitation of the upper and lower coils is different: it is this ratio which determines the position of the pivot point. In practice, each coil has an X and a Y component, so there are in fact four actual variables (currents or voltages) in any single set of double-deflection coils.

Most alignments in a transmission electron microscope involve adjusting a set of double deflection coils; there are usually about four sets positioned at various places down the column. Figure 2 shows a column with rather exaggerated misalignments. The most commonly-adjusted coils, mounted between the condenser system and the specimen plane, allow the user to shift the illuminating beam. An important step in any normal alignment procedure is to adjust the tilt pivot point of these same coils, so that when we want to change the angle of illumination of the beam, the beam itself does not move away from the area of interest. This is usually achieved by flipping the beam between two opposite values of tilt, as shown in Fig 3. If the image plane (that is, the plane on which the objective lens is focused) is not the same as the plane of the pivot point, then as the tilt oscillates, two spots appear which the user is asked to bring together. What is actually happening is that the ratio of the excitations in the upper and lower coils is being adjusted. Similar principles apply to all the deflections coils. In a full alignment, many modern microscopes do not tell the user which set of coils are being adjusted or why: the manual or the computer itself will simply tell you to adjust a pair of knobs until something is achieved – for example, to make the image stop wobbling, to make two images merge as one, or to move a feature to the centre of the phosphor screen.

PAIRS OF LENSES

If we understand the dynamics of a pair of lenses, we can quickly develop a strategy for lining up a whole TEM column, which typically consists of six or seven lenses. Consider Fig 4a, which shows two lenses mounted on top of one another. Electron beams emanate from a source at P_1 and are focused by the top lens to a point at P_2. This point then acts as a second source, which is in turn focused by the lower lens to another crossover at P_3. If we increase the strength of the top lens, then P_2 moves up the column, and in order to keep a focal point at P_3 we must also decrease the strength of the lower lens. In this picture we have only drawn beams coming from single points in particular planes which pass through the lenses at different angles. It is also informative

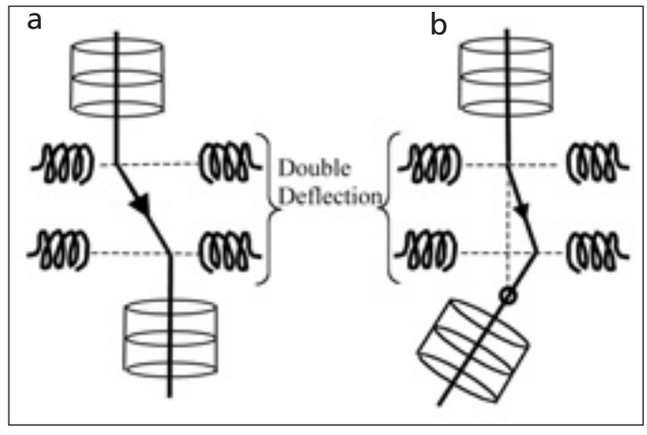

Figure 1:
Correction of shift (a) and tilt (b) between groups of lenses or other optical components.

