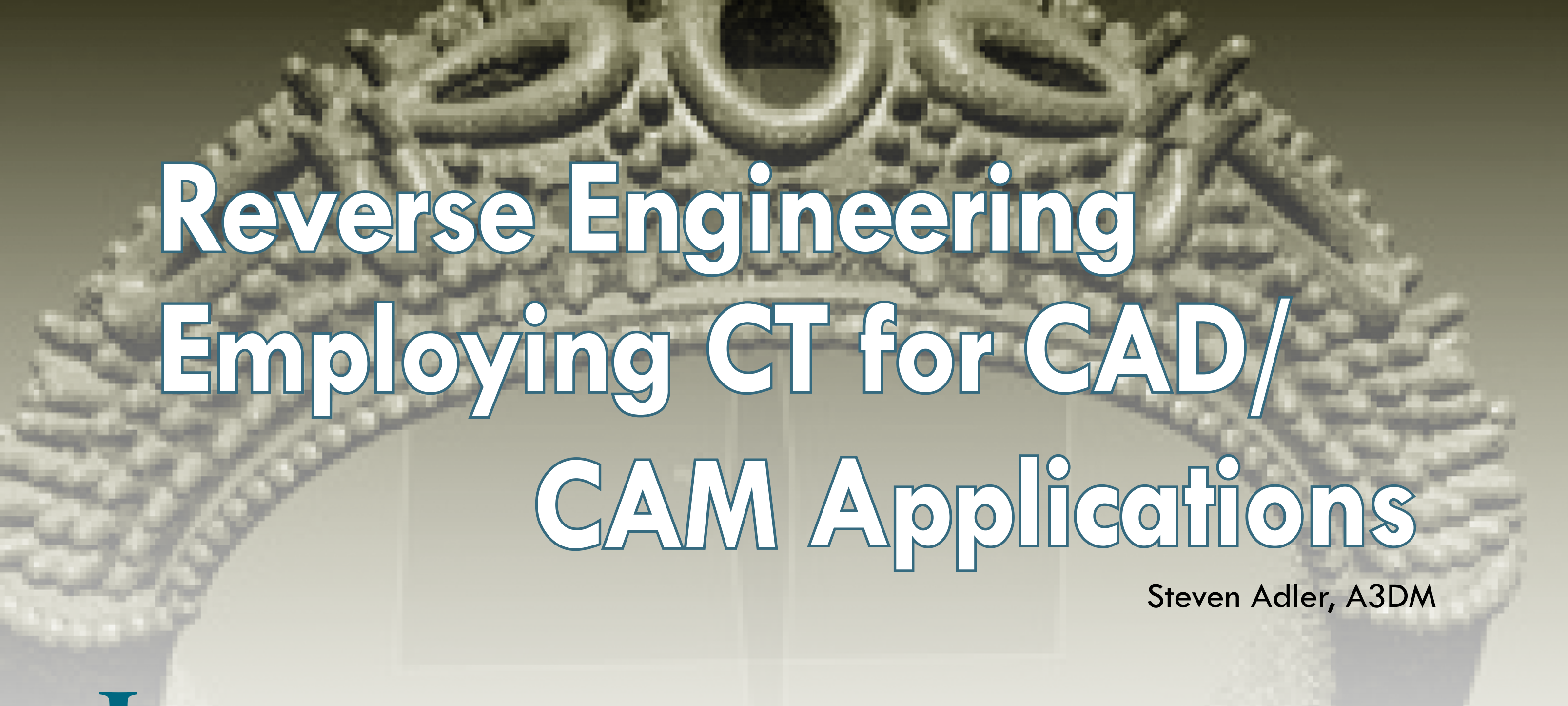

Reverse Engineering Employing CT for CAD/CAM Applications

Steven Adler, A3DM

In the CAD/CAM environment, the ability to capture the complete internal and external geometry from a complex object has been limited and costly. Recently, a new series of micro-CT desktop scanning devices has emerged and, along with advancements in the Windows operating system, these technologies will provide for a cost-effective method to import complex geometries directly into CAD libraries.

This article explores current technology as a utility in digitizing hand-made jewelry findings and designs. In addition, we consider the new software programs that will be needed to make micro-CT data suitable for interactive CAD applications.

