

VARIABILITY IN MICRO-COMPUTED TOMOGRAPHY IMAGES FOR NON-DESTRUCTIVE EVALUATION OF FRICTION-STIR WELD QUALITY

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ABSTRACT

Micro-computed tomography (MCT) provides a tool for creating three-dimensional images of a sample by combining a series of two-dimensional “slices” of the object. This capability has led to an increasing number of applications of MCT data in research, including non-destructive evaluation and three-dimensional reconstructions of objects. However, a lack of standardization in the imaging process may lead to inconsistent results if the researcher is not aware of the factors which impact the resolution, detail, and density accuracy of the scan. This work addresses the variability present in the Xradia MCT-400 data and suggests techniques for controlling that variability. Sample preparation, including size, placement, and composition, imaging parameters such as threshold values, x-ray sample counts, scan resolution, and conversion of the output format for subsequent use of the data are discussed in the context of non-destructive evaluation of weld quality for friction stir welding of aluminum, but are universal for all applications. This work was performed in part during the Research Experience for Undergraduates (REU) hosted at SDSM&T in the summer of 2013.

Keywords

Micro-computed tomography, X-Ray reconstruction, Friction stir weld evaluation

INTRODUCTION

Research utilizing micro-computed tomography (MCT) has become extensive and diverse in recent years. Applications of these systems can be found in biomedical, computational, materials and geologic sciences, but all have encountered the same problem: lack of standardization regarding setup, imaging, and post-processing. The unfortunate result of this is that research conducted at

different locations typically generates different results and reduces or eliminates the chances of repeatable accurate imaging.

To assist in a multi-disciplinary usage standard for the research conducted with MCT, we address the key components of the MCT process: mechanism of imaging, post-imaging / postrendering editing, and reconstruction of images while discussing the variabilities that exist at each stage of this process.

Non-destructive evaluation of friction stir weld samples is a very important result of this standardized technique [2]. The process itself includes moving a rotating pin-tool between two pieces of materials to create a very high quality bond or joint [2]. Friction stir welding can produce hidden defects within a weld, called wormholes. A structurally unsound joint can go undetected and result in dangerous consequences should it ever be employed in high-strain applications [2]. The results of a defect-free weld yield some of the highest strength bonds in homogeneous and heterogeneous materials fusing.

METHODS AND RESULTS

Imaging—Understanding the parameters that are essential to the imaging stage is the simplest way to create a standard for research that is repeatable for any imaging process. Each of the following parameters comprises a piece of the full tomographical recipe. By adhering to precise measurements while setting up a recipe, different researchers and facilities will be able to duplicate images and validate measurements.

The main imaging component behind MCT is the X-ray system which consists of the X-ray source and the image-processing detector (see Figure 1 as taken from South Dakota School of Mines and Technology's (SDSM&T) Xradia Micro-CT 400). As with all X-ray images, materials being imaged are rendered as a variance of relative densities within either the material or the surrounding air. The image is subject to detail changes depending on the distances of the source to the

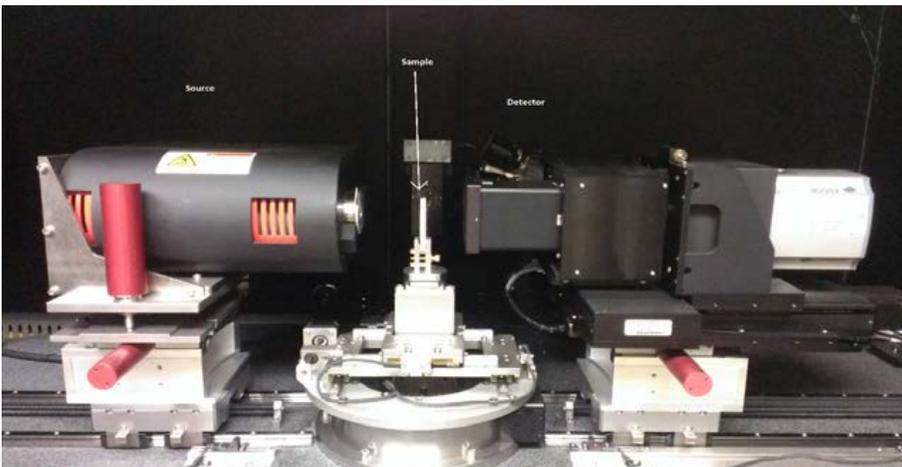


Figure 1. Xradia XCT-400 components.

