

INVESTIGATION OF CARBON FIBER ARCHITECTURE IN BRAIDED COMPOSITES USING X-RAY CT INSPECTION

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ABSTRACT

During the fabrication of braided carbon fiber composite materials, process variations occur which affect the fiber architecture. Quantitative measurements of local and global fiber architecture variations are needed to determine the potential effect of process variations on mechanical properties of the cured composite. Although non-destructive inspection via X-ray CT imaging is a promising approach, difficulties in quantitative analysis of the data arise due to the similar densities of the material constituents. In an effort to gain more quantitative information about features related to fiber architecture, methods have been explored to improve the details that can be captured by X-ray CT imaging. Metal-coated fibers and thin veils are used as inserts to extract detailed information about fiber orientations and inter-ply behavior from X-ray CT images.

1. INTRODUCTION

Textile reinforced composite materials are used in many aerospace, industrial and commercial applications. One benefit of using textile reinforcements is that the reinforcement can be made to conform to complex shapes either by fabricating preforms to net shape or by deformation of a compliant preform during fabrication. Although this is beneficial for manufacturing, it presents challenges in the design, analysis, and testing. X-ray CT inspection can provide high resolution visual information about local fiber angles, fiber undulation, and the presence of defects. However, to take full advantage of the X-ray CT data, methods for automated data analysis need to be developed to quantify variations in local fiber architecture and to provide data that can be used in structural analysis. In this paper an approach using metal coated carbon fiber tows and lightweight metal coated carbon fiber veil as a tracer materials for X-ray CT inspection is examined. The tracer materials are placed between layers of (0/+60/-60) braided prepreg during layup of composite panels. X-ray CT inspection is then performed on sections cut from the cured panels. Data analysis methods for quantifying inter-ply nesting and fiber tow undulation are developed using this data, and an approach for using the data to provide fiber tow geometry input for finite element analysis is described.

X-ray Computed Tomography (CT) is a non-destructive technique used to create images of the internal features of solid objects. This process involves the use of x-rays to create cross-sections of a solid object, which are combined to create a 3-D virtual model. X-ray Microtomography (micro-CT) refers to the pixel size of each cross-section being in the micrometer range. In this work, X-ray micro-CT is being utilized, but is referred to more generally as X-ray CT. A CT image can be referred to as a ‘slice’ and corresponds to the image of the scanned object if were to be sliced open along a plane.

The use of X-ray CT to characterize the microstructure of fiber-reinforced composites is a promising approach. However, for composites of carbon fibers in a carbon-based matrix, difficulties arise due to the similar densities of the materials. This causes poor contrast among the constituents. As a result, features that are readily apparent visually are difficult to extract from the data using automated image analysis methods. Some methods for improving contrast for X-ray CT of ceramic composites have been studied [1-5]. Many of these approaches involve techniques applied during fabrication of the composite. Since the processing methods for carbon fiber polymer matrix composites are different, another approach is needed.

2. EXPERIMENTAL METHODS

2.1 X-ray CT

Composite coupons were scanned using X-ray Micro-CT. The microfocuss X-ray source used was an X-ray WorX XWT-225-SE. The detector was a Dexela 2923 flat panel high speed, low noise X-ray detector. Computing was performed on an NSI SuperComputer with 3D visualization software including NASA custom software. The resolution capability was dependent on part size. Coupon geometry was square with thickness ranging from 3.175-6.35 mm, and lateral dimensions ranging from 12.7-101.6 mm. Resolutions in the range ~10-25 μm were achieved. Additional details of the X-ray CT setup for some of the scanned parts are listed in Table 1.