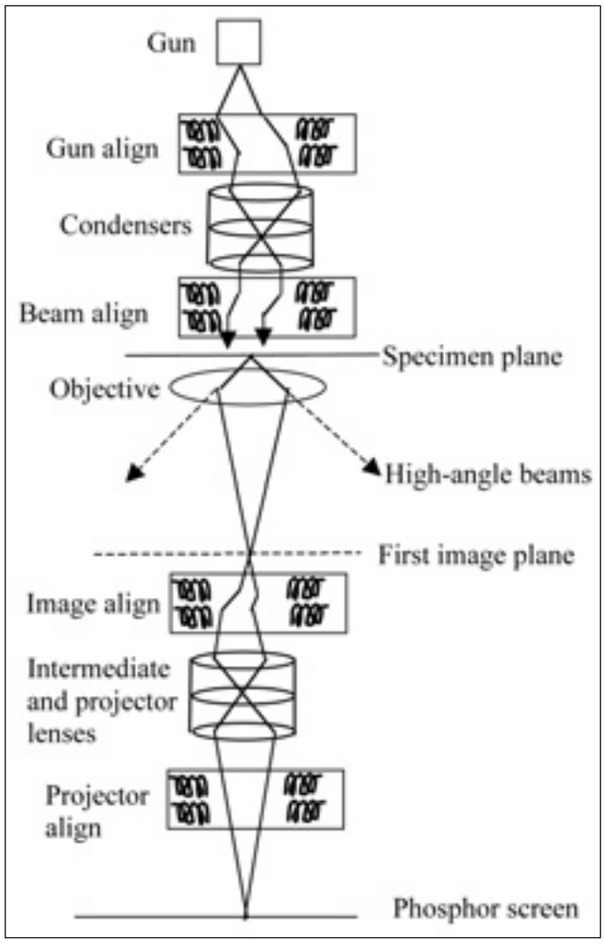

Figure 2:
Schematic of the main groups of lenses mounted above and below the objective lens. Deflection coils are mounted at various points down the column.

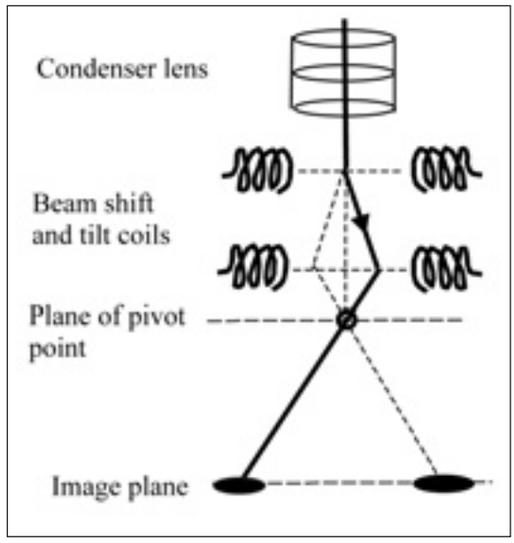

Figure 3:
Adjustment of tilt purity. We assume the objective is focused on the 'image plane'. As the beam oscillates between two tilt conditions, two patches of intensity are seen in the image. The aim is to bring the plane of the pivot point into coincidence with the image plane.

to think of beams which have come from different points in a particular plane, but which all go through the centre of each lens, as shown in Fig 4b. We see from the latter diagram that the magnification of a feature lying in the plane of point P_1 (the grey pointer) is magnified or demagnified by the time it reaches the plane of P_3, depending the relative excitations of the two lenses.

As a general rule, if any lens is increased in strength, another lens must be reduced in strength to keep a feature (whether it's the source, a point in the specimen, or a diffraction pattern) in focus. Two lenses coupled in this way also form a range of magnifications of the feature, depending on the ratio of their strengths. Of course, we can extend this simple analysis to any number of lenses mounted in series. An important skill in understanding electron optics is to maintain a picture in your imagination of how beam crossovers (points where beams are brought to a focus) are moving up and down the column.

A SIMPLE EXAMPLE: GUN SHIFT

Now let's consider a common alignment procedure which involves deflection coils and lenses. Figure 5 shows a simplified condenser system, involving two lenses labelled C1 and C2, and two sets of double-deflection coils, D1 and D2. The picture has been drawn with a large gun shift. If you want to understand alignment procedures, this a very good place to start. The computer which controls the TEM will have a screen which shows the strengths (the currents) in all the lenses. Find this page, and then change 'spot size': one lens, which I have labelled C1 in Fig 5, will get stronger; another, which I have labelled C2, will get weaker, just like the pair of lenses in Fig 4. You can focus the intensity on the phosphor screen by altering 'intensity' or 'brightness' (the name depends on the make of the microscope) which you will find just alters the strength of C2. Focus the image of the source, and then change spot size: the magnification (of the source) changes, just as shown in Fig 4b. When C1 is strong, the image of the source is small. Historically, 'spot size' was a numerical figure (say 1-10) which corresponded to the strength of C1. Nowadays, some microscopes call spot size 10 ('large spot value') a 'small spot', because the image of the source is small, and therefore good for microanalysis – all rather confusing.

