Electron Yield of a Carbon Fiber Composite

Matthew Robertson and JR Dennison

Materials Physics Group
Utah State University

Abstract: As electron yield models continue to evolve and improve, a study of carbon fiber materials was conducted to try and understand more complex nanoscale structures and their influence on electron yield.

Introduction

Electron yield is a material property that describes under electron bombardment the ratio of electrons which leave the material versus the number of electrons which enter the material. It is measured by irradiating a sample with an electron beam and measuring the ratio of secondary electrons emitted from within the material to incident electrons from an electron gun. Electron yield is used in understanding, modeling, and mitigating spacecraft charging. It is also used in scanning electron microscopes, particle accelerators, plasma TV displays, phototubes, electron multipliers, microwave multipactors, ion thrusters, and high-voltage insulators.

Spacecraft charging is a concern to NASA because it causes most environment-related anomalies in spacecraft.[1] The better understood the electron emission and transport properties of a material, the better spacecraft charging can be mitigated. The purpose of this research is to refine models for electron emission and transport phenomena by understanding the influence of nanoscale structures.

The electron yield of a sample is influenced by many factors.[2]Every material has its unique electron yield which is determined by its chemical composition and electronic structure. The yield is also energy-dependent and varies with the energy of the incident electrons. The surface of the material has a big impact on the electron yield. This is because most electron emissions originate near the surface of a material. Even a thin layer of another material on the surface of a sample can have a dramatic effect on the yield.[3] Modeling electron yield becomes more complex when dealing with multilayer effects.[4]

The electron range in a material determines the scale at which surface features are relevant. As the energy of the electrons increases, the further they penetrate a material (see Fig. 3). At low energies only surface features on the scale of a few nanometers affect the yield. As electrons increase in energy and penetrate deeper into the material, a greater range of surface features become relevant. For surface features such as multilayer effects to be seen they need to be on the scale of electron penetration depth.

Modeling the electron yield of multilayered materials is dependent on the electron yield of the different materials, the depth of the surface layer, and the range of electrons in the materials. While we currently have simple slab models for multilayered materials, they do not consider other factors such as surface roughness, contamination, or other complex surface structures.

By studying the electron yield of more complex surfaces, It should be possible to extend current multilayer models to more dynamic structures. The complex nanoscale features of advanced composite materials provide an opportunity to study electron yield of more complex surfaces. For this study data were taken on a carbon composite material and its constituent materials, epoxy and carbon.

Carbon Fiber Composites

Carbon-fiber composites have a complex three-dimensional nanoscale structure consisting of both an insulating epoxy matrix and conducting carbon fibers Composites materials are a great candidate to study because of their unique nanoscale structure and their widespread adoption in the aerospace industry for their high strength-to-weight ratios and other extreme properties. Data for these new materials are essential for engineers to make decisions on which materials to use in their spacecraft.[5] Studying the electron yield and other properties of composite materials will provide the data needed to model and understand how two discrete materials and their nanoscale structures influence the electron yield of composite materials.

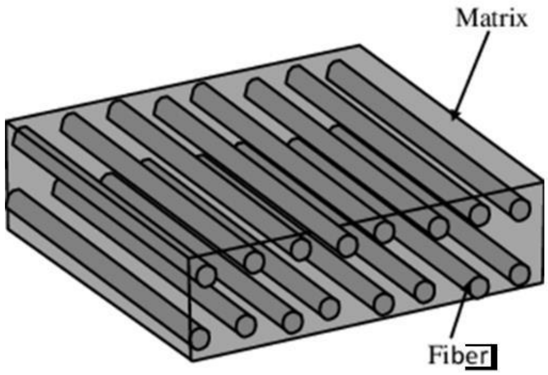

Figure 2. Schematic of an advanced composite material. Strands of a reinforcement fibers embedded in an epoxy matrix.

Composite materials are characterized as being a material constructed out of two or more materials. Advanced composite materials such as carbon fiber are characterized using a resin reinforced with a fiber material (see Fig. 1). Fibers used in advanced composite manufacture come in various forms, including tows, yarns, roving, chopped strands, and woven fabric mats.[6] Understanding the electron yield of these complex structures should help to better extend simple multilayer models to more complicated surfaces.