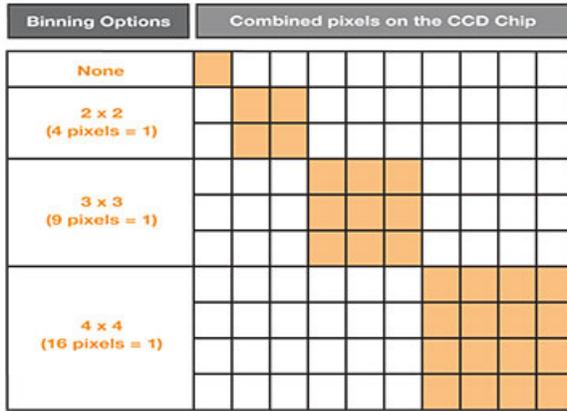


Figure 2. Example of binning and resolution impact [4].

sample and the sample to the detector; the behavior is analogous to a flashlight shining on any object and the resulting shadow being cast against some flat surface. This is due to the conic and divergent beam emitted from the X-ray source and the distance to the detector. As the distance from the source (focused with a filter or otherwise) to the sample is increased, a more precise representation of the material is attained as most divergent X-rays miss the detector. As the detector’s distance from the sample is increased, the sample becomes artificially enlarged which will reduce resolution but can provide a more detailed view of fields of interest. The particular sample in Figure 1 is a piece of a friction stir weld. Larger samples can be run intact to avoid unnecessary damage to a finished joint.

Nearly all MCT devices will have different size capacities, resolutions, and distance options for placement of source, detector and sample. After an image has been calibrated for tomography on any particular machine, the manufacturers of MCT devices propose that the standard for resulting calibration be concisely defined by voxel size, or cubic pixel measurement.

An additional parameter of standard X-ray imaging lies in the use of binning. Binning is a technique used with difficult-to-scan materials such as highly-dense alloys or large samples with defractive properties that can obscure the detection. It works by artificially boosting the count of X-ray particles detected in the imaging process by doing neighborhood sampling and averaging of surrounding pixels in the image with the current pixel (illustrated in Figure 2) [4]. This results in a less-clear image and reduced resolution but is sometimes needed for otherwise un-scanable materials.

MCT differs from standard X-ray imaging in that the sample is not statically fixed once the source and detector have been configured. With MCT, as with medical CT-scans, the source and detector are rotated about the sample as seen in Figure 3. With most non-medical MCT machines, such as SDSM&T’s, the sample is rotated throughout the scan.

This results in two-dimensional images, called slices and, when taken at small enough rotational adjustments, can be fed through a back-projection algorithm to reconstruct three-dimensional digital representations of the material [3].

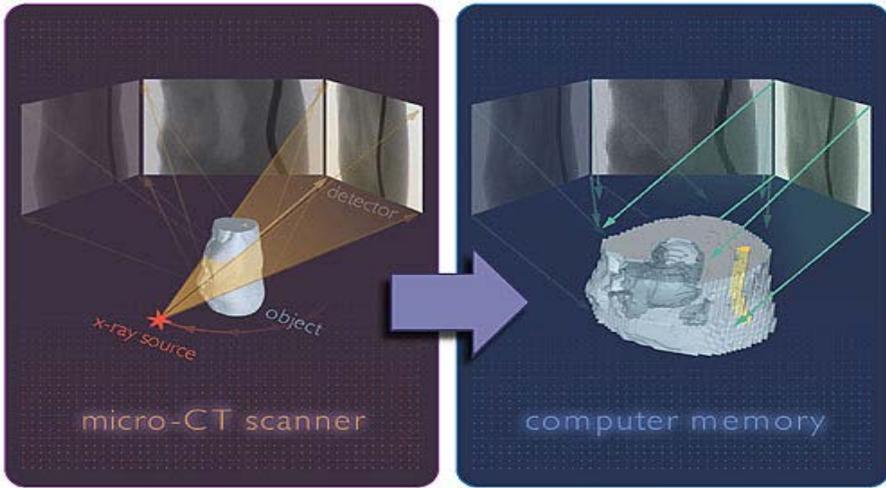


Figure 3. Imaging and projection of MCT [3].

Further, linear slice traversals through the material at each unit of resolution can be produced by layering the transposed images. Back-projection starts with a masked area to be determined either by system or user to specify the material of interest and omit all other data. This process is then used to construct a histogram of each image as captured by the MCT while rotating the sample and normalizing the changes. Finally, the images are correlated based on the rotation and distance information known at the time of imaging; this results in a finished tomography [3]. At the stage of creating a tomograph it is crucial to report the source's exposure time length, power settings, filters being used, number of reference images (pictures of no sample during the tomography for calibration during the sample scan), angles rotated and number of images.

Without consideration for power, distance, exposure and angle configuration, it is nearly impossible to produce the same image from the same sample. An example of faulty results can be found in the research done on behalf of a third-party consultant at SDSM&T who wanted to investigate talc dispersion across a polymer surface. The XCT-400 was built with an anticipated resolution of 20 μm for a voxel, but was teased to 0.26 μm by adjusting the distances between source and detector. When computing the average size of talc particles and volume percentage dispersed across a sample of polymer, we found that varying these parameters could yield discrepancies of up to ten times each other's measurements.

Another example of poor calibration can be seen in friction stir welding worm-hole defect analysis. In such a case, using the incorrect power settings and filters can produce large ringing artifacts that obscure the image. Though nearly any quality of scan can be used to detect the presence of large defects, smaller defects and their characteristics can go unnoticed or misrepresented when X-ray diffractions are captured by the image processor. In most cases these defects (easily seen

along the side of Figures 4 and 5) can help fill in the pores or wormholes caused by a bad friction stir process.

Most Micro-Computed Tomography systems provide a way to save a digital copy of the recipe for later use. We recommend securing a digital recipe and manually validating voxel size before proceeding to any post rendering.

Post-Imaging and Touch-up Rendering—Different MCT machines have different standard output tomography data formats. We recommend that the output be specified as either the format made by Digital Imaging and Communications in Medicine (DICOM) or as layered png images. This will enable more cross-platform cooperation; Avizo Fire 8 by Visualization Science Group, which is the software of choice for SDSM&T, will handle both of these formats as well as the proprietary txm and txm-exm formats from the XCT-400. When selecting the data format to be evaluated, the operator should be aware that some are compressed, such as the txm-exm format, and may lose image quality and any measurements kept by the MCT machine during tomography renderings. Furthermore, many detailed and multiple-framed tomographies will be quite large. The larger data set, without any software support for formats larger than the rendering computer’s memory, will result in very poor rendering, editing and analysis performance. Indeed, it is not uncommon to have tomographies of 40GB or larger in the non-compressed formats.

After the data set has been imported into Avizo, the first stage for analysis is to define the region or regions of interest of the tomography. This can be done by creating an Ortho-Slice module in the project view located along the right side. From here, artifact avoidance can be done by selecting the area of material that is of interest using a Sub-Volume module. This removes the blooming as seen in Figure 4 and will yield the material as selected in the bounded regions.

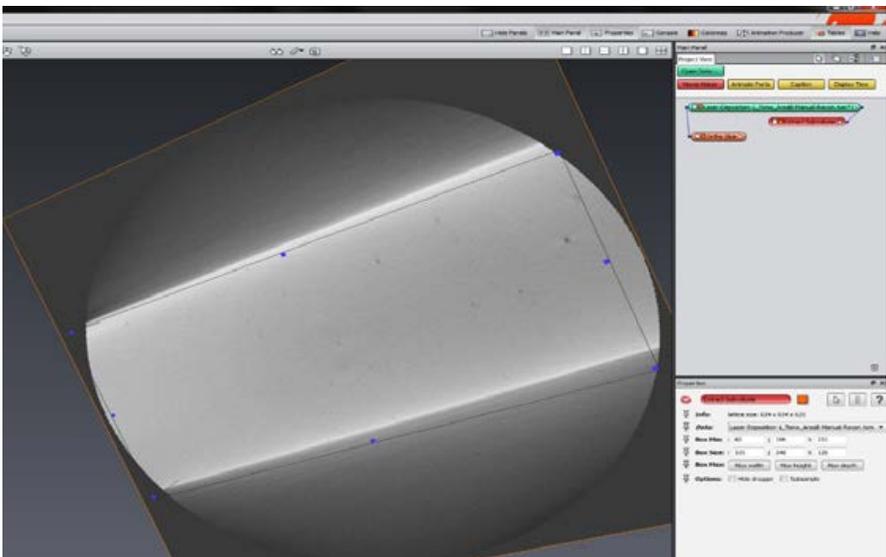


Figure 4. Avizo Fire Ortho-Slice and Sub-Volume modules.

The Sub-Volume module is configured by slice count in each axis as recorded by the MCT during processing. As a result, the real measurements of the selected material can be calculated by multiplying the voxel size by each of the number of slices selected in this selection operation. After selection, the material extracted can sometimes artificially re-expand to fill the resolution of the full tomography and will greatly reduce the image quality. If the software being used supports resampling the data, as Avizo does, it is advisable to do so against the original tomography to restore the lost detail.

After all necessary volume operations have been finished, or if the artifacting is not sufficient to interfere with material selection, an Interactive-Thresholding module can be attached for improved clarity. Thresholding is the ability to select the material by its density (or in the X-ray image its grey-scale value) by selecting upper and lower limits on a histogram of the tomography. The results can be very good and simple to produce if no severe artifacts are in the scan. Figure 5 illustrates a selected section of a friction stir weld joint with a defect or air-pocket inside of it. By thresholding the high end of the histogram to the material while keeping the low end where the sample becomes air, the material can be instantly transferred out of the artifacts and air. Avizo will show what is selected by highlighting the area.

Thresholding is inherently an inaccurate stage of the post-rendering process. To accurately identify structures more complex than the binary rendering of air and material illustrated in Figure 5, someone who understands the material needs to estimate the density that correlates to each material. Given the variabilities present in the imaging stage, in some research, the thresholding was done in such a way that the resulting materials constituted the volume fraction anticipated in fiber fatigue testing. This particular step, though producing variable results, can be repeatedly tested and adjusted if the densities thresholded against are recorded [1].

By working this procedure in reverse in conjunction with reconstruction, we have found that details of the nature of friction stir weld defects become more apparent than before. These results can be seen in Figure 6, with the axes enabled

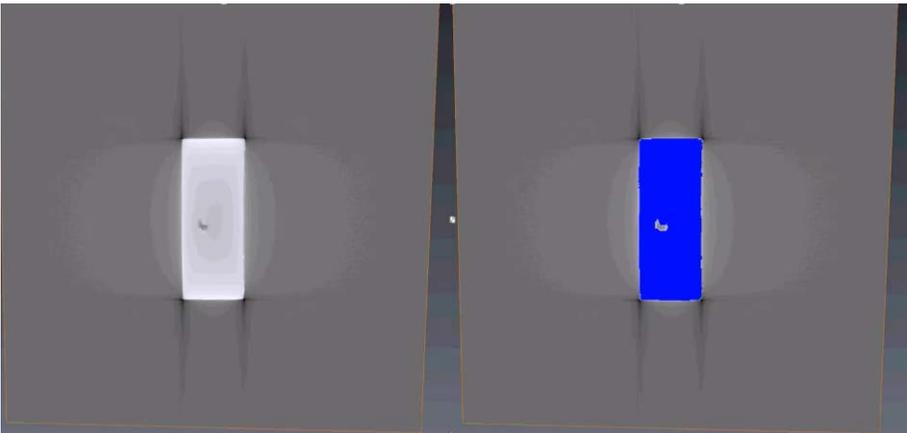


Figure 5. Avizo Fire Ortho-Slice (left) and the thresholded data(right).

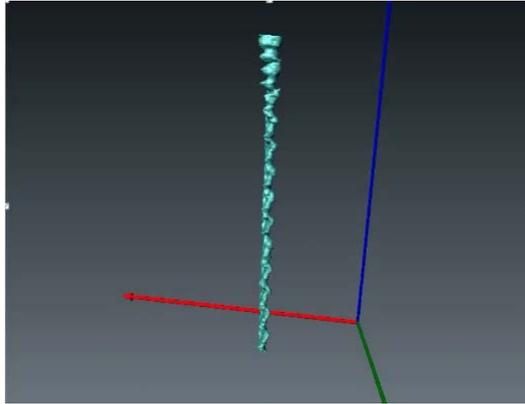


Figure 6. Avizo Fire wormhole defect rendering. For perspective, the three axes are shown.

for perspective. Such data have become paramount to research to remove these defects at weld run time [2].

Reconstruction—Once a thresholded area has been selected and applied, a new data set will be produced with only the selected materials present with no variability in density or gray-scale. This rendered material can be transformed easily into a surface using the Generate-Surface module. While generating a surface from the thresholded material, one must be aware that the smoothing configurations will remove data from the material scanned before to make a more natural surface. If using a scan of materials that is nearly at the limit for resolution of the MCT, one must consider turning off all smoothing operations.

The results of this module can be seen in Figure 6 and can be exported to 3D printing solutions like MakerBot, movies for analysis, or as the surface itself to 3D-pdf documents. Mathematical analysis is also possible and can be done with Avizo's internal systems or exported to Matlab or Abaqus for further evaluation. For assistance in the evaluation of wormhole defects, the surface renderings can be simplified to triangles and then the normal vectors of each can be computationally mapped to better understand the curvature at each selected elevation (Figure 7).

Using the built-in Label-Analysis and Volume-Fraction modules, one can quickly calculate each separate particle in the surface and generate metrics on surface area and volume or the ratio between the empty and the thresholded data. These results are also heavily dependent upon whether any smoothing had occurred previously as the surface's structure can change substantially.

Comparison—To illustrate the differences in quality these steps can make, we ran an experiment using a section of friction stir weld joint. In Figure 8, the image on the left was constructed using a binning factor of two to approach five-thousand X-ray counts at six seconds of exposure and being scanned at 65 kV. The scan on the right has been constructed using no binning factors and at the power setting of 85 kV for 10 seconds of exposure. Both images were produced using a source distance of 100 mm and a detector distance of 80mm and both were run using the same low-energy filter (LE-5 by XRadia). It should be noted

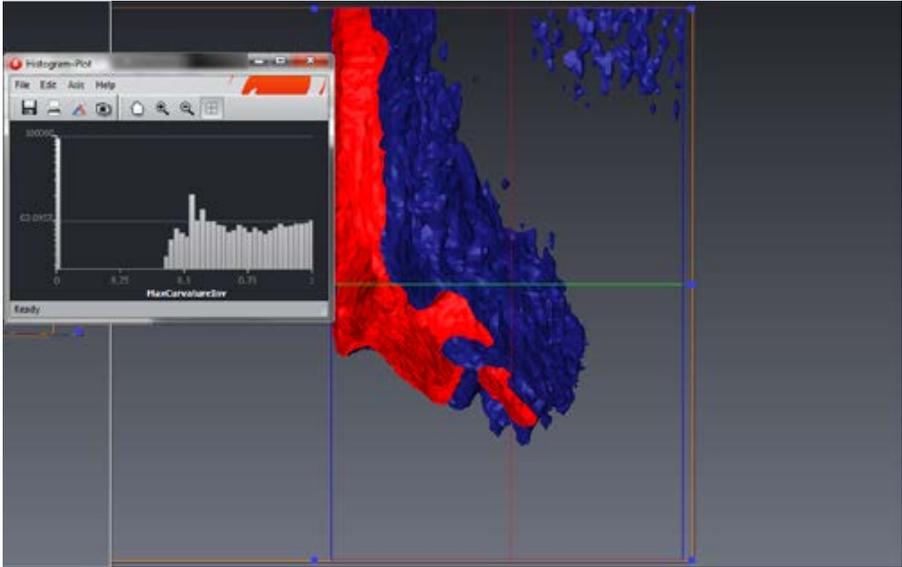


Figure 7. Avizo Fire wormhole defect analysis using Matlab's curvature evaluation via plugin.



Figure 8. XCT binning and power settings effect on defect detail. The image on the left looks clearer, but does not contain the same blur because the binning has balanced out the curvature on this sample.

that though the image on the left looks clearer, it does not contain the same blur as the binning has balanced out the curvature on this sample.

The improved defect detail of the image on the right will facilitate better post-imaging evaluation and a more realistic estimation of the defect's behavior. These scans were both modified using a Sub-Volume module to remove air and excess material. After completion, resampling was conducted on each tomography to ensure that all clarity possible persisted to the thresholding stage. The results after all thresholding and rendering can be seen in Figure 9 and the profile of the image in Figure 10. The red material is a common defect found between samples, and the blue region is unique to the 85 kV sample (the right image in Figure 8).

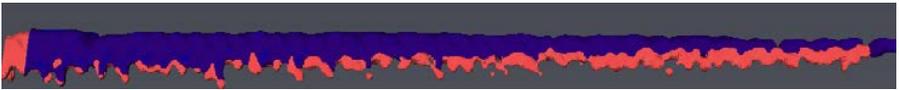


Figure 9. Comparison of surface renderings given imaging differences.

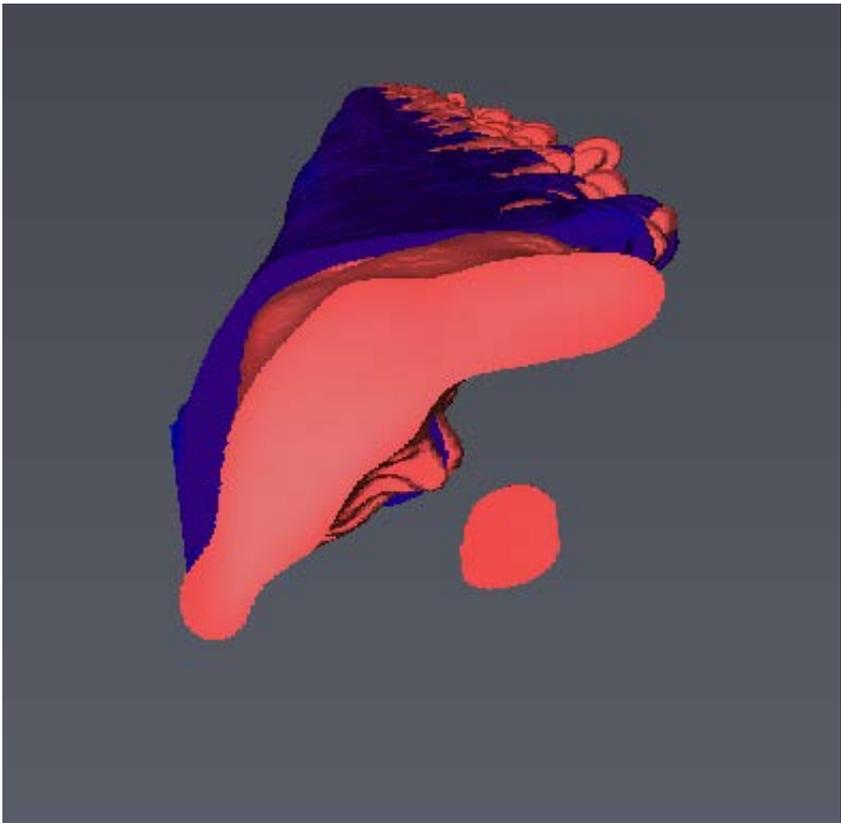


Figure 10. A profile image of Figure 9.

DISCUSSION

While MCT use in research is rapidly becoming a frequently-used tool, failure to report settings and properly use the technologies associated with this process generally precludes repeatable experimentation. Creating awareness of correct sample preparation, imaging and post-processing configurations can mitigate many uncertainties regarding resolution, detail, and density measurements. The accuracy in non-destructive evaluation of friction stir welding is paramount as the joints made are among the highest strength bonds currently produced.

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