Scanning Electron Microscopy

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Introduction –

Scanning Electron Microscopy is a research practice that utilizes a beam of electrons to generate 3D images of the surface topography of a substance. This practice has been tested and approved by various engineers and scientists to identify the characteristics and composition of unknown substances. Learning these features has led to improved safety and sustainability of various materials. Additionally, students can benefit from learning about the application of SEM research to improve the quality of global architecture. Three points covered in this paper concerning SEM are - Understanding how scanning electron microscopy works, the information it provides, and its applications to information presented in the classroom.

Inner Workings of SEM -

Microscopy is the scientific discipline that works with the visualization of structures that are too small to be observed with the human eye. This field is used in many different disciplines including biology, materials science, and nanotechnology. By using different forms of radiation or particle beams such as light, electrons, or X-rays, microscopy magnifies features at micro to atomic scale dimensions. There are two main types of electron microscopy, however, this paper will only focus on one being Scanning Electron Microscopy (SEM). SEM is an imaging technique that uses a focused beam of high energy electrons to generate images of surface topography and composition. This is different from light microscopes, which still use photons. SEM uses electrons allowing for higher resolution, down to the nanometer scale.

In short, microscopy involves directing a beam-whether light, electrons, or X-rays at a specimen, using the interaction between this beam and the sample to generate an image. The resolution of a microscope, or its ability to distinguish between two closely spaced points, is constrained by the wavelength of the radiation employed. Shorter wavelengths correspond to higher resolution capabilities. While optical microscopes are limited by the wavelength of visible light (400–700 nm), electron and X-ray microscopes have significantly enhanced resolution due to their use of much shorter wavelengths. Electron microscopy uses a beam of electrons in place of light, making images at very high resolutions.

In SEM, a beam of electrons is emitted and focused into a spot using electromagnetic lenses. As the beam scans across the specimen's surface, it interacts with the atoms in the sample, producing various signals, including backscattered electrons, X-rays, and secondary electrons. These signals are detected and used to form high resolution images or analyze elemental composition. SEM is used in fields such as biology, forensic investigations, electronics, and materials engineering. For example, in materials engineering, SEM allows researchers to investigate failure mechanisms or characterize defects in devices like transistors or integrated circuits.

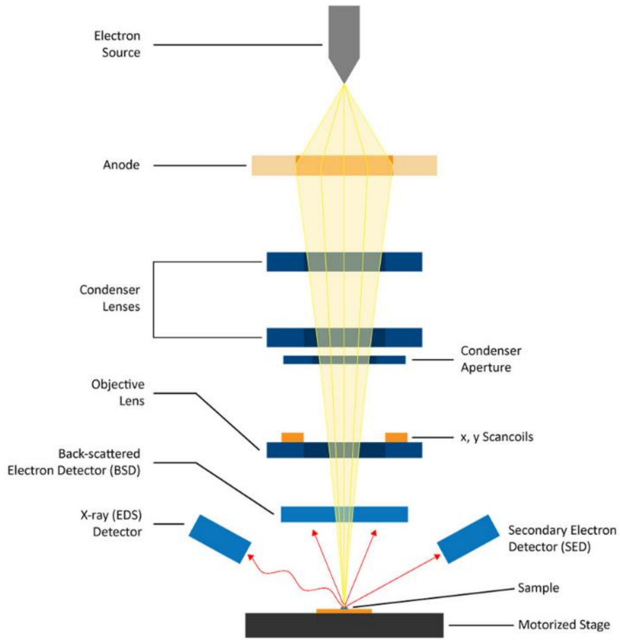


Figure 1 - Schematic of a scanning electron microscope. Photo taken from Nanoscience.com

For SEM to work properly, each sample needs to be set up properly. The samples are dehydrated and then coated with a thin layer of conductive material. This process is especially needed for non-conductive biological specimens. While SEM doesn't provide internal structural information like transmission electron microscopy, it does have the ability to provide 3D like images, making it a very useful tool for surface analysis.

Different microscopy techniques have unique interactions between the incident radiation and the specimen to see detailed information. X-rays are generated by accelerating high-energy electrons and directing them toward a metal target. The sudden deceleration of the electrons results in the emission of X-rays, which can be directed at samples for imaging or analysis. In electron microscopy, interactions between the electron beam and atoms in the sample generate various detectable signals. These include secondary electrons, which provide topographical information; backscattered electrons, which are sensitive to atomic number; and characteristic X-rays, which are used for elemental analysis.

The phase-contrast merging technique uses differences in the refractive index of structures within a sample to enhance contrast, especially in specimens where absorption differences are minimal. Phase-contrast imaging is employed in both X-ray and electron microscopy to see features that would otherwise be too difficult to see.

