OPTIMISING THE PERFORMANCE OF A TUNGSTEN HAIRPIN SCANNING ELECTRON MICROSCOPE

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Abstract

With many scanning electron microscope operators using their instruments based upon training given during the initial installation, information is being lost or misunderstood. Modern techniques may in many cases be applied to the older tungsten hairpin instruments. These actions enable the operators to obtain far more information and a better understanding of their specimen, both of its surface and the immediate sub surface. Optimisation of the electron gun parameters and the accelerating voltage for the tasks in hand, plus strict alignment procedures, when added to thoughtful positioning of the specimen, provide the operator with improvements in the quality of their information.

Key Words: Electron gun performance, filament position, anode-grid cap relationship, optimising specimen position, optimising imaging signals.

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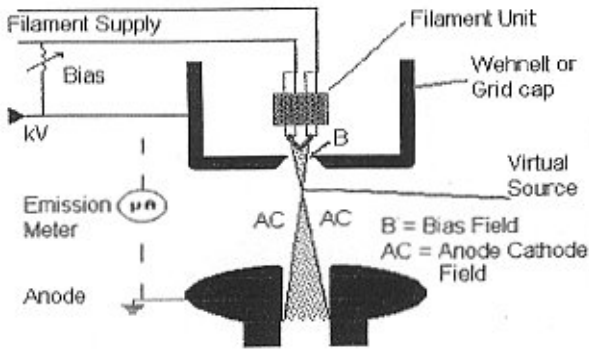Telephone and FAX number: +44-1280-814774
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Introduction

The author of this paper is a consultant in electron microscopy, his business taking him to many of the English speaking countries of the world. During this work it has become very clear that prior to his visits the operating procedures being used date back to those set down when the instrument was first installed. As a result of this deficiency there are many areas of science where the results attained do not fully display the true textures and information that the specimen carries. The advent and use of the field emission gun has revolutionised the use of the scanning electron microscope (SEM). This technique has introduced and enhanced a number of procedures that may be pursued in a reduced form, with the subtle adjustment to a tungsten hairpin instrument. In this paper the areas most affected by these actions or inaction are discussed in relation to performance, which here is considered to be an improvement in image resolution or signal to noise ratio. All of the data published in the manuscript is taken from the work carried out routinely by clients during SEM training courses.

Improving Techniques

Electron gun adjustments

The heart of the scanning electron microscope is the electron gun; set it up correctly and the investigative opportunities available to the operator are considerable. The electron gun (Fig. 1) may be adjusted such that tasks may be performed over a very wide brightness range (amps/cm^2/steradian). Using low brightness levels reduces the potential performance of the instrument: smaller spot sizes and hence higher magnifications are not usable, but there will be an increase in the life of the filament. Conversely the electron gun may be run at such a high brightness level that performance beyond that claimed by the manufacturer may be possible; that is, more current in smaller spot sizes enables not only higher resolution but also a better signal to noise ratio. In this case the sacrifice is filament life and column cleanliness.

Haine and Einstein (1952) demonstrated that there are four important parameters which affect the efficiency

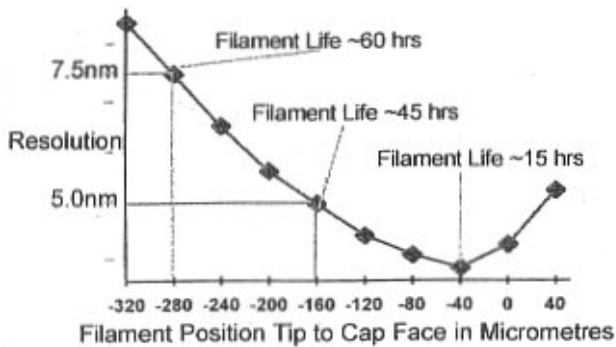**Figure 1**. The components of the electron gun.

Figure 2. The position of the filament tip in relation to the front face of the grid cap is compared against outright resolution.

of the electron gun: (i) the filament to grid cap distance (ii) the bias field (iii) the anode to cathode field and (iv) the temperature of the filament. Operators seldom investigate the manipulation of these areas; therefore the optimisation of their instrument for a particular task is ignored. Experimentation would demonstrate a considerable advantage in certain areas, with (i) filament position optimisation improving signal level and resolution (ii) anode to cathode distance having an additional performance affect at low accelerating voltages.