Table 1. X-ray CT equipment and setup details

	12 ply, 63.5 mm square composite	12 ply, 12.7 mm square composite	6 ply, 12.7 mm square composite
X-ray Source	XRayWorX	XRayWorX	XRayWorX
focal spot mode	Microfocus	Microfocus	Microfocus
voltage	80 kV	90 kV	90 kV
current	60 μA	50 μA	50 μA
Detector	Dexela 2923 [2216]	Dexela 2923 [2216]	Dexela 2923 [2216]
pixel pitch	[75 x 75] microns	[75 x 75] microns	[75 x 75] microns

mode	Freerun (High gain)	Freerun (High gain)	Freerun (High gain)
binning	1x1	1x1	1x1
framerate	4 fps (250.004 ms integration time)	4 fps (250.004 ms integration time)	4 fps (250.004 ms integration time)
Distances:			
tube to detector	760 mm (FDD)	760 mm (FDD)	760 mm (FDD)
tube to part	260 mm (FOD)	100 mm (FOD)	100 mm (FOD)
zoom factor	x2.92	x7.6	x7.6
fixturing	on rotational stage	on rotational stage	on rotational stage
filter	50.8 μm copper	50.8 μm copper	50.8 μm copper
CT Scan:			
# projections	1800	1800	1440
# frames averaged	4	4	4
resolution	25.9 μm	10.5 μm	10.4 μm

2.2 Image Post-Processing

Image processing for the X-ray CT data was primarily performed using Avizo 3-D visualization and analysis software (FEI Company, Hillsboro, OR). Additional analysis was performed using MATLAB (Mathworks, Natick, MA) and LS-PrePost (Livermore Software Technology Corporation, Livermore, CA). Using Avizo, filtering was applied and attempts were made to isolate the composite constituents. While this proved to be difficult due to the similar densities of the materials, when high contrast materials were included in some scanned parts, Avizo was very effective at isolating these materials. The geometric features of these high contrast areas were exported in STL format. This STL data was further analyzed within MATLAB and LS-PrePost.

2.3 High Contrast Materials

For most experiments, 6- and 12-ply panels were fabricated using (0/+60/-60) braided prepreg and autoclave curing. The prepreg was made using T700S carbon fibers (Toray Carbon Fibers America, Inc., Santa Ana, CA) and TC275-1 epoxy resin (TenCate Advanced Composites, Morgan Hill, CA). High contrast materials were placed between selected plies during lay-up. Panels were vacuum-bagged and cured in autoclave. Smaller parts were then cut from the cured panels for X-ray CT scanning.

In addition, forming of simple shapes was considered using a mold (Figure 1) made by 3-D printing.

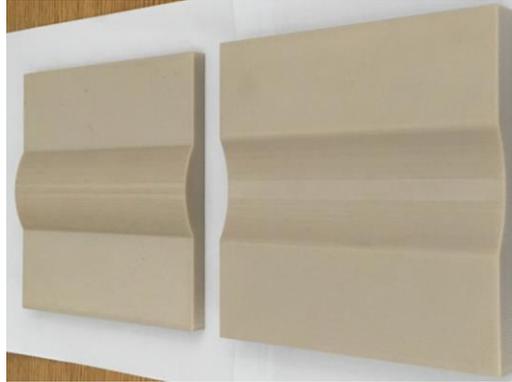


Figure 1. 3-D printed mold for forming of triaxial braided carbon fiber polymer matrix composite prepreg layups; mold dimensions are 152.4 mm square with a 50.8 mm wide, 6.35 mm high cylindrical bump.

3. RESULTS

3.1 Architecture Variations

Sections of composite panels were first examined without using contrast enhancing materials between plies. Large distortions of fiber tows are easily detected visually in images from the X-ray CT scan of a 12-ply flat panel (6.35 mm thick and 63.5 mm lateral edge) (Figure 2 b, d, and e). However, attempts using Avizo to segment the data into individual fiber tows and resin had failed. The contrast was too poor, and the results gave only cloudy images from which no quantitative information about local fiber tow orientation could be gained. It was also not possible to determine the extent of inter-ply nesting because of the poor contrast.