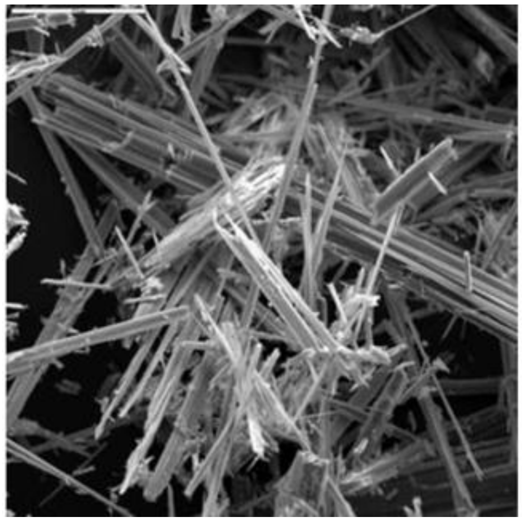
Applications of SEM -

Scanning electron microscopy produces comprehensive 3D photos of the surface formation of materials at immense magnification rates, spanning from ten times to one million times the actual structure size (Mohammed & Abdullah, 2019, para. 1). At such high levels of magnification, the resolution on an SEM is relatively clear, allowing scientists and engineers to view precise images of the material under study. When a material is viewed closely, information regarding the exterior characteristics, such as texture, detail, and shape can be easily viewed at the nanoscopic level. This close interaction shows several details that are not readily viewed by the naked eye. By viewing the imperfections and chemical composition of the substance, with some assistance from Energy Dispersive X-Ray Spectroscopy (EDS), issues such as corrosion, degradation, and wear can be minimized or prevented. 3D renderings are then generated from the images, allowing researchers to conduct simulations of processes occurring in real time.

Below is an image taken by a SEM from the USGS Denver Microbeam Laboratory. (Swapp, 2024, para. 9). The detail presented in this 3D image shows details on the nanoscale that humankind cannot see with the naked eye.

Figure 2

Picture taken by SEM



Note. This picture was produced by USGS Denver Microbeam Laboratory in 2024, which shows a close-up shot taken by a SEM. From, *"*Scanning electron microscopy (SEM)*"* by S. Swapp*,* 2024, (https://serc.carleton.edu/research_education/geochemsheets/techniques/SEM.html).

According to Science Direct, "[SEM]...converts the received signal into gray-scale data, and displays it on the screen" (Xiao et al., 2022, para. 18.4.1.1). Viewing the details of the material at this level can expand the scientific and engineering knowledge of a material. Inspecting the structure of the metal on a magnified level can improve the knowledge held by scientists and engineers. This holds several practical applications, such as improving the stability of skyscrapers, reducing safety uncertainties, improving longevity and increased durability. Additional data that can be determined from SEM consists of resistance, adhesion, coating uniformity. Tests that can be conducted using the given SEM data consist of materials failure inspection, semiconductor manufacturing, and corrosion research.

One study in particular looked at a penny under a high-powered scanning electron microscope. This study was conducted on the bottom level of a lab at the Thomas J. Watson Research Center to minimize vibrations. The researcher placed the penny into the study chamber and shot a beam of electrons down the microscope. The secondary electron detector picked up the signals from the SEM machine and generated 3D images onto a computer screen at a resolution of .0002 microns. The researcher was then able to navigate around the image and then increase or decrease the magnification to focus on different qualities of the specimen. This research can be beneficial for determining if the quality of a material is good enough to replace more expensive materials like those used in computers (Research, 2024).

Scanning electron microscopy can be combined with EDS (energy-dispersive X-ray spectroscopy). This allows material engineers to analyze a sample's structure and arrangement. If a material is made of an unknown structure, engineers, scientists, and researchers are able to display information regarding the chemical components of the questionable substance by bouncing X-rays bouncing off the substance.

Scanning Electron Microscopy can additionally be used to analyze the crystals and microstructures within various alloys and metals. Using SEM in metals and crystals allows scientists to understand the strength of the compound or element by viewing the grain boundaries, phases, and crystal orientations. Understanding these elements can lead scientists to create stronger, more wear-resistant material that can be used in machines, the medical field, the architectural industry, and several other commercial and consumer applications. Conductivity, corrosion resistance, and ion-compatibility are understood through the lens of Scanning Electron Microscopy.