Resolution variations, as the distance between the filament position and grid cap are changed, are demonstrated in Figure 2. In a typical SEM electron gun, as the filament is moved towards the grid cap aperture and the bias adjusted to retain a standard emission current the gun brightness and as a result the resolution of the instrument are improved. Through experimentation the optimum filament position may be found for both routine microscopy and for high resolution imaging. In Figure 2 the maximum performance was achieved with the filament tip 40 μm back from the front face of the grid cap aperture. The instrument used was specified to attain 5 nm resolution,

but with the filament position optimised for performance better than 4 nm resolution was attained. The filament was expected to last for no more than 15 hours under these conditions and the column would require cleaning every 45 hours of use if the technique was pursued over a number of filaments. Under operating procedures that demanded less performance from the microscope the filament was set at a filament to grid cap distance of 280 μm, a resolution limit of approximately 7.5 nm a typical filament life of around 60 hours. The instrument resolution claim of 5 nm would have dictated a 160 μm spacing and an estimated filament life of around 45 hours.

The filament to grid cap distance affects the action of the bias field, the shorter the distance the weaker the bias field affect. Most operators rely upon the bias field to reduce the temperature of filament saturation by setting the filament away from the grid cap. With this action the bias field has a greater influence, the funnelling affect of the field brings the electrons to an earlier saturation, fewer electrons are required to fill the effective grid aperture. As less heat is required to attain saturation, there is less evaporation of tungsten from the filament, less oxidation of the filament and therefore the life of the filament is increased.

The geometry of the electron gun has to be designed by the manufacturer to be optimised for the highest accelerating voltage that the instrument may attain in order to minimise the possibilities of high voltage discharge. This feature sets the anode to cathode distance; commonly 1 mm for every 2 kV. The formation of the virtual source relies upon filament to grid cap distance, the level of bias field and the anode to cathode field. In a system where the gun geometry is optimum the source is likely to be in the region of 50 micrometres in diameter and the instrument will be capable of reaching its specified test resolution. Once the accelerating voltage is changed away from the highest level the geometry is no longer optimum and if other adjustments are not made the brightness of the electron gun degrades and as a result performance falls.

Figure 3 may act as a guide to how much performance is compromised by accelerating voltage changes. If an operator needs to obtain an improved brightness from a much lower accelerating voltage than the design value, then this will require bringing the filament nearer to the grid cap aperture and raising the height of the anode. In this way the gun brightness will be increased to levels nearer to the design criteria and that will produce a virtual source as near as possible to the 50 μm data point. Such adjustments typically offer around a 20% improvement in signal level. As a very crude rule of thumb at the highest accelerating voltages a 50 micrometres source will provide 5 nm resolution, a 100 μm source 10 nm resolution, working on the principle that the condenser system will
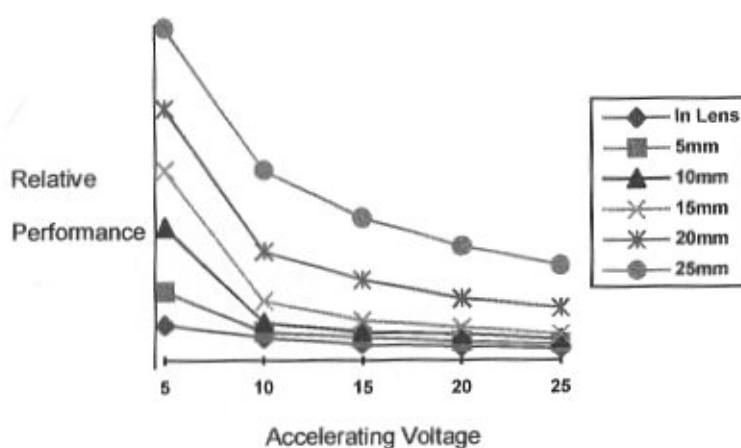
Figure 3. The graph indicates the relationship between accelerating voltage, working distance and resolution.

provide a maximum of a 10000 X probe reduction as its resolution factor. At accelerating voltages below 10 kV other factors begin to influence instrument performance to a greater extent than may be recovered by simply adjusting the electron gun geometry.