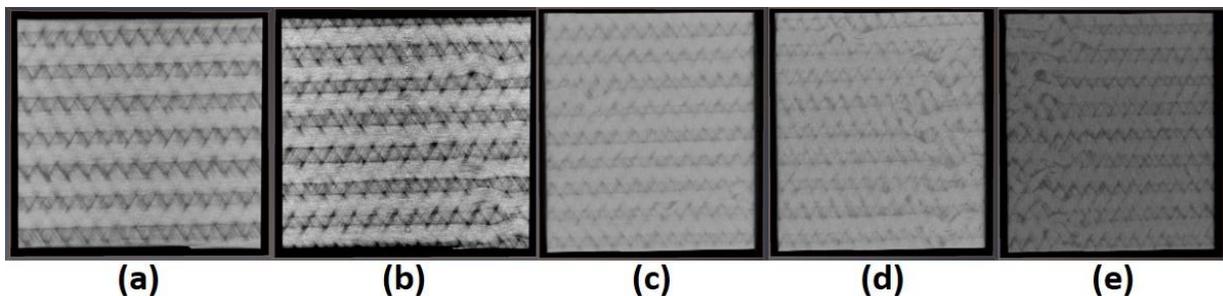


Figure 2. X-ray CT slices of 12-ply, 63.5 mm square panel, axial tows horizontal. Each slice represents a different location in the thickness of the panel. (a) Axial tows appear straight at this location. (b-e) Axial tows appear deformed at these locations.

3.2 Fiberglass Veil Inserts

In a first attempt to measure inter-ply nesting, a 304.8 mm square, 12-ply panel was fabricated, with ply deliberately staggered so that axial tows in adjacent plies were nested. Thin fiberglass

veil material (squares of approximately 25.4mm size) was placed at two locations near the center of the panel on plies 1, 6 and 11 (Figure 3). After curing, a 63.5 mm square subpanel containing the fiberglass patches was cut from the panel and X-ray CT scan was performed.

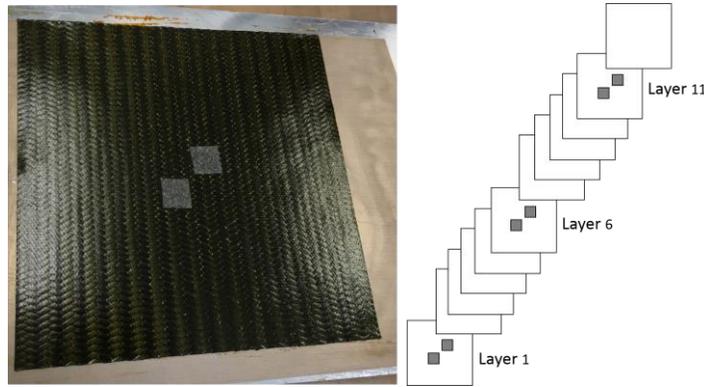


Figure 3. A 304.8 mm square prepreg panel was made that included 25.4 mm square fiberglass veil patches placed at two locations near the center of the panel on plies 1, 6 and 11.

The intent was to provide a large contrast between the fiberglass and other constituents. In analyzing the data, however, it was difficult to recover the fiberglass material; additionally, there was very poor resolution in CT slices in the thickness direction (Figure 4). To obtain better resolution, two smaller pieces were cut from this subpanel: a 25.4 mm square piece and a 12.7 mm square piece. Each of these smaller pieces was cut from an area containing the fiberglass patches.