Introduction

In my field of CAD/CAM (computer aided design/computer-aided manufacturing) for the jewelry industry, I have been asked to source a cost-effective method allowing a jewelry manufacturer to digitize and incorporate handmade jewelry designs in a CAD software environment. For the purposes of this article, I define this process as "reverse engineering". Depending on the jewelry design, there have been a limited number of non-destructive methods viable for this process to date.

The primary method for reverse engineering has been manual measuring devices like dividers, calipers or computer-linked touch probe devices to determine primary dimensions and reference points. From these reference points a technical drawing is made which a CAD programmer can extrapolate curves to create a digital version of the design. Depending on the detail and human interpretation, this method has met with limited success in achieving an accurate, cost-effective reproduction. This is a time consuming process and prone to human error. Yet, the advantage of these reference points is that the resulting CAD data can be easily modified to provide a variety of new iterations of the design.

The more recent method is the use of multi-pass/multi-axis laser scanning, which has the ability to capture more dimensional data that a CAD programmer uses to re-create the design. While laser scanning reduces the level of human interpretation required by the CAD programmer, the raw data is not easily modified in most CAD programs. Laser scanning is most effective for simple geometries as it cannot easily capture undercuts and internal features that are found in complex jewelry designs such as galleries, hollows and though-hole settings. As this technology evolves, laser scanning will improve our ability to capture handmade designs for CAD, however, it will require substantial post processing time and human interpretation.

To address the complexity of geometries found in fine jewelry where laser scanning is not viable, I have been exploring the capability of Computerized X-ray Tomography (CT) to reduce the need for human interpretation. X-ray micro-tomography scanning is not limited to a line-of-sight angle and can address the complete internal and external geometry of any object without constraint. Recent advances in this technology have increased the resolution significantly and have allowed for the development of smaller and less expensive systems. The resolution of these systems is highly suitable for small plastic and wax parts such as those used in fine jewelry production.

There are several fundamentals to face in a transition using scanning devices for CAD applications. Computer operating systems, hardware and applications will play a role in the success of the process. To achieve the precise feature and surface resolution required for fine jewelry applications, the scanning device will create huge numbers of data points required to describe the items geometry. These data points, referred to as point cloud data, define the volume of an object by the application of a dense polygonal surface. However, these surfaces lack the manipulation points provided in the native NURBS or solids used in CAD. Therefore, this "dumb data" cannot be easily modified or used to provide new design iterations in a native format. In recent years several software vendors have begun to address this dilemma by creating utilities that operate directly on a polygonal mesh. These software programs will play a critical role in providing usable data for CAD applications and CAM output devices.

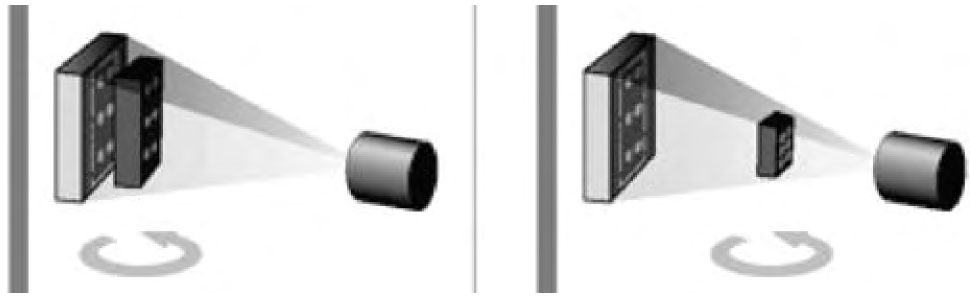

Figure 2 — Focal Length vs Resolution

Subject Study

In selecting a design for micro-CT evaluation, I took a worst-case scenario in terms of geometry complexity and the precipitous effect this might have on the resulting data file size. A ladies ring with many prongs, setting holes, and a faux mill grain edge which I have used to demonstrate detail at jewelry trade shows seemed to fit these criteria. Starting with a design created in Rhinoceros, a NURBS-based CAD modeling program, I exported this design to an STL (stereolithography) polygonal surface format used by 3D printers. I then processed this data to a photopolymer plastic pattern using the Envisiontec Perfactory Mini device. As an added benefit of our evaluation, this pattern would allow us to later compare the relative accuracy of the Envisiontec rapid prototyping pattern, the resulting scan data and the original CAD specifications for analysis.