Filament saturation and gun alignment

Before moving further we should discuss filament saturation, which would be much better described as saturation of the gun as other variables other than filament heating influence saturation! Most manufacturers use biased gun systems (Haine *et al*., 1958) where filament to grid cap distance, grid cap aperture size, applied bias and accelerating voltage may all affect saturation. Filament saturation occurs when the effective grid aperture can no longer transmit the increased number of electrons produced through the heating of the filament, this makes further adjustment in the heating of the filament unnecessary. The visible presentation of saturation, as judged by monitoring probe current or a wave form, is that the maximum probe current or maximum signal has been attained.

Unless the filament is correctly saturated and aligned the improvements in electron gun geometry are wasted. Only the most sensitive signal assessment will result in an accurate setting of filament saturation and alignment, whilst attempting to retain as long a filament lifetime as possible under the desired conditions. The common practices of viewing the brightness of the image on the screen to set saturation and alignment, or taking the pseudo filament image as being accurate, result in a poor judgement and/or operator variations in the assessment of saturation and alignment, causing a degradation in image quality.

The author has on repeated occasions compared the resolution and signal to noise of instruments where the operators have used poor saturation techniques, that is in relation to the more accurate probe current or wave form procedures. The practice of setting the saturation for the day or for the week should be frowned upon. Each time the accelerating voltage is applied, if resolution or enhanced signal to noise levels are your criterion, then the saturation and the alignment of the gun should also be checked.

In order to attain a reasonable level of performance at each accelerating voltage the emission current should be adjusted, through the bias or emission control. In order to attain an emission current that enables the full potential of the instrument to be attained. The following guidelines may be of assistance (the variation in value is due to the manufacturers' current measuring criteria). European instruments - LEO (Cambridge, UK) run at 400 μA under normal circumstances but this may be adjusted to a lower level through the software. Philips (Eindhoven, The Netherlands) normally operate at around 50 μA, whilst Camscan (Cambridge, UK) are ideal at around 120 μA (1.2 on their meter). Japanese instruments perform best at around 100 μA above any standing current that may be generated as the accelerating voltage is changed. The standing current is the emission meter reading when the high voltage is applied whilst the filament is turned off. These values are typical for average filament settings and hence average filament life.

Further reading on this topic is provided in Goldstein *et al*. (1992), Oatley (1972) and Reed (1975).

Specimen-detector geometry

The relationship between the specimen surface and the specimen chamber dictates the image that will be produced. The Everhart-Thornley detector is able to collect both secondary (SE) and backscattered (BSE) electrons (Everhart 1958, 1959), only through "in lens" detection systems is it able to discriminate between these two signals. As secondary electrons are attracted into the detector the only major signal variable available to the operator is through the generation of different levels of backscattered electrons. Variations in accelerating volt-
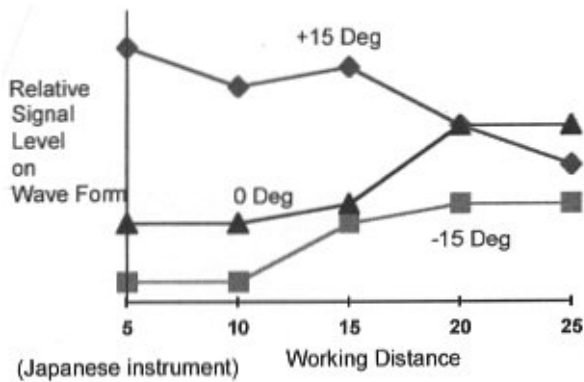
Figure 4. Specimen tilt variations of +15 degrees, 0 degrees and -15 degrees are compared with the resulting sig-
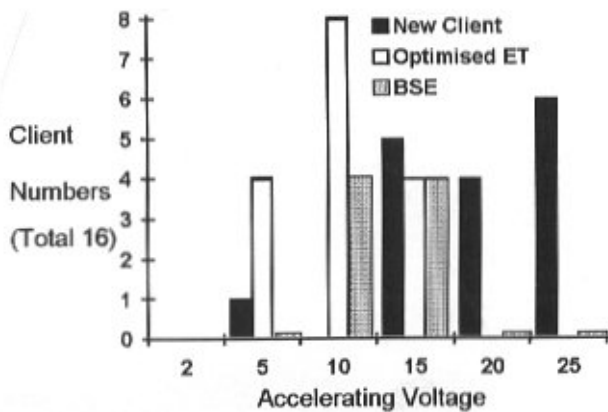