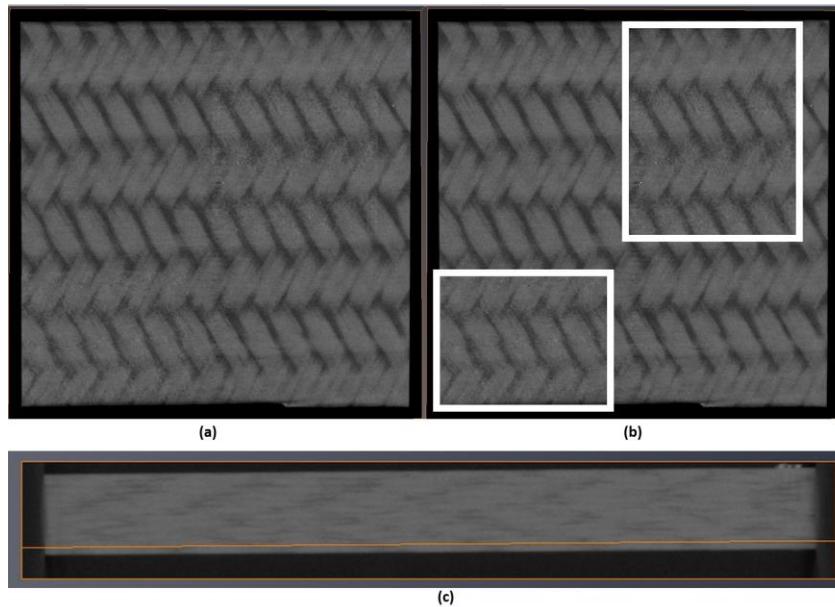


Figure 4. (a-b) Duplicate images of a CT slice after filtering containing fiberglass patches; (b) has boxes around the patches. (c) CT slice showing the poor resolution in the thickness direction.

The fiberglass patches were qualitatively much more visible in the data from the smaller pieces. In the thickness direction, especially for the 12.7 mm square piece, bits of the cross-section of the fiberglass patch can be recovered (Figure 5). In Avizo, filtering was used to enhance the intensity of the pixels representing these fiberglass bits. These bits could then be isolated, and these steps could then be automatically applied to all the CT slices in the thickness direction. The results were able to be 3-D rendered to recreate an image of the fiberglass patches (Figure 6). The manual processing in Avizo as described was ~5 hours. This data was extracted as an STL file for further quantitative analysis. Although these results might be useful, it would be much better to recover images with more clarity and hence more accurate data for quantitative analysis.

3.3 Metal and Other Contrast Materials

Single digital radiograph (DR) scans were used instead of full X-ray CT scans in an effort to simultaneously test multiple materials for use as high contrast inserts. A full X-ray CT scan involves thousands of individual DR scans, and the data from each are combined to form the CT data set. The advantage of testing contrast in a single DR is that a near-instant image can be obtained, and the image is representative of how the material may appear in a full CT scan. This strategy also saves time by avoiding fabrication of composites containing the high contrast material inserts. The disadvantage is that all contrast values through the thickness of the scanned material are averaged into a single image.

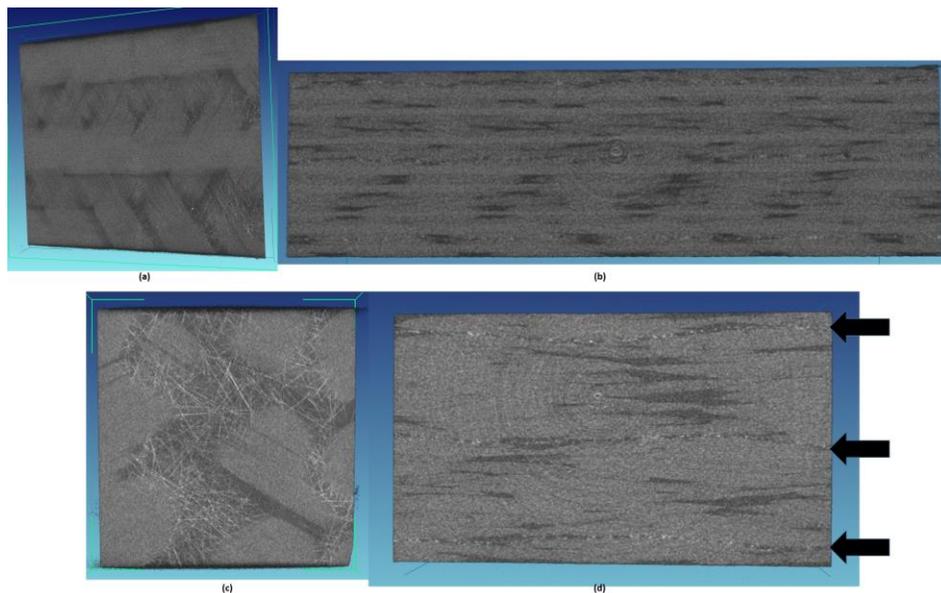


Figure 5. (a-b) CT slices for a 25.4 mm square part containing fiberglass patch, (b) shows the thickness direction. (c-d) CT slices for a 12.7 mm square part containing fiberglass patch, (d) shows the thickness direction and arrows mark the approximate locations of the patches (horizontal).