Micro-CT Scanning Systems

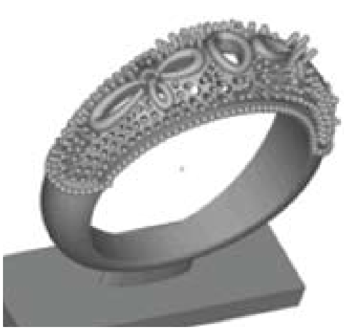

Figure 1 — Study Subject Rhinoceros NURBS Design

Two systems developed in Europe were found that appeared to be ahead of the curve in this new technology.

The first system was developed and manufactured by Skyscan, of Aartselaar, Belgium, under the direction of Alexander Sasov. Dr. Sasov has distinguished himself as an authority on the subject of X-ray micro-tomography and the application of scanning electron microscopy. For our tests we selected the Skyscan 1172 and also used the Skyscan test data for a comparative study of post-processing software programs for data file size reduction.

The second system examined was manufactured by Werth Technologies of Giessen, Germany. Established in 1955, Werth is known worldwide in the field of metrology. Werth has developed unique multisensor coordinate metrology software, which combines data from each sensor type. The most recent Werth multisensor offering is a micro-CT scanning device Werth calls the Tomoscope. Our tests utilized the coordinate touch sensor on several defined patches to insure a higher degree of output accuracy.

CT Scanning Principals – Hardware

X-ray tomography has been available for medical applications since the early 1970's. It uses several hundred 2 dimensional X-ray shadow images that are recorded at rotations of either 180 or 360 degrees around the object being scanned. The current spatial resolution of medical CT systems is limited to about 1 mm. By 2005, compact micro-focus X-ray sources were being developed by several firms. These new X-ray sources coupled with slow-speed cooled CCD (charge-coupled device) sensors to capture the 2D images and faster more powerful desktop computers make high resolution imaging available for laboratory and commercial business applications today.

Currently, these slow-speed CCD chips are limited in resolution due to a short focal length of the device and limited output of the X-ray source. In the two systems tested, the scan envelope was limited to less than 50 mm in the X- and Y-axis with some variations during procedure in the Z-axis. This focal length allowed us to obtain a resolution range between 0.007 – 0.028 mm by adjusting the target distance from the emitter. Using a variety of software algorithms, larger objects can be scanned in multiple passes. However, the resulting data is large and has proven unmanageable by most post-processing software programs. Coincidently, these machines are well suited for object sizes in fine jewelry applications.

CT Scanning Principals – Reconstruction Software

With several hundred two-dimensional grayscale images from the CCD camera chip, the 3D reconstruction of the scan object is achieved by complex software routines that have evolved from the early medical CT scanning systems. The three methods used are Fan Beam, Cone Beam and Spiral Beam. The Fan Beam method is a narrow linear section of the image, which utilizes only the central section of the X-ray beam where there is minimal distortion. Reconstruction time using this method is the fastest, yet it requires a longer scan time for each linear acquisition in the Z-axis.

The second method now growing in acceptance is Cone Beam or Feldkamp Algorithm reconstruction where the full two-dimensional images are used. Since the beam is inclined towards the corners of the CCD, the values are modified by weighing coefficients based on the distance of the X-ray beam as it relates to the target object and the background projection location on the CCD. While the Cone Beam method takes far less scan time, the actual reconstruction time may be longer depending on the computer speed.

Lastly, the Spiral Beam or Heliacal method is the most recent algorithm. It combines the Cone Beam method with the continuous rotation and elevation of the object during the scan. This method requires additional compensation for the distortion that takes place as the distance increases between the X-ray source, scan target and background CCD. This also takes the longest scan time and the longest reconstruction time. The primary advantage of the Spiral Beam method is that larger objects can be incrementally scanned in the Z-axis with the addition of hardware functionality adding to the Z axis envelope.

Data Conversion – 2D Images to Point Cloud

The reconstruction of 3D objects from micro-tomography involves computations from an array of two-dimensional grayscale digital shadow images. The range of grayscale for each pixel is calculated on a scale 0–256. This numerical value would then correspond to the density of the object based on the absorption of X-rays passing through the target and then projected to the 2D detector.

