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How Will X-ray Computed Tomography Impact Your Future?

John Korbin & David Peterson

Sandia National Laboratories

Albuquerque, New Mexico, United States

For most people, the term CT-scan, or X-ray Computed Tomography, is associated with medical imaging used by hospitals to diagnose and treat illnesses. This same process can be used to transform the jewelry industry in ways yet to be fully explored.

Background:

X-ray vision has been the dream of kids since at least 1906. Alongside colorful ads for sea monkeys, comic books promised that you could send away for a pair of special glasses that would give you the power of Superman. You could see deep into the world around you and reveal truths that would have otherwise remained mysteries. This dream is about to be realized, almost.

Figure 1 – 1960s advertisements for X-ray glasses [1] [2]

Nearly everyone has, at one point in their life, had an X-ray taken to examine a broken bone or some other suspect body part. X-ray light shines through you and onto a digital, or in days gone by, a photographic plate imaging the structures beneath your skin. X-rays were discovered by accident in 1896 by

Wilhelm Röntgen when he noticed that one of his Crookes' tubes caused a fluorescent screen to glow despite being obscured by an opaque sheet of cardboard [3]. Unlike visible light which is unable to permeate deeply into objects, X-rays have low attenuation (or absorption) rates which allow them to pass easily through materials.

Röntgen also discovered that "the density of the bodies is the property whose variation mainly affects their permeability." This meant that his new discovery could be used to image objects of varying density (i.e. bone and tissue, Figure 2). For the medical community, the obvious applications quickly became apparent and within a few years X-rays were an established method of medical diagnosis.

Figure 2 – Radiograph of a rat from a Röntgen Ray Apparatus (X-ray) sales pamphlet [4]

After an initial period of uncertainty about their safety and practicality, x-rays were turned into a novelty. These nonmedical applications including the iconic Foot-o-Scope shoe fitting stations [5] and X-ray Specs mentioned earlier. This explosion into the pop culture drove their acceptance by the public and lead to advances in x-ray technology.

In 1961, Allen MacLeod Cormack and Sir Godfrey Hounsfield realized that a popular math problem from the 50s, called the Inverse Problem, could be applied to medical x-ray scanning. The Inverse Problem describes the idea of solving for a function from a finite set of observations. Its name is derived from the fact that one "starts with the results and then calculates the causes." [6] Combining multiple x-ray images taken of a slice through a head (Figure 3), Cormack and Hounsfield calculated the original cause of the x-ray attenuation and invented x-ray CT [7]. In 1979 Cormack and Hounsfield were awarded Nobel prizes for this work and its impact on society.

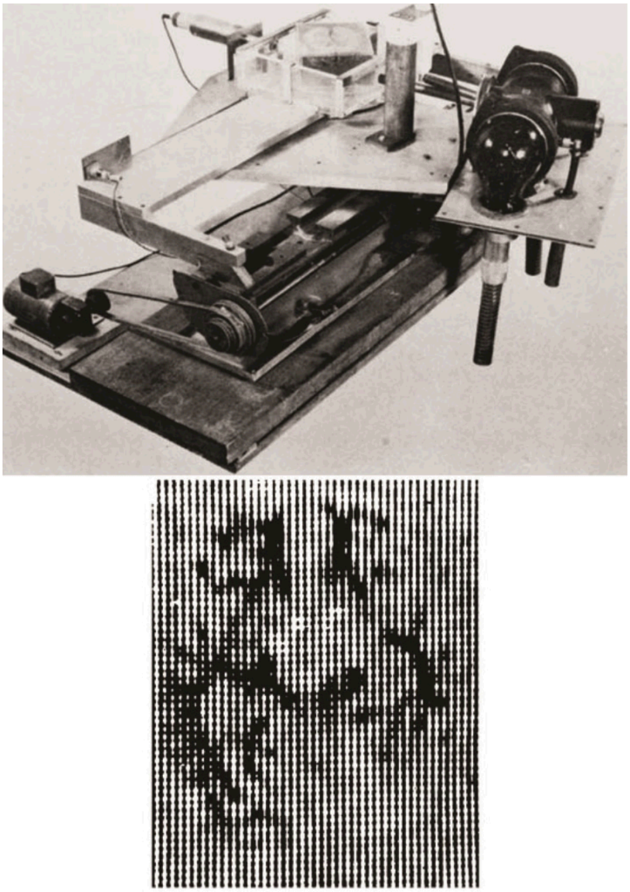

Figure 3 - Hounsfield's Electric and Musical Industries Ltd. head scanner and first image (1969)

To compute the inverse problem and convert a set of scans to an image, the first CT required nine days of scanning and two hours of reconstruction time [8]. The resulting image was only 80x80 pixels but had enough resolution (~2 mm) to distinguished between tissue types in a preserved brain. In 1973, the first generation of commercial CT machines reduced acquisition times to 20 seconds and increased the resolution to 320x320 pixels. By 2017, modern nondestructive analysis CT machines using GPU based reconstruction techniques can acquire 2000x2000x2000 pixel (32 gigabyte) data sets in less than 15 minutes.

Along with increases in speed, miniaturization of CT machines has lead to desktop sized units. Starting in 1982 with the development of x-ray microtomography (XMT) by Elliot and Dover, systems have continued to drop in price, size and complexity. This has increased the availability of these machines to various non-medical communities further driving the development of X-ray CT technologies. Along with commercial desktop units (Figure 4), multiple groups of amateur scientists are working on open source hobby grade machines (Figure 5).