Now think what's happening to the crossover between the lenses. As C1 increases in strength, it moves up the column. In the case of a gun lens shift error, the crossover moves slightly diagonally, as shown by the big arrow in Fig 5. The standard way to correct this misalignment is to start ('step a') by running C1 strong, so that crossover gets as close as possible to the optic axis. We then correct the 'beam shifts', i.e. the shifts D2, so that the illumination spot moves to the centre of the phosphor screen ('step b'). Next, reduce C1 (lower spot size, according to the old nomenclature – 'step c'), and correct D1, the gun shift ('step d'). We repeat from step a. If we reverse the order of steps (b) and (d), the gun gets progressively more misaligned: the alignment routine is divergent. You can check this out for yourself and draw successive ray diagrams to understand why one method works, but the other does not. All alignment strategies, for all lenses, rely on similar methods. The trick is to think through a way of moving a crossover closer to the desired optic axis, and then adjusting the deflection coils which will improve the overall alignment most effectively.

THE MAIN PRIORITIES

The most important lens in a TEM is the objective. To get good resolution, it has to reinterfere electron wave components that scatter from the specimen up to large angles (the dotted lines subtended from the specimen plane in Fig 2). However, because it has a large magnification, these same beams are nearly paraxial by the time they reach the first image plane (see Fig 2). The main problem with any electron lens is the aberrations introduced to high-angle beams, but only the objective deals with very high-angles: all the other lenses below the objective process nearly paraxial rays, and so their quality is relatively unimportant. The three or four lenses below the objective are only there to provide magnification and to select the particular plane (the first image plane or the back focal plane, selected by pressing the diffraction button) which is mapped onto the phosphor screen or CCD detector.

As an ordinary user, your task is to make sure the condenser system is aligned within itself (as described in the previous section), and then that the illumination is steered directly down the optic axis of the objective lens. As a gen-

eral rule, if something moves sideways (non-concentrically) as a lens is changed in strength, then that lens, or the alignment above or below it, is off axis. If we wobble the strength of the objective and the image shifts, then this means the illumination is tilted: this adjustment is often called the rotation centre, and is often undertaken by varying beam voltage (the 'voltage centre'). Other alignments in the lower half of the column are less crucial and less likely to change from day to day. If you notice that a feature of interest located at the centre of the phosphor screen does not remain there as a function of different magnifications (or, in the case diffraction patterns, camera lengths) then this is a good indication that the projector system is misaligned. These errors are corrected by a set of one or more deflection coils below the objective lens ('image shift'). As magnification and camera length change, some lenses are switched off in certain ranges, and so the computer will often have a memory for 'image shift' for every range of such settings. If these are not correct, the centre of the phosphor screen may not correspond to the centre of the first image plane (see Fig 2), which means that procedures that rely on a feature position (or image wobble) being corrected at the centre of the phosphor screen will not give optimal alignment.

CONCLUSIONS: THE REAL WORLD

The above represents a simplified rationalisation of nearly all transmission electron microscope alignment strategies, but the real world is never quite that simple. I conclude by mentioning some of the main difficulties which complicate real systems. In my experience, the most confusing problems arise from the objective pre-field or mini-condenser lens now commonly employed in all high-performance microscopes. This means the main illumination beam deflectors are correcting the alignment before the final condensing lens. This is particularly important when aligning TEM/STEMs. The problem is that shifting the beam over the objective pre-field introduces tilt at the actual specimen plane. Shift purity, important for STEM work, can only be obtained for very small fields of view and only very close to the optic axis: on some microscopes, this alignment is to be considered so sensitive it is only available to the site engineer.