Through a series of calculations on intersecting images, these same grayscale values are converted to 3D units called voxels, which is how the resolution is calculated for each micro-CT scanner. The variations in grayscale values also define the surface perimeters and interior features of the target throughout the 3D reconstruction. This is an advantage to jewelry designs where undercuts are common and a complete geometry is required. The reconstructed 3D voxel version of the scan data derived from the 2D images is then converted to point cloud data by calculating the vertices of all voxel surfaces that define the volume of our scanned object.

Data Conversion – Cloud Point to Polygonal Surface

As previously described, point cloud data defines a 3D object as a mass of points. When working with small objects at resolutions in the micron range, the number of points can be in the billions, making data file sizes problematic: sometimes they exceed five gigabytes in size. To make the data more manageable for further design use, the next step is to translate the object from a mass of points into a logical set of points that define a polygonal surface or watertight mesh. Changing from point cloud to mesh data with fewer data points reduces the file size considerably.

Figure 6 — Grayscale Pixel

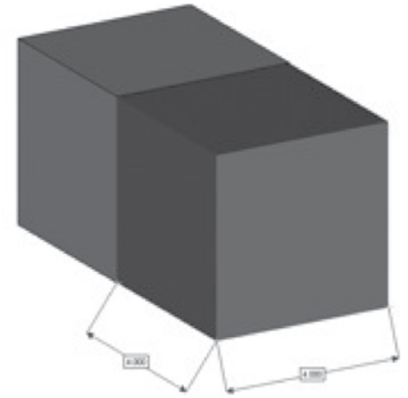

Figure 7 — Grayscale Density Voxel

A polygonal surface is defined by the triangulation of points from the modified point cloud surface. Each surface triangle is defined by three points in the X-, Y-, and Z-axis along with a normal direction, which defines the inside or outside of the surface. The most popular format is the STL file type and is widely used in 3D printing and CNC milling. Creating a polygonal surface provides a reduced data file size. However, each triangle could measure less than 0.025 mm, so there are millions of triangles and a file size of several hundred megabytes.

Data Decimation – Triangle Reduction

When presented with a polygonal surface data file of several hundred megabytes, practical uses are limited. Most 3D printers and CNC mills can process these larger files directly. However, if modifications are required the file size must be reduced in size and format suitable for CAD software. Reducing a polygonal surface is described as data decimation or triangle reduction.

There are several application software programs designed to operate on polygonal mesh files. In the past 10 years mathematical methods have emerged for re-meshing and

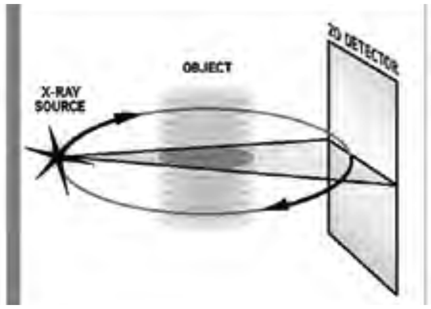

Figure 3 — Fan Beam Algorithm

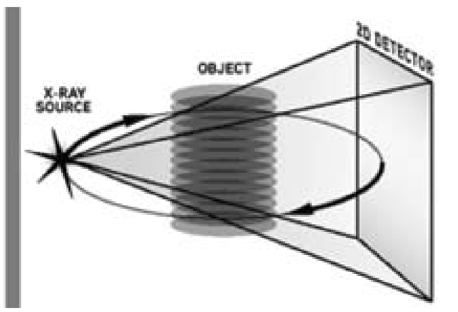

Figure 4 — Feldkamp Cone Beam

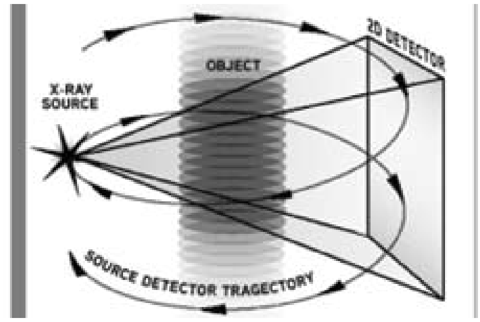

Figure 5 — Heliacal - Spiral Beam Algorithm Algorithm