Multiple disciplines now utilize desktop CT machines to enhance their workflows. For example, paleontologists are replacing the once tedious process of removing a fossil from its matrix with a quick CT scan which can then be examined leisurely by any number of researchers [9]. Just as the paleontological community has adapted this technology to answer difficulties in their workflow, X-ray CT could also benefit the jewelry industry.

Figure 4 - An example desktop CT by Bruker. [10]

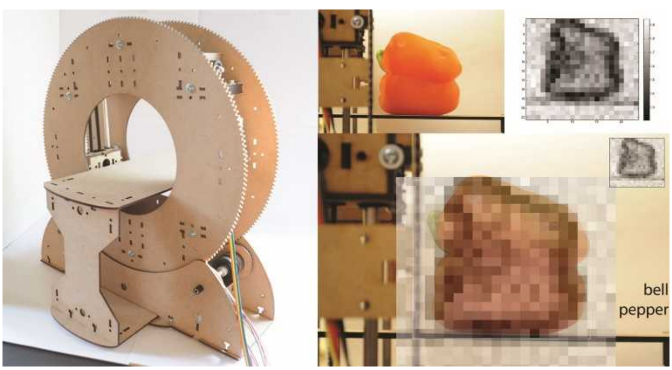

Figure 5 - An open source CT machine designed by OpenCT. [11]

CT on the Workbench:

The jewelry makers of today inhabit a very different world from where they were even 10 years ago. The introduction of 3D scanning and printing has fundamentally changed the methods available to hobbyists, artisans and mass producers. Desktop CT scanning is an untapped resource that can take this industry to the next level in both design and production. To demonstrate the advantages made possible by CT imaging, four test cases showcasing various applications of this technology were developed; still, these barely scrape the surface of potential CT applications.

Stone Cutting:

What masterpieces could be realized if you could see the best way to remove a gem from its matrix (or for that matter, determine if the stone itself is even good enough to warranty it)? What disasters could be avoided by seeing hidden flaws before the first cut?

To determine what can be seen in "as mined" material, we scanned several specimens with obvious inclusions. The first two examples shown are Almandine garnets from Alaska and pseudomorphs of Limonite after Pyrite from the Bullion King Gold Mine, CO (Figure 6 & Figure 7). These scans easily revealed the hidden material within the matrix exposing several large crystals which are not apparent from the outside of the rocks.

Figure 6 - Alaskan Almandine garnet; slice from scan (left), rock (center) and 3d print (right). Arrow indicates internal crystal visible only in scan and 3d print.

Figure 7 - Pyrite crystals; rock (left) and 3d model (right).

This success drove us to scan several more materials with the hope of being able to identify promising gem specimens within otherwise plain ores. In this attempt, we scanned a chunk of matrix rock from Yogo Gulch, Montana (Figure 8). There was a flake of sapphire visible externally, so we hoped there might be more within. What we found were several small stones and that the speck on the outside did in fact represent a much larger crystal. Fortunately, this process also revealed cracking within this gem, ruling out extraction and cutting. The CT inspection prevented exploratory removal of the gem preventing wasted effort and the frustration from discovering this flaw later.

Figure 8 - Sapphire in matrix; rock (left), crystal (middle) and 3d print (right).

The final mineral specimen we scanned was an opal owned by Ian Bone of Queensland, Australia (Figure 9). We could clearly see the opal layers within the matrix and identified possible promising cutting paths.

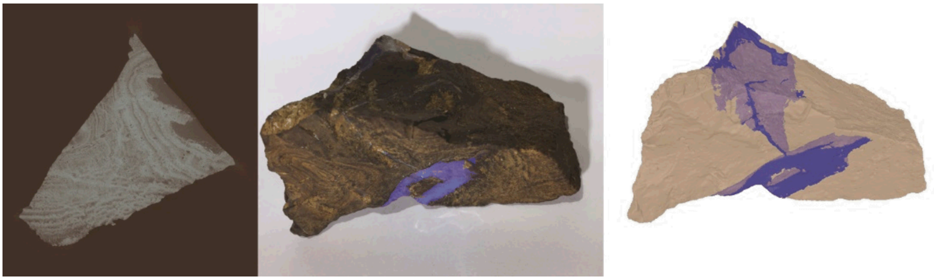

Figure 9 - Australian Opal; scan slice (left), rock (center), and 3d model (right).

The data gathered from the X-ray CT scans revealed previously hidden aspects of these ores. While the scan is not yet able to predict details like color, clarity, and quality; the details that are revealed allow jewelers to determine whether the mineral specimen is more valuable than the potential outcome of a cut [12].

Design:

As already mentioned, 3D printers have had a dramatic impact on the jewelry design community. They allow artisans to digitally sculpt creations with flawless symmetry, incredible detail, or simply without the manual skill required to shape a model by hand. This is perfect for generating contemporary, innovative designs. However, if a request comes in for a new take on an old design, there is no easy method to digitize a physical model. Optical scanning techniques have recently made great technological strides and reduced the cost and complexity of their systems. However, cameras can never get a complete picture of a convex design or material obscured behind stones. That is, if there are any deep valleys, holes, or objects in the way the light is unable to see beyond these obstructions. Direct surface probing can also be attempted but this requires expensive equipment which is also limited in its ability to reach around corners or behind barriers. Often, manual creation of the digital asset is the only option but this can be expensive and requires a skilled designer.