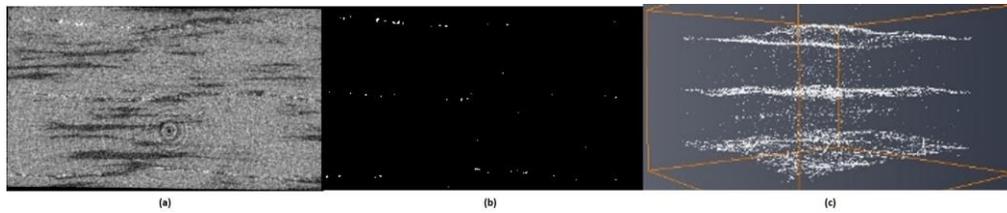


Figure 6. (a) CT slice from Figure 5(d) which was filtered to enhance the pixels representing fiberglass bits. (b) Fiberglass bits isolated. (c) Fiberglass bits from all slices rendered into a 3-D image.

For these tests, wood, plastic and lead samples were taped to a small piece of composite and the single DR performed. The results for the lead solder were very promising in terms of its contrast against the composite constituents (Figure 7, top); however, because metal has a much higher density than the carbon materials, there is a possibility that the data in the CT scan would be obscured near the metal. However, the lead solder did not appear to obscure the adjacent area in the single DR. The plastic materials, especially the plastic tape, did not seem to provide a strong contrast. The wood is visible in the DR and helps to provide information for the comparison of the densities of these materials. However, wood would not be a good choice as a tracer material since it would likely interfere with the composite microstructure.

Based on these results, another single DR was performed on a small piece of composite affixed with copper/nickel coated carbon fiber mesh and tows of nickel-coated graphite fibers of various amounts. Some of these metal-coated materials appeared to have a good contrast in the DR image (Figure 7, bottom).

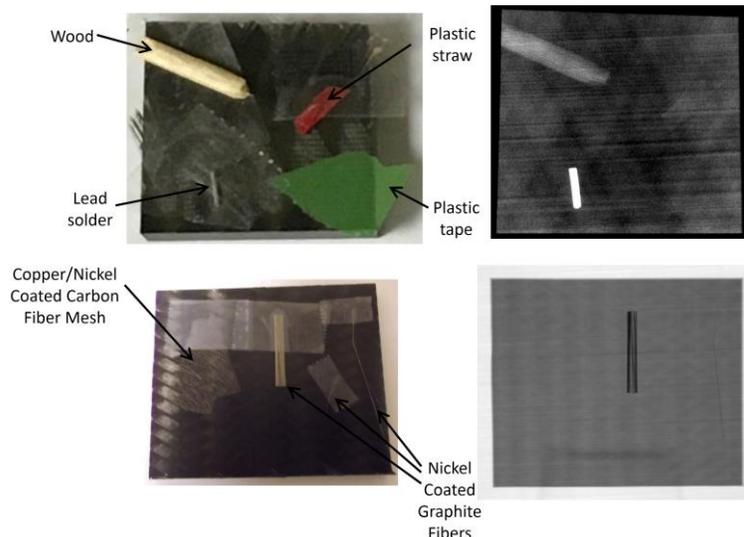


Figure 7. Single digital radiographs (right) were performed on small pieces of composite with different materials taped on them (left).

Because air shows contrast in a CT scan, an insert was made using phenolic resin beads which had been dissolved in ethyl alcohol and painted on a fiberglass veil. Since these beads are hollow microspheres, it was hypothesized that they would appear as air in the CT data and therefore in contrast to the carbon constituents.

A 12-ply part was fabricated using the bump mold from Figure 1. Laid in between plies 6 and 7 were a bundle of metal-coated fibers, a strip of metal-coated veil, and a strip of fiberglass veil that had been painted with phenolic beads. After curing, 25.4 mm square pieces were cut from locations in the bump area which contained the contrast materials (Figure 8).