Further complications arise from mechanical misalignments in the objective and other groups of lenses and the fact that there are never enough groups of deflection coils to correct everything perfectly. The upper and lower objective lens polepieces always have a tiny residual misalignment. This leads to the reversal centre (found by reversing the objective lens current – usually only ever undertaken nowadays in the factory), the current centre (found by wobbling the lens current), the voltage centre (found by wobbling the electron voltage) and coma-free axis (the optical centre of the lens) all being in slightly different positions: in a perfect system, all these would be coincident. For the other lenses, imperfect positioning of the deflectors, necessitated by physical design constraints, leads to various alignments becoming coupled. This is particularly true in some modern condenser systems. So, for example, you might find that changing bright-field tilt will affect the gun shift alignment and/or condenser aperture alignment. In the ideal world, these would be separate, orthogonal adjustments. It is important, therefore, to identify the main variable (i.e. the one that affects most others) and then get that right first. If in doubt, always iterate several times around an alignment strategy which is convergent. The manufacturer's alignment procedure will almost certainly be optimised to do this, although the suggested order may at first be mystifying. But if you wish to get the very best performance out of your machine, it is definitely worth understanding what is going on.

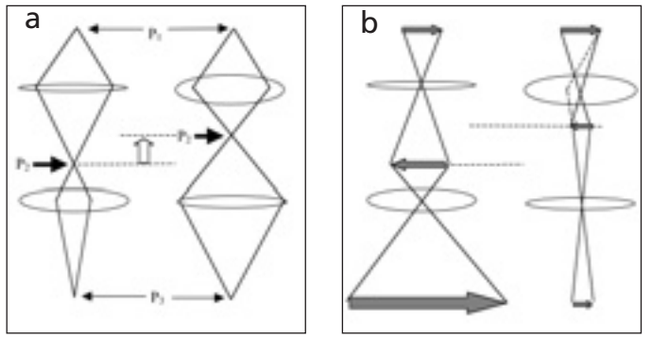

Figure 4:
(a) Two coupled lenses. As the upper lens gets stronger (fatter), the crossover moves up the column. The lower lens needs to be weaker (thinner) to keep the image focused at P_3. (b) The same changes as illustrated in (a), except we now plot only beams that pass through the centre of the lenses to illustrate the change of magnification introduced. Beams are not actually bent at the central plane, but for every beam that passes through the centre of the lower lens, there was a beam (one is shown dotted) that passed through the upper lens, but not through its centre.

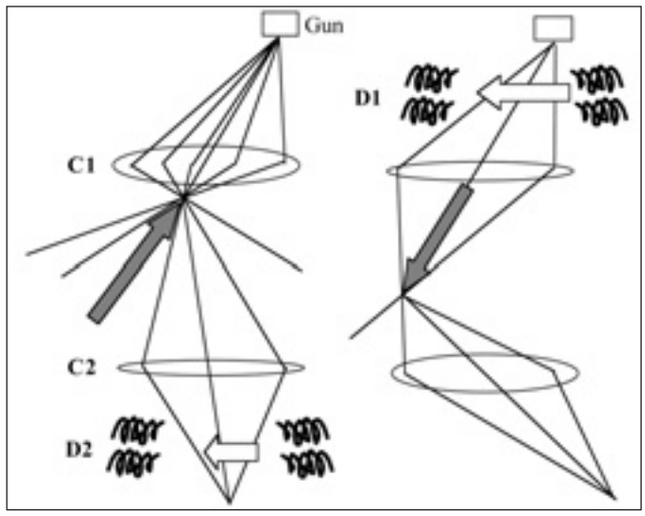

Figure 5:
An exaggerated illustration of gun shift misalignment. As the upper (C1) lens is strengthened, the first beam crossover moves closer to the optic axis; beam shift (D2) is adjusted in this condition. When C1 is weakened, the first crossover moves diagonally away from the optic axis: gun shift (D1) is now adjusted.

FURTHER READING

The manual of your microscope should outline the best alignment strategies. Examine the ray diagrams and cross-sectional drawings to understand exactly where lenses, crossovers and alignment are located. Some manufacturers provide further documentation which explains why certain alignment strategies are preferred.

Most electron microscopy texts include basic ray diagrams for imaging and diffraction mode.