X-ray CT is well suited to overcome these challenges. We scanned a set of rings to determine how easily a digital model could be constructed from each sample (Figure 10 & Figure 11). A simple surface can be built by walking the data, using contrasting density to determine changes in materials. This yields satisfactory results for simple parts.

Figure 10 - Rings by Stephen and Nancy Attaway

Figure 11 - X-ray images of example rings (20 µm resolution)

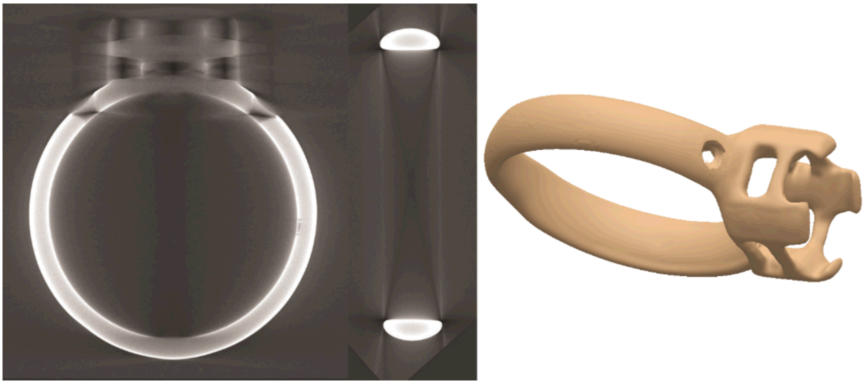

Figure 12 – Ring #1; scan slices (left) and solid model (right).

One limitation that needs to be pointed out is that, while it can be trivial to identify the highest density parts of an object, lower density stones are difficult to see. Reconstruction "noise," or shadows, can also become a problem when trying to extract a model from a scan of a complex part. The scanning orientation, energy and method all contribute to how easy or difficult a scan is to post process. Scanning Ring #3 in a vertical orientation produces artifacts and noise (Figure 13). Scanning this same ring in a tilted orientation reduces these artifacts simplifying the extraction of a solid model (Figure 14).

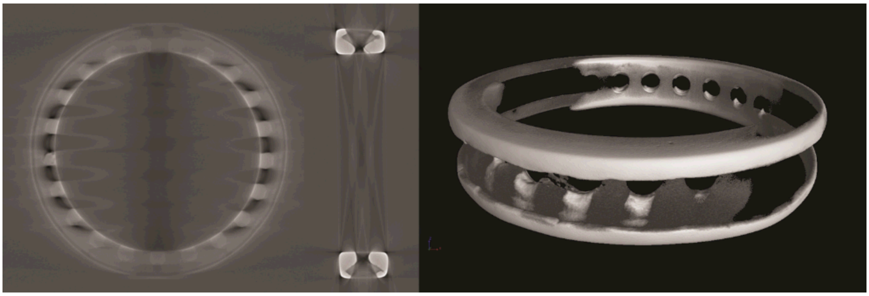

Figure 13 - Ring #3 Vertical Scan (perpendicular slices, left and center) and Solid Model (right)

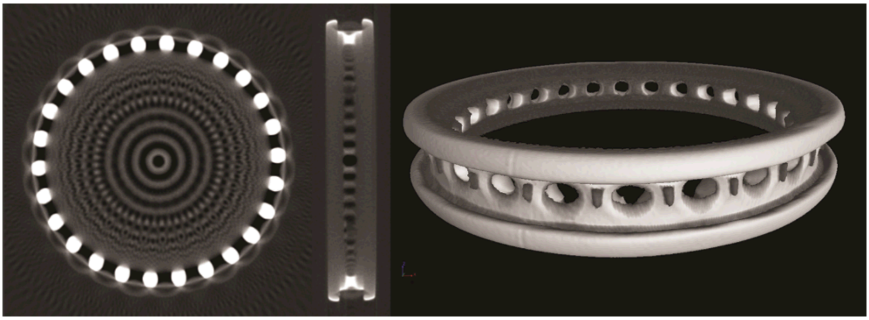

Figure 14 - Ring #3 Tilted Scan (perpendicular slices, left and center) and Solid Model (right)

There are new methods being developed to solve some of these problems including neural network based segmentation algorithms and advanced CT reconstruction techniques, but there is no definite date when these tools we be available. In the meantime, even if some manual postprocessing is required to add uncaptured geometry, the initial reconstructions demonstrated above would considerably speed up the digital jeweler's process.

Manufacturing:

A staple in jewelry manufacturing, lost-wax casting uses handmade sculptures (or increasingly 3D printed pieces) to create molds which are in turn used to allow cast duplication of the design in a metal of choice. To understand subtleties of the lost wax process, we scanned a standard flask before burn out. We found that while the x-rays could penetrate the flask, they didn't have the required contrast to identify the defects we were interested in studying (Figure 15).

Figure 15 - Casting flask (left) and x-ray CT slice (right).

We redesigned the plaster mold to remove all metals and reduce the diameter allowing us to the get a higher resolution, "cleaner" scan.

Figure 16 - CAD model of lost wax test specimen

With this new mold design set, we created three test specimens using various lost wax treatment techniques; specifically, we focused on exploring casting defects from 3D printed wax parts. The design included a textured pattern, lettering, and through-holes (Figure 16). Various post-print curing treatments were performed to the lost wax specimens to determine whether the treatment changed the state of the mold prior to casting. The treatment of each specimen is listed in Table 1. All specimens were cleaned in an ultrasonic bath with Dawn® dish soap.

Table 1 - Lost-wax Plaster Specimen Treatments

Specimen	Treatment	Specifications
1	None	None
2	Light	2 minutes in a B9 creations LED light cure box
3	Heat	340 °F for 1 hours

The specimens were prepared by Dr. Stephen Attaway on a B9 Creator using a mix of Cherry and Red resins. The wax was placed in a Dixie® pill cup and covered with Ransom & Randolph Ultra-Vest® BANDUST™(Figure 17). A vacuum was not applied during the curing process, which may have left bubbles in the cured plasters. The exact nature of each part was kept hidden until after the scans and analysis were competed to limit any bias during the analysis.

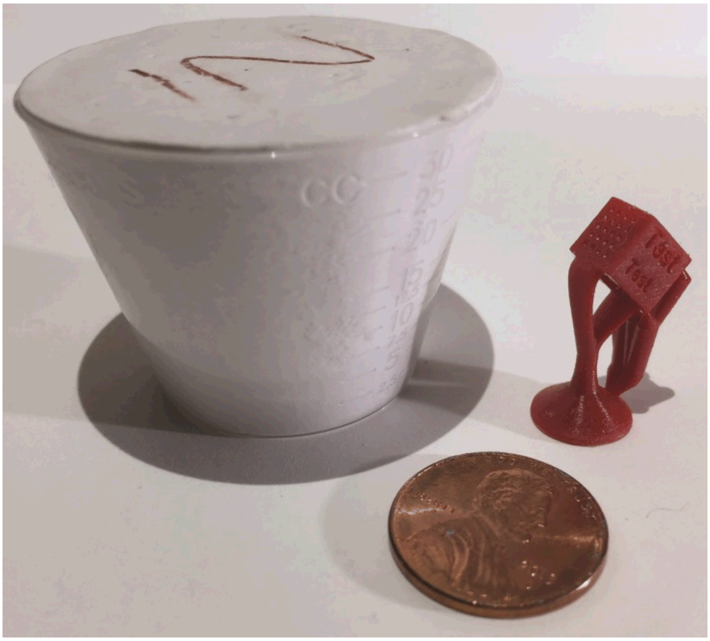

Figure 17 – Casting and wax test piece for scale

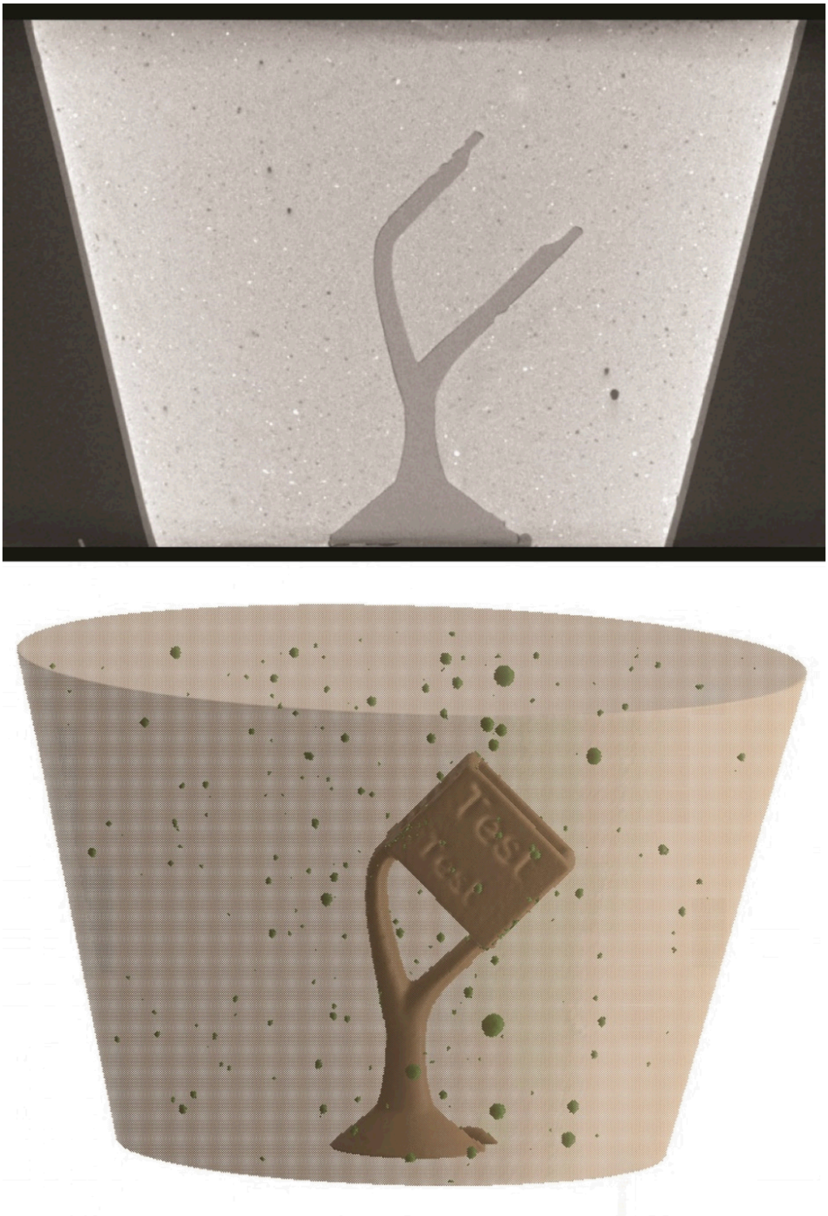

Figure 18 - Results from the CT of sample #3. A slice through the reconstructed volume (right) and the processed volume segmented into each material (wax, voids, and plaster) (left).

The specimens were all scanned at the same resolution (25 µm) and segmented to show the wax and air bubbles within the plaster (Figure 18). PolyWorks Inspector, a software package originally designed for inspection of auto industry parts, was used to compare the segmented wax geometries to the original digital models.

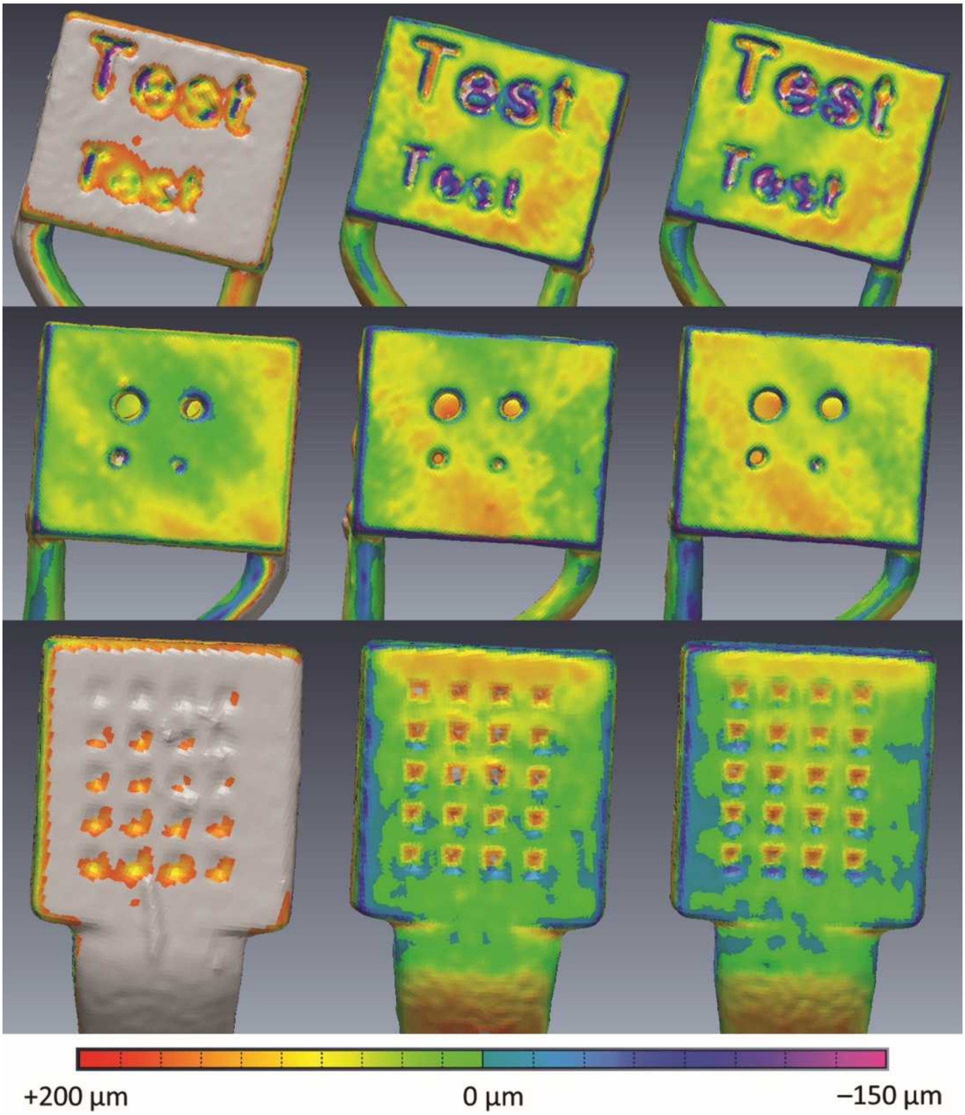

Figure 19 - CT reconstructed wax forms with measured deviations from CAD geometry (from left to right, specimens 1, 2 and 3). Grey colored regions are outside the distances shown within the error color bar.

We found that the wax specimen prepared using technique #3 produced the most accurate geometry. Specifically, the letters were the clearest and the holes approximately the right shape and size. The wax prepared using technique #1 was oversized and had lost almost all detail in the smallest text and two smallest holes.

In addition to these 3D reconstructions, we selected eleven slices from the CT scans to compare the quality of the plaster around the waxes. The locations of these slices are shown in Figure 20. In each slice, black corresponds to a low relative density and white corresponds to a high relative density. The intensity of the images is not correlated between samples. In each figure, samples 1, 2 and 3 are in order from left to right.

Many defects are apparent within the plasters which could be studied in much greater depth. One such defect is the appearance of multiple delaminations of the plaster from the wax in the corners of sample #1.

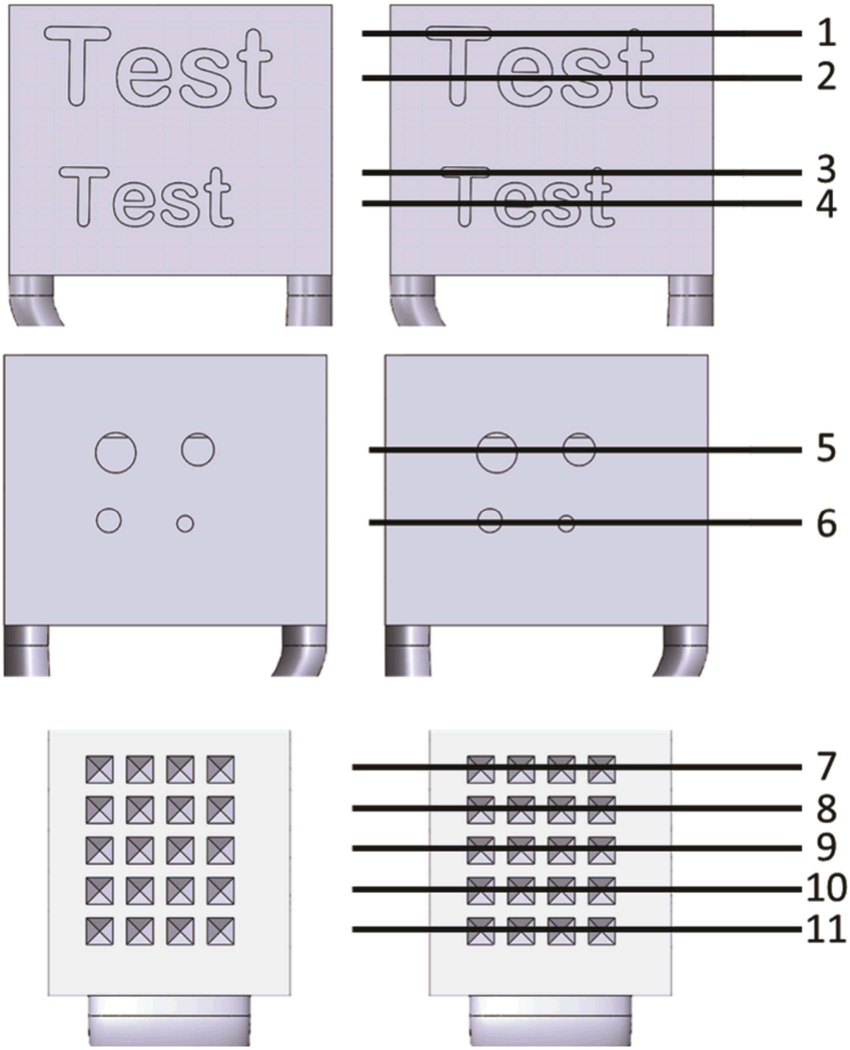

Figure 20 - Slice Locations

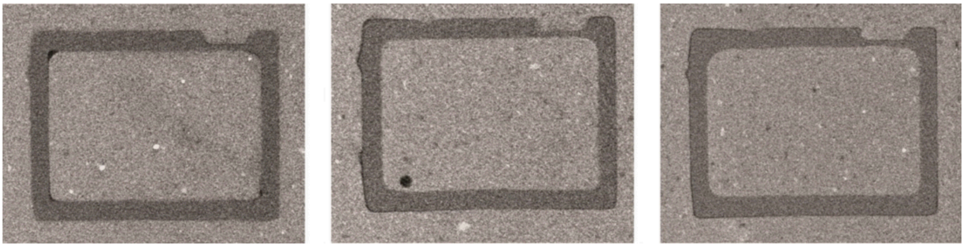

Figure 21 - Slice 1 through the top of the large “T” (Untreated, Light cured, and Heat cured from left to right)

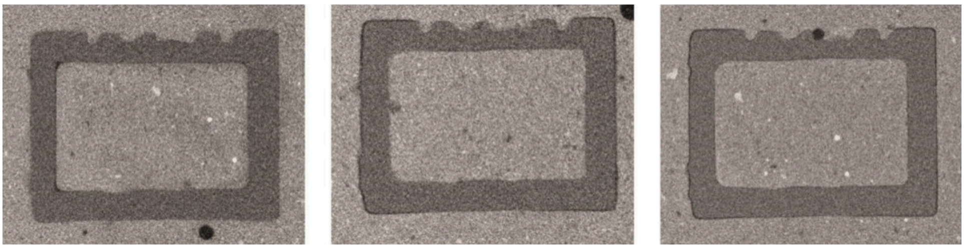

Figure 22 - Slice 2 through the middle of the large text (Untreated, Light cured, and Heat cured from left to right)

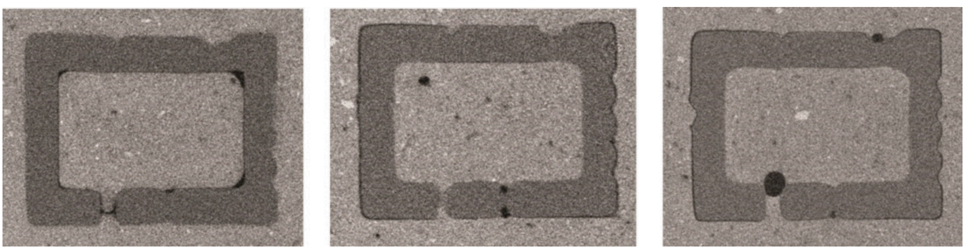

Figure 23 - Slice 3 through the top of the small “T” (Untreated, Light cured, and Heat cured from left to right)

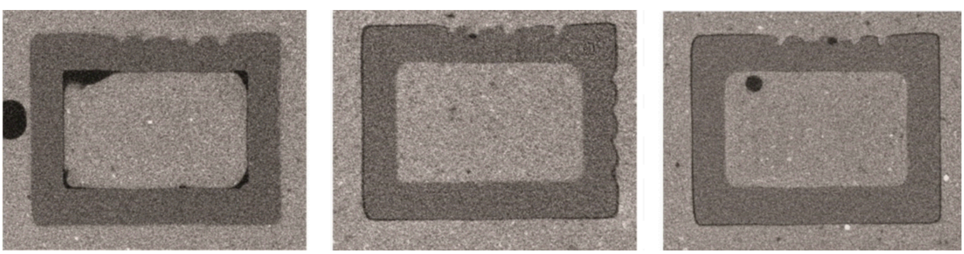

Figure 24 - Slice 4 through the middle of the small text (Untreated, Light cured, and Heat cured from left to right)

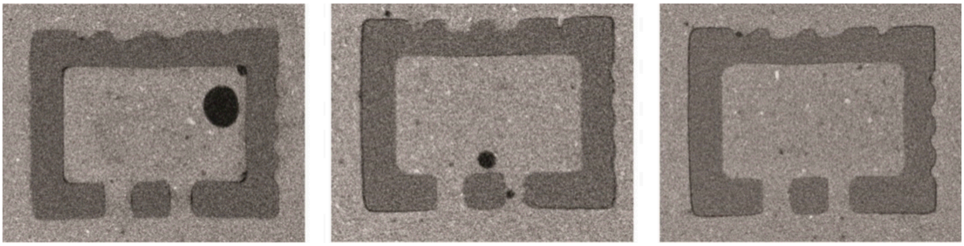

Figure 25 - Slice 5 through the large set of holes (Untreated, Light cured, and Heat cured from left to right)

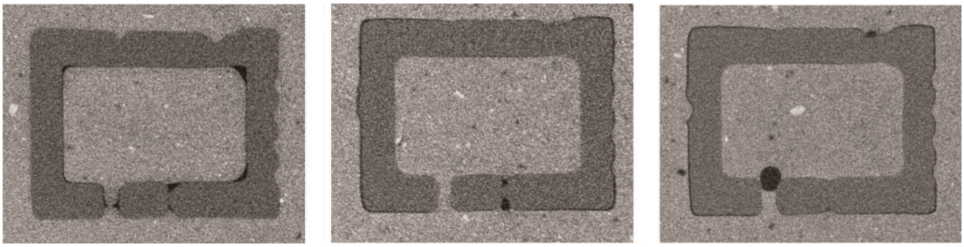

Figure 26 - Slice 6 through the small set of holes (Untreated, Light cured, and Heat cured from left to right)

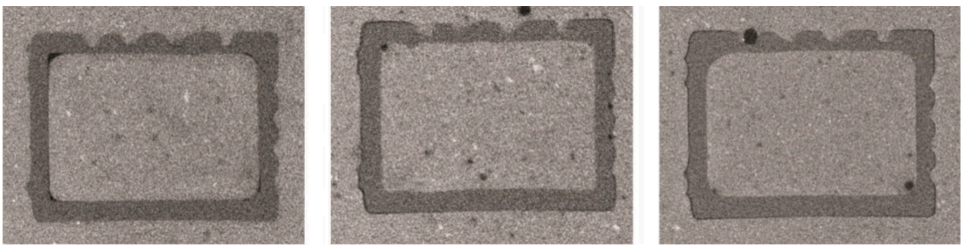

Figure 27 - Slice 7 through the first line of texturing (Untreated, Light cured, and Heat cured from left to right)

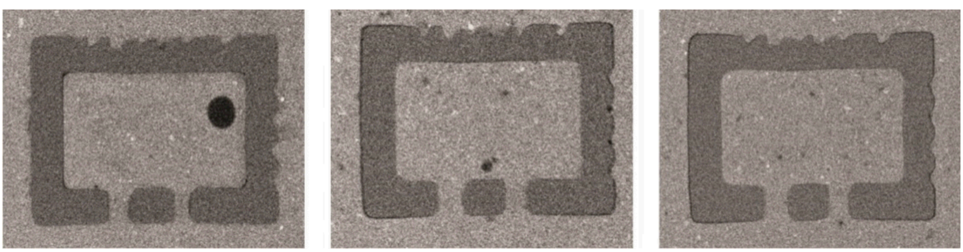

Figure 28 - Slice 8 through the second line of texturing (Untreated, Light cured, and Heat cured from left to right)

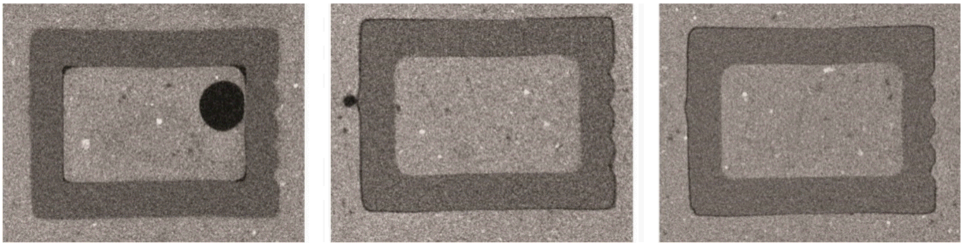

Figure 29 - Slice 9 through the third line of texturing (Untreated, Light cured, and Heat cured from left to right)

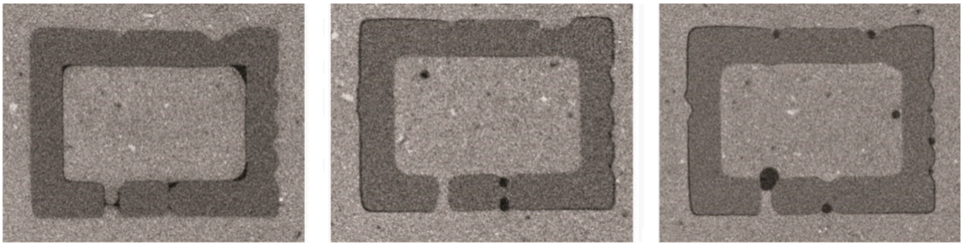

Figure 30 - Slice 10 through the fourth line of texturing (Untreated, Light cured, and Heat cured from left to right)

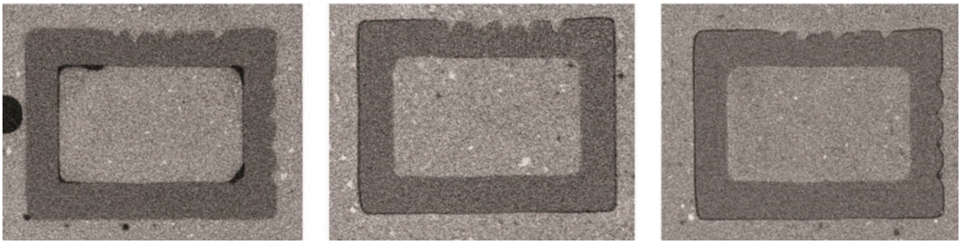

Figure 31 - Slice 11 through the fifth line of texturing (Untreated, Light cured, and Heat cured from left to right)

In addition to these tolerance comparisons of different casting techniques, X-ray CT can be used to analyze other steps in the jewelry manufacturing process. We could have just as easily explored the question of how well a burnout progressed during the heating cycle or whether a specific technique reduced carbon residue. A desktop CT machine would allow every designer to answer the questions that they have always had in the back of their minds. What have you always wondered about during the steps you can't directly view?

Purchasing:

At both the beginning and the end of the jeweler maker's workflow we find the problem of purchasing. How do you know you're getting what you paid for? When purchasing products such pearls, how do you know that you're getting a true quality product? These potentially valuable objects don't always show their true value from a limited external examination. We studied this issue by scanning cultured and natural pearls to see the secrets hidden within (Figure 32). The scans were at 6 and 12 μm resolution, respectively.

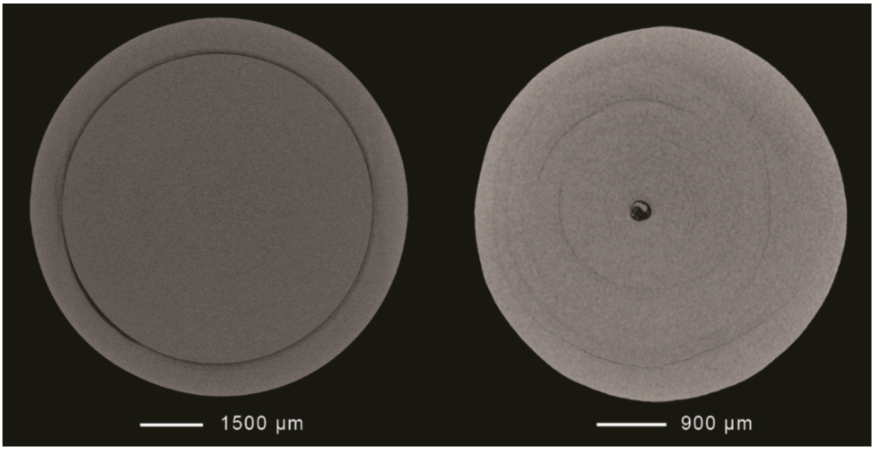

Figure 32 - Pearls cultured (left) and natural (right).

These images speak for themselves in terms of internal composition, but to examine some of the implications, lets discuss the obvious traits visible in the scanned images.

In the cultured pearl, it's readily apparent where the nucleus bead ends and true pearl begins. This is pivotal to determining the value of the pearl as well as its durability. The X-ray CT scan method of pearl valuation requires further examination, but can arguably be more effective than drilling a hole, the only accurate method currently utilized [13], which damages the specimen. The utility of scanning natural pearl is evident from the initial techniques discussed regarding gem inclusions in mined ores; the CT scan of these pearls gives great insight into the best orientation or way to place a hole or mounting hardware without causing unnecessary damage. It's also a very simple way to determine if a pearl is truly natural, or a convincing culture.

Conclusion:

The potential benefits of desktop X-ray CT scanning for the jewelry industry are wide and deep. The data gathered from CT scans can improve every step of the jewelry making process from evaluating raw ores taken from the ground, improving design efforts, ensuring quality production practices, and reducing purchase uncertainties.

Figure 33 – The first x-ray image, Mrs. Röntgen's Hand [14]

Technology is progressing at an impressive pace. Modern digital CT scans are extremely advanced compared to the first images produced with photoreactive plates. Still, it is humbling to realize that the jewelry community was impacted by the first glimpse we had into the world of x-rays. After all, alongside the bones of her hand, Mrs. Röntgen immortalized her wedding band.

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