Figure 5. This graph indicates the accelerating voltage used by internally trained operators (No Training) compared with when the operators have undergone training where the accelerating voltage and type of electron detector have been varied.

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age, detector size and both detector and specimen positions, affect backscattered electrons and therefore change the number of backscattered electrons that enter directly into the Everhart-Thornley detector, or that contribute to the image through conversion to SE3. Whilst there have been very many papers on the beam specimen reactions and the electron signals produced by the specimen and the specimen chamber (Seiler, 1983), very few operators deliberately take advantage of these reactions and many produce images with limited or degraded information as a result. Different SEM instruments will process signals in different ways. As a result there will always be a microscope that will generate better quality images of a particular specimen, but not necessarily all specimens. Here is a case for owning different types of instrument in order to optimise a laboratory's information gathering potential.

The reduction in the lens aberrations and the effects of external fields on the incident electron beam at short working distances result in an improvement in performance, particularly at the lower accelerating voltages (Fig. 3). Other performance variations also accompany a change in working distance or specimen tilt (Chapman, 1986). As mentioned earlier, changing the working distance being applied to a specimen changes the number of backscattered electrons entering directly into the Everhart-Thornley detector or producing SE3. By taking advantage of a change in the electron content an image may be varied to optimise the information it carries. Some investigations may require true surface information, their priority SE1. Other investigations may require sub surface detail making BSE1, BSE3 and SE3 their priority. Plotting the signal change as a specimen is moved within the vertical plane helps an operator to determine the position for maximum or minimum backscatter. In Figure 4 minimum backscatter means minimal sub surface detail whilst maximum backscatter means maximum BSE1, BSE3 and SE3 collection by the Everhart-Thornley detector. Most images produced using a tungsten hairpin filament have considerable contributions of backscatter and SE3. Increasing the number of backscattered electrons and SE3 entering the detector at low magnifications increases the signal level, enhances the third dimension affect and reduces the affect of charge. However excess backscatter content at higher magnifications will tend to degrade resolution due to the greater diameter of the zone of backscatter emission compared with that of secondary emission. The most important of these findings for many operators is the position for minimum charge.

Many very experienced operators fail to see the relationship between specimen position and charge, thus complicating their operation by forcing the use of specimen coating which may only add confusion during image interpretation. Very short working distances, in-lens detection and twin detector systems, will offer high resolution images when it is often information not resolution that is the goal. Situating the specimen at some distance from the lens in order to generate backscatter information, which then enters the detector directly (BSE1) or indirectly (SE3) may often be very much more beneficial in relation to image information and ease of access to this information.

Seiler (1983) who lists many works and books relating to secondary electron emission provides references for further reading on this topic.

Accelerating voltage

A variation in accelerating voltage is without doubt the best method to use when trying to understand a material (Joy and Joy, 1996). There is no doubt that the best accelerating voltage for a vast range of materials is nei-

ther 20 nor 25 kV. Application after application that the author encounters in his work are better served by accelerating voltages other than what we must unfortunately term "the norm". "Surface" studies of bone, aluminium alloys, plastics, animal tissue, even nickel alloys and very many other materials are best served with much lower accelerating voltages than those routinely used by most scanning electron microscopists. Clearly the volume of material involved with the creation of an image is not taken into account, nor the ratio of secondary electron to backscattered electrons contributing to that image and most times the backscattered image is ignored completely. It is unfortunate that the role of a consultant carries with it a level of secrecy that does not permit the publication of the many stunning applications of the correct procedure when accelerating voltage variation and signal type are being considered.