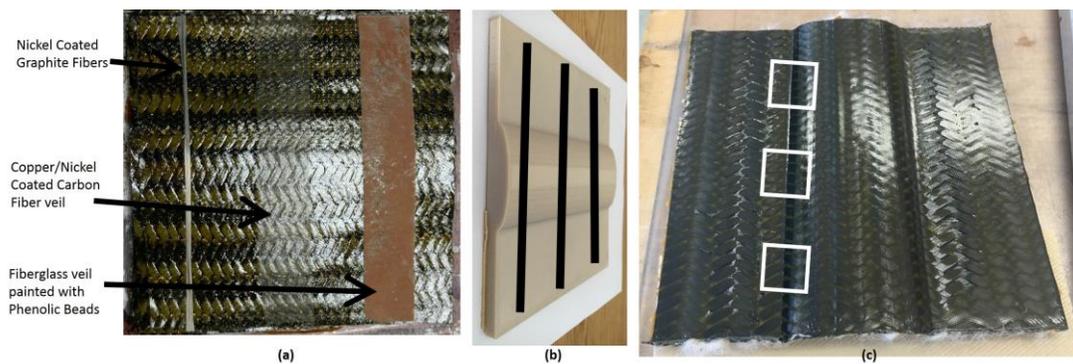


Figure 8. (a) A 12-ply part was fabricated containing strips of contrast materials between plies 6 and 7. (b) A forming mold was used, with contrast materials laid perpendicular to the mold bump. (c) Pieces were cut from areas spanning both the flat and curved area as well as containing contrast material.

The results for the metal-coated fibers and metal-coated veil were very promising (Figure 9). The contrast of the metal material in the CT data was very good, and isolating the material in Avizo was easy. After isolating the contrast material, it was possible to export its geometric features for quantitative analysis. For the material coated with phenolic beads, the contrast in the CT data was good, but similar densities throughout the part caused issues in attempting to isolate the material using Avizo. In addition, it appeared that this material also created a larger gap between the composite plies; any inserts to be added to composites should have as little effect on the natural microstructure as possible.

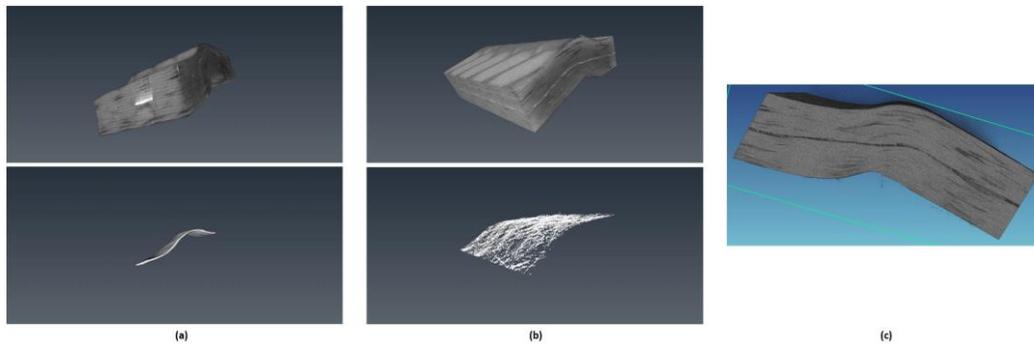


Figure 9. (a) CT data of composite part containing metal-coated fiber tow; the tow was easy to isolate using Avizo. (b) CT data of composite part containing metal-coated veil; the veil was easy to isolate using Avizo. (c) CT data of composite part containing veil coated with phenolic beads; while the contrast was good, it was not possible to isolate the material using Avizo.

Another 12-ply panel was fabricated containing tows of metal-coated fibers, and various coupons were cut for CT scan. The metal-coated tows were easy to isolate using Avizo, and showed much detail; some of these results can be seen in Figure 10. Once a tow is isolated, it can be covered with an iso-surface mesh using Avizo (Figure 11). This 3-D triangular mesh can be exported as an STL file. As an example, this STL file was imported into LS-PrePost, where a surface fit operation was performed. The data points from this 2-D surface could then be used for quantitative analysis. The steps described can also be used in a similar way for parts containing the metal-coated veil material.

There is currently work in process to embed high contrast tracer material into the braided material itself. For this, tracer plies are being fabricated by replacing entire tows of carbon fiber with tows of tracer material. Panels will be made using these tracer plies and resin infusion methods. In addition, metal-coated veil patches will be placed between plies.

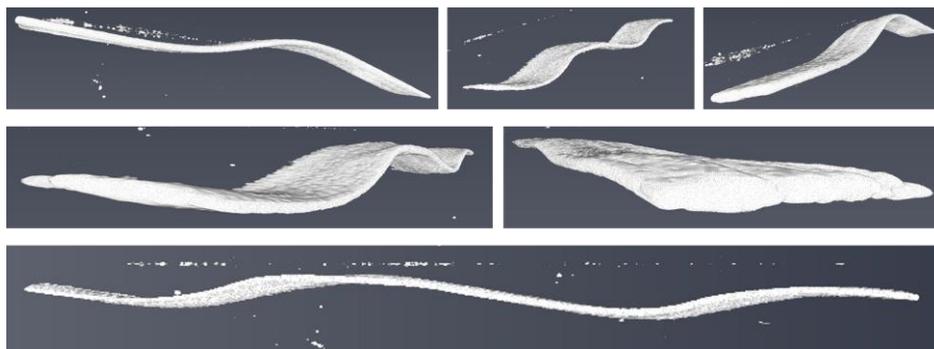


Figure 10. Images from CT scans of metal-coated tows contained within composites, after tows were able to be isolated using Avizo.

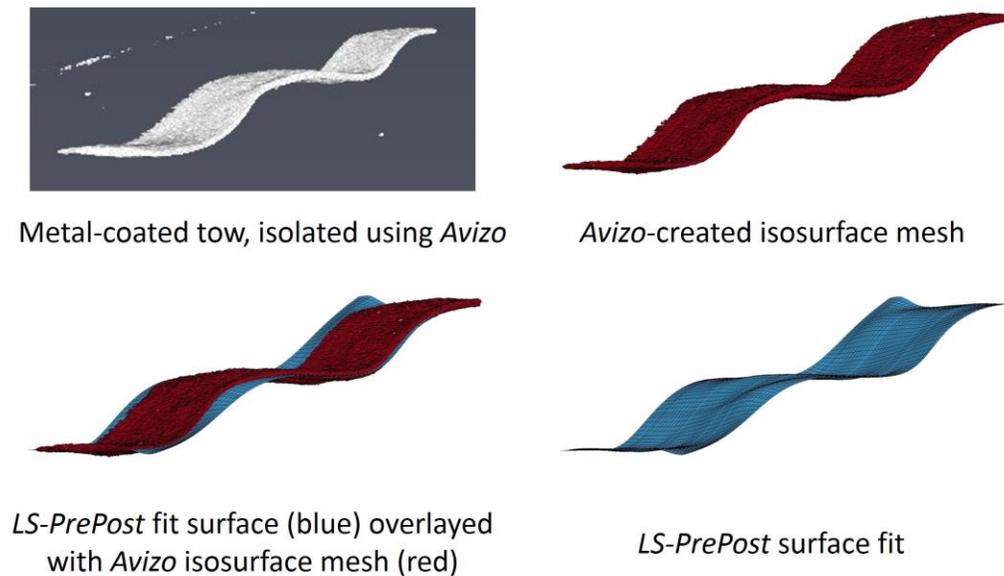


Figure 11. An example of the steps for extracting data from isolated metal-coated tows for use in quantitative analysis.

4. CONCLUSIONS

Methods have been developed for recovering quantitative data about the microstructure of braided carbon fiber reinforced polymer matrix composites. Through the use of metal-coated materials as inserts, better contrast among the composite constituents in an X-ray CT image can be obtained. It has been shown that metal-coated fiber tows and very thin metal-coated fiber veil inserts between plies can be used as tracers to track inter-ply nesting of axial tows and intra-ply undulation of bias tows. These high contrast materials can be easily isolated in image processing software, and the geometric details exported for quantitative analysis.

5. REFERENCES

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