Data

The electron yield data were taken in an ultra-high vacuum chamber with the use of two different electron guns ranging in energies from 15 eV to 30,000 eV.[7] The use of a hemispherical grid retarded field analyzer helps to capture electrons ensuring a high accuracy of the data. The total electron yield of a carbon fiber material and its constituent materials are shown in Fig. 2.

Of the three data sets the graphitic carbon has the smoothest curve. This is because carbon is a conductor and is not prone to charging. Insulators like epoxy tend to charge up and distort the data.[2] When insulators charge up it can have a dramatic effect on the electron yield.[8] Typically, charging moves the electron yield towards a value of one. This can be explained by remembering electron yield is the ratio of electrons out over the number of electrons in. When this ratio is less than one this means more electrons are going into the material than leaving the material. In an insulator this would result in a net negative charge build-up. A negatively charged sample will repel incoming electrons which will reduce the number of electrons that enter the sample shifting the ratio closer to one. An example of negative charging can be seen at around three-

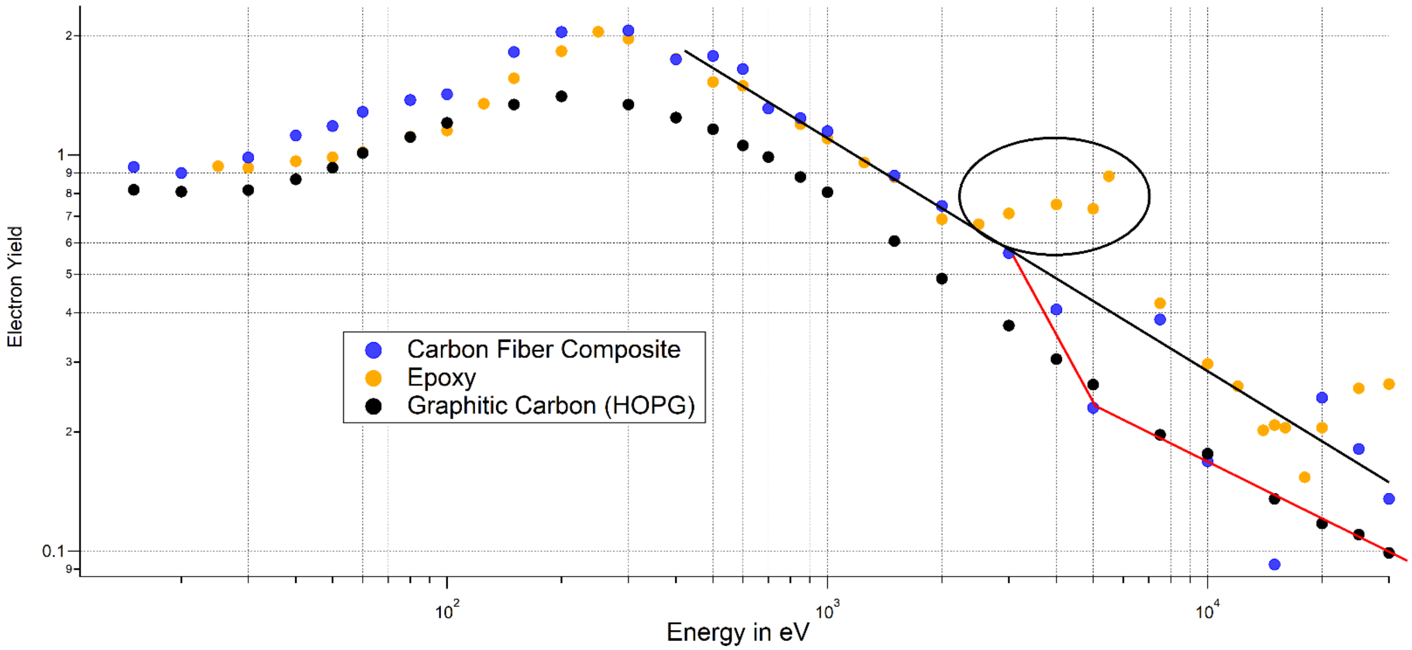

Figure 1. Total electron yield of a carbon composite and its two constituent materials. The black circle highlights an example of negative charging moving the yield towards one. The black and red line is an aid to help see possible trends in the data.

thousand electron volts highlighted by a black circle in Fig. 2.

In the case electron yield is greater than one, more electrons are leaving the material then entering. This will result in a net positive charge. The positively charged sample will reattract low energy secondary electrons, increasing the number of electrons entering the sample and once again moving the ratio or electron yield closer to one. Effects of positive charging might be seen in the epoxy data between 30 eV and 100 eV. There is reason to suspect the epoxy yield data should be higher, closer to that of the carbon composite electron yield data.

Analysis and Results

The first basic prediction was the carbon fiber data would be some average of the two base materials. If this were the case, the electron yield curve of the composite would lie somewhere between the carbon and epoxy yield curves. However, looking at the data it seems as though the carbon fiber composite data lies mostly in line with the epoxy data than with the carbon data. To understand the data and what to expect, it is necessary to better understand the surface features of the carbon fiber composite.

A surface layer of epoxy is typical in carbon composites, due to the impregnation process of the epoxy matrix. This sample was cited to have a surface layer of 25 μm of epoxy.[9] In epoxy an electron is estimated to have a range of 25 μm at an energy level just above 20,000 eV (see Fig. 3). If the sample has a 25 μm layer of epoxy, then we should only begin to see multilayer effects once the electrons have penetrated this surface layer at around 20 keV. In this case, at energy levels below 20 keV, the data of the carbon composite material would look just like the data for epoxy.

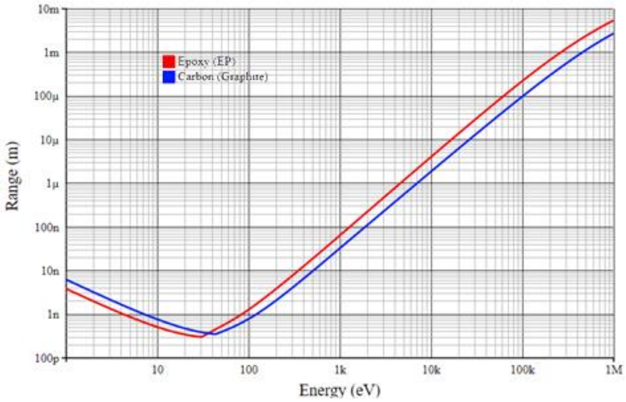

Figure 3. A graph of the Range of an electron vs energy in eV in epoxy (red) and carbon (blue)[10].

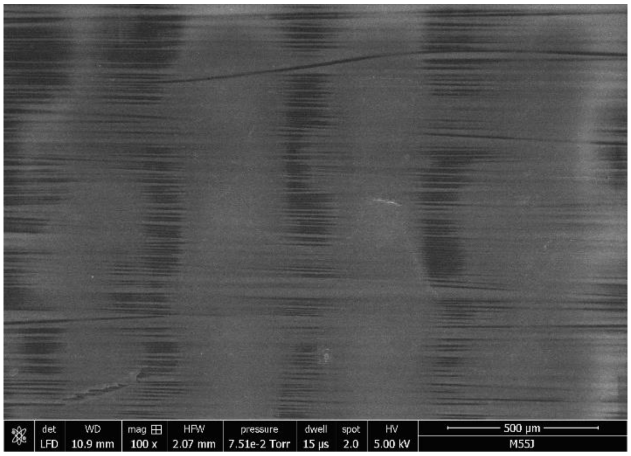

Figure 4. SEM picture of carbon fiber composite sample. Image was taken at 5 KeV.