Researchers choose SEM over TEM when they want to capture the exterior topography of some substance. 3D images of the surface can be generated using SEM whereas TEM can only generate 2D images. According to Frontiers in Neuroanatomy, “signals provide a three-dimensional (3D) surface topography and information on the composition of specimens, respectively” (Koga et al., 2021, para. 1). When SEM is combined with Energy Dispersive X-Ray Spectroscopy (EDS), researchers can obtain valuable data regarding the chemical structure on the outside of the substance. Additionally, TEM requires the observed sample to be very thin, forcing researchers using the opposing technique to carefully consider the size of their object. Max Knoll invented the SEM with the intention of creating a device that could process data regarding small or large samples (1970, para. 4.1.1). TEM on the other hand visualizes the layout of atoms in a substance, gets a much better resolution, can view the defects, planes, and crystal structures in a material. Additionally, according to Nature.com, “However, the attainment of high-quality SEM images is contingent upon the high conductivity of the material due to constraints imposed by its imaging principles.” (Gao et al., 2024, para. 1). So, researchers seeking a fast 3D model should consider using SEM, whereas more detailed 2D surface study should be conducted using TEM.

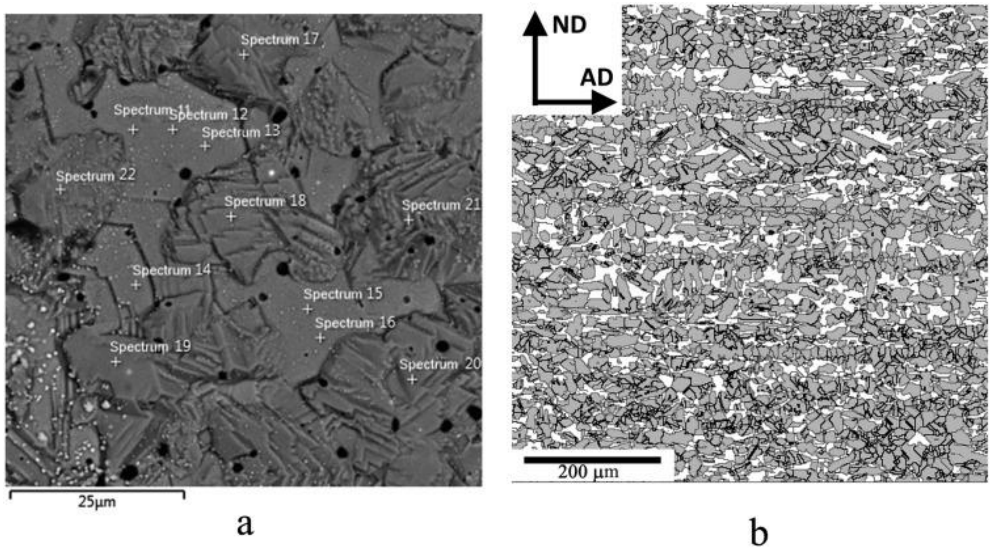
Relevance of SEM to Materials Engineering (ENGM 310) –

The SEM method has significant relevance and influence within the Materials Engineering field. Not only does SEM apply to the broader Materials Engineering field but it also has strong relevance to several of the topics covered this semester. Two topics that SEM relates to that have been covered previously are phases within phase diagrams and failure.

First of all, SEM can help determine the phases present in a material. This topic was covered in chapter 9 of *Materials Science and Engineering* (Callister & Rethwisch, 2020, 252). In chapter 9 section 9 it introduces the concept of different compositions at different temperatures(Callister & Rethwisch, 2020). Within these different compositions there are different phases which express themselves in various ways throughout a material. For example, a phase (say alpha) could be forming particles while the other (say beta) is forming in layers. This type of forming and interconnection between phases could be related to their distribution which is one thing that SEM is fairly good at capturing. SEM has been used for this application before as seen in the following quote, "According to scanning electron microscopy (SEM) undertaken using electron microbe analysis (Fig. 3a) and orientation microscopy as phase maps (Fig. 3b) a brass sample consisted of the β′-phase (Cu0.55Zn0.45, structural type B2) and α-phase (Cu0.65Zn0.35, structural type A1) (was) approximately at 30:70" (Lobanov et al., 2021). Here one can see that SEM was used to determine a relationship between the phases (alpha and beta) within a brass sample. Once one has this ratio, one could consequently use this to help calculate the exact composition or temperature similar to the problems in the text.