Figure 5 demonstrates the accelerating voltages used by new clients in a recent six-month period, that is clients who have not had an outside influence on their microscopy. The majority of the sixteen laboratories routinely ran their microscopes at between 15 and 25 kV only one new client working already at 5 kV.

During a course the clients are taught about the variation in image presentation when the accelerating voltage and type of detector are varied. After a course, without exception, the clients optimised their information at lower accelerating voltages and many found that backscattered images contained more information than the conventional Everhart-Thornley image, this area being particularly informative in failure analysis.

Conclusions

Are we not as microscopists also scientists and is not a scientist someone who uses scientific methods? The Concise Oxford Dictionary definition of "scientific" is: "according to rules laid down in exact science for performing observations and testing soundness of conclusions, systematic, accurate". I submit that many SEM operators are not being scientific and systematic when they decide upon the accelerating voltage to be used, the brightness of their electron gun, the working distance that they use and the signal mix that produces the maximum amount of information from their specimens.

After visiting an average of 25 different laboratories, world wide, per year over the last 16 years the author has to conclude that past teaching methods and our understanding of the SEM fall far short of what I am sure we would all desire.

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Discussion with Reviewers

B. Breton: Anode-grid spacing is optimised as a function of accelerating voltage, do not some if not all scanning electron microscopes provide an anode height adjustment, interchangeable anodes or a spacer?

Author: I am afraid the vast majority of scanning electron microscopes are now not supplied with a "low kV" anode, although some Cambridge and JEOL instruments have had this facility in the past. In order to improve performance in this direction we are often forced to mount home made spacers beneath the anode or have a taller anode custom made. Users must be aware however that when a manufacturer uses a sealed column liner it is not possible to use anode spacers as this action usually breaks the vacuum seal. It is most important that operators, when using a "low kV mode", with a short anode to grid cap distance, indicate very clearly on the microscope that a higher kV should not be used for damage to the electronics could be very severe!

B. Breton: It is generally considered that the Everhart-Thornley detector is a secondary electron detector and, in common usage, approximately 90% of the signal will be secondaries?

Author: I think we must clarify that the Everhart-Thornley detector is not just a secondary electron collector, although in an "in lens" system such as used in your laboratory it certainly does perform in this way. In "conventional" out of lens systems it is documented by Everhart (1958) and Everhart *et al.* (1959) that 65% of the signal stems from SE, 5% by BSE and 30% by BSE converted to SE that are "released at the walls of the SEM", that is converted backscatter from the lens surface. Thus up to 40% of our imaging information is influenced by BSE.

I. Müllerova: For which type (or types) of the scanning electron microscope did you do measurements or calculations plotted in Figures 3 and 4?
Author: All of the experiments mentioned in the paper have been carried out on all the more popular scanning electron microscopes and many of the less well known machines too! The performances seem about the same but I will admit that instruments did excel our resolution expectations when the specimen was moved into the lens. Even low cost twin detector systems proved to have very high resolution levels.

I. Müllerova: You seem to suggest that backscatter dominates most images? Can you be more specific with this statement?

Author: As I mentioned earlier, Everhart (1958) and Everhart *et al.* (1959), and many others referenced by Seiler (1983), have indicated a high level of backscatter or converted backscatter entering the Everhart-Thornley detector. A simple experiment is to obtain a wave form from an image under these conditions and then to insert a backscattered electron detector. You will see the dramatic drop in signal due to the BSE being absorbed by the detector. The higher the density of the specimen the higher the level of backscatter and the more dramatic is the signal drop. With any specimen the presence of shadows indicates a high degree of backscatter, secondaries are attracted into the detector and therefore do not produce strong shadows, but most will agree the presence of shadows add character and depth to their image. The higher the accelerating voltage that we use the greater the level of backscatter contributing to our image. One reason for reducing the accelerating voltage is to reduce the contribution of backscattered electrons and SE3 so that the true specimen surface may be better visualised. On some instruments we are forced to place carbon "absorbing plates" on the bottom of the final lens and apertures in front of the Everhart-Thornley detector in order to obtain a more pure SE image i.e., less BSE influence (Chapman, 1986).