An SEM image of the sample (see Fig. 4) provides us with some more information about the surface. The picture was taken at 5 keV. Although the SEM image does not give us a measurement of the depth of the epoxy surface layer it does provide us with evidence the surface layer is likely much less than 25 μm. The SEM image shows us the carbon fiber strands are visible to electrons at an energy level of at least 5 keV. If the above-cited surface depth of epoxy was correct, then the SEM image should only have a view of the epoxy surface. In the SEM image black horizontal strands are visible. These strands were measured to be between 5 μm to 8 μm in diameter. The data sheet for this sample cites the carbon fibers to be around 5 μm in diameter.[11] The black stripes seen in the image are most likely the carbon fiber strands within the composite. Another part of the image worth pointing out is the vertical stripes of bright spots on the image. Bright spots in SEM images can mean the material is charging up and making it difficult to capture. the epoxy on the surface is probably charging and causing the bright spots. It could also mean the layer of epoxy is not uniform on the surface. This could explain why there are sections where the carbon fibers are clear and sections where it is more difficult to see them.

With this new information it is expected at the very least to see multilayer effects from the carbon fiber layer below the epoxy layer at an energy level of 5 keV. Looking again at the data, the electron yield of the carbon composite has its first major deviation from the epoxy data at 4 keV. At this energy level the electron yield data drops down lower than expected

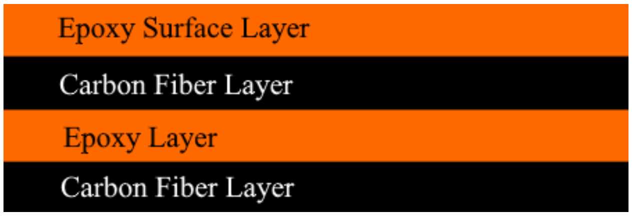

Figure 5. A cross-sectional simplified approximation of a carbon fiber composite. The slab model consists of alternating homogeneous layers of epoxy and carbon.

nearing the carbon data. At 5 keV and up there are some data points that appear to be following the carbon data more than the epoxy data (see red line in Fig 2).

This sample is cited as having a fiber volume ratio of 60%.[11] Even after penetrating the epoxy surface it is still expected there will be a mixture of epoxy and carbon. Also, the surface layer should continue to have a big impact on the yield even after electrons penetrate the surface. The electron yield curve should lie somewhere between the epoxy and carbon electron yield curves at high energies.

Modeling Composite Yield

There are two simple ways to approximate the carbon fiber to predict what the energy-dependent electron yield data might be. One method is to approximate the carbon composite as alternating layers of epoxy and carbon (see Fig. 5). In this slab model the carbon fiber layer has a thickness of 5 μm, the diameter of the carbon fiber strands. According to the range graph, it takes an energy level of 20 keV to penetrate 5 μm of carbon. For an electron to penetrate down into a third layer it would need to first penetrate the epoxy surface and carbon fiber layer, this would require an energy of at least 20 KeV. This allows further simplification of the model by using only two layers. A surface layer of epoxy followed by one layer of carbon. This bilayer approximation allows the use of simpler bilayer models to predict the electron yield

Figure 6 shows the results of a multilayer experiment using carbon and gold. In this experiment a series of carbon samples were prepared with increasingly thick surface layers of gold[12]. At low energies even the thinnest gold surface of 1 nm has an electron yield curve close to gold. This is because there is little penetration of the surface layer at low energies. At higher energies the electron yield begins to deviate from the gold curve. The energy level it begins to deviate and by how much it deviates depends on the thickness of the surface layer. For example, the 1 nm gold on carbon sample's yield curve begins to deviate from the gold curve at around 400 eV. This sample's yield curve is also much lower than the gold curve. The 50 nm gold on carbon sample does not begin to deviate from the gold curve until 4 keV and its yield never drops too far from the gold curve. This situation is like the epoxy layer on top of the carbon composite. Although we do not know the exact thickness of the epoxy layer, we should expect at higher energies for the electron yield to decrease due to the carbon layer below it. Depending on the thickness of the epoxy surface layer we should expect the electron yield to fall somewhere between the epoxy curve and the carbon curve.

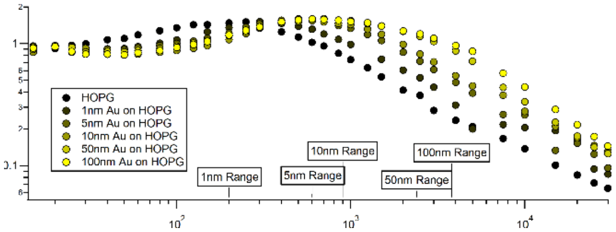

Figure 6. Layers of gold with thicknesses ranging from 1nm to 100 nm on top of carbon[12].

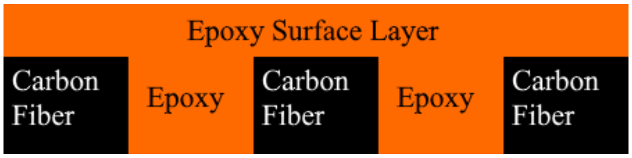

Figure 7. Cross-sectional view of a simplified approximation of a carbon fiber composite.

The bilayer model is a good starting point, but it is easy to see by looking at the SEM image the carbon fiber layers are not homogeneous. There are gaps between the fibers and these spaces are filled with epoxy. We can model this by assuming equally spaced stripes of alternating carbon and epoxy below the epoxy surface (see Fig 7). In this case, once an electron has penetrated the surface it has equal odds of either entering a carbon or epoxy patch or pillar. If an electron enters an epoxy patch, then it is no different than if the sample was bulk epoxy. If the election enters the carbon patch, then it should return a yield result like the two-layer approximation. Assuming the electrons are spread evenly among the two materials then the resulting electron yield should be a weighted average of the two yields. Depending on the relative widths of the carbon fiber and epoxy pillars and the thickness of the epoxy surface layer. This approximation would also result in an electron yield curve between epoxy and carbon at higher energies. Where the curve would lie between the constituent's yield curves will depend on the patch sizes of the epoxy and carbon stripes.

These two simplified models should give us a good starting point to begin to understand the electron yield data. Both models predict the curve will mimic the epoxy curve at low energies. At high energies the two simplified models predict a curve which lies somewhere between the carbon and epoxy. Although on average the electron yield curve does seem to fall between the two curves, the data is too noisy to know for sure. There may be interactions the approximations are not accounting for and the data could be correct, but there is reason to suspect the data above 4 keV is inaccurate.

Taking data on materials prone to charging can be difficult and as discussed above can change the electron yield of the data. Another possibility for the noisy data could be a non-uniform surface layer. If the epoxy on the surface varies a lot in thickness, then this could change the electron yield data depending on the location of the electron beam on the sample. Also, differences in the roughness of the epoxy on the surface of the composite versus the roughness of the bulk epoxy could give different yields than expected.

Conclusion

Further work will be required to fully understand and model the electron yield of the carbon fiber composite material. further characterization of the surface layer of epoxy will be needed. Knowing the exact thickness of the epoxy layer on the surface and how uniform it is will help in making predictive models. It will also help to know if any special adjustments need to be made in how the data is being taken. Special attention needs to be made to dissipate any charging between measurements. Although these methods were used the first time the data were taken, there is evidence of charging within the data, to suggest these methods were not working as efficiently as they should have.

It will also be helpful to prepare a series of carbon samples with increasingly thicker layers of epoxy on the surface. Electron yield data on these new samples will be useful in a couple of ways. By comparing the new samples to the composite data, it will be possible to see how accurate the simple two-layer approximation of one epoxy layer and one carbon layer is to the composite material. The data will also be needed to validate the second proposed model of patches or pillars of carbon and epoxy beneath the epoxy surface layer. According to the patch model the electron yield should be some sort of weighted average between bulk epoxy and carbon with a layer of epoxy on top.

This first set of data has helped to begin to understand the electron yield of the carbon fiber composite sample. It has also given insight into the next steps to be taken to come up with an accurate model for its unique structure. Cleaner high energy data and data on new multilayer epoxy-carbon samples should provide the necessary tools to successfully model the electron yield of this and other composite materials.

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