Figure 3

SEM data displaying alpha and beta phases of a brass sample



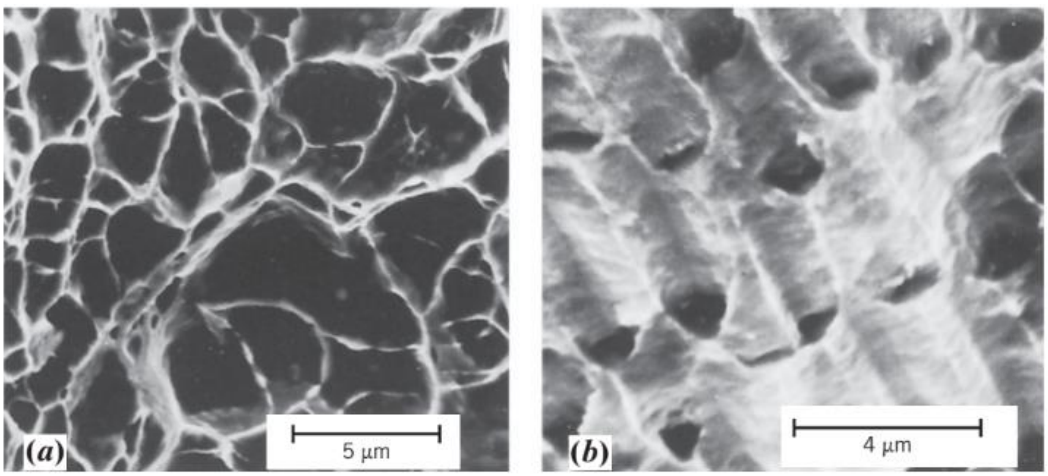
Note. A picture displaying both the electron microbe analysis (a) and orientation microscopy (b) as phase maps. From “Specific features of crystallographic texture formation in BCC-FCC transformation in extruded brass” by M. Lobanov et al., 2021, *Journal of Alloys and Compounds*, 882, (https://www.sciencedirect.com/science/article/abs/pii/S0925838821016406).

It could also be seen that when SEM is employed to determine phases it is also typically coupled with an X-ray method like EDS (energy-dispersive X-ray spectroscopy) or something similar which the study above did later on (Lobanov et al., 2021). An X-ray analysis method can put more confidence in the results gathered from SEM and provide more data relating to the composition (while SEM primarily focuses on morphology). The data gathered with an X-Ray method can sometimes contradict with the conclusions drawn using SEM depending on the sample and so using both is recommended in this area of study in order to improve the rigor of the research.

Second, SEM helps determine the failure of a material. Failure was covered in chapter 8 and since failure is heavily dependent on imaging (seeing how and where a crack propagates) it can become clear how SEM could be used in this study. In fact, most of the images contained within chapter 8 are figures taken from scanning electron fractography which is the specific name for SEM when it is used for failure analysis (Callister & Rethwisch, 2020, 213). One such image in the text displays several ductile fractures (dimples) with different axial loadings -

Figure 4

Scanning electron fractography



Note. Picture displaying spherical ductile fractures (dimples-like characteristics) caused by uniaxial tensile loads taken by an SEM method. From *Materials Science and Engineering: An Introduction* (10th ed., p. 213), by Callister & Rethwisch, 2020, Wiley.

SEM has numerous benefits and there are many reasons why it is used within failure analysis. As stated again here, “The most widely used method for studying fracture surfaces is scanning electron microscopy (SEM). The high resolution, good depth of field but ease of specimen preparation makes it highly suitable for examining polymer composite surfaces” (Greenhalgh, 2009). To emphasize, SEM is incredibly skilled at displaying the depth of a sample. This is important when considering failure as it can display the topography of a surface and how the sample reacts to the given load. Because of this, it can be better than other options like a typical optical microscope (which typically would not provide enough detail) or other visual procurement methods. While the quote above specified polymers, SEM is by no means refined to this. In fact, the book primarily talks about it in reference to metal fracture applications (Callister & Rethwisch, 2020, 213). Since SEM is simply a 3D imaging procurement method the type of material should not, theoretically, restrict the results.

Additionally, one particular test using SEM determined when and where certain fibers ruptured under tension which would be an example of failure (Alwani et al., 2015). While not as a direct consequence of SEM, this same research was primarily concerned with the properties of the fibers - the elastic modulus, the brittleness of the material, average tensile strength among other properties. These types of properties were covered extensively in chapter 6 (Callister & Rethwisch, 2020). This shows that SEM can be used to discover or relate to even other aspects of Materials Engineering not mentioned within the scope of this paper which makes SEM a truly unique and invaluable method.

Conclusion –

In conclusion, scanning electron microscopy (SEM) is an imaging tool that has been used throughout the years to help scientists and engineers sort, classify, and advance humanity's understanding of materials. Three particular aspects of SEM that were covered in this paper were a basic understanding of how scanning electron microscopy works, some of the information it provides, and its applications to information presented a materials course (ENGM 310). SEM is an innovative tool and currently holds a valuable place within the engineering field by researching different aspects of material properties and failure. In the end, SEM has grown the world's understanding of the matter that exists everywhere. This matter being the material that God choose to create and form the earth with and through which humanity can cultivate and grow – glorifying Him all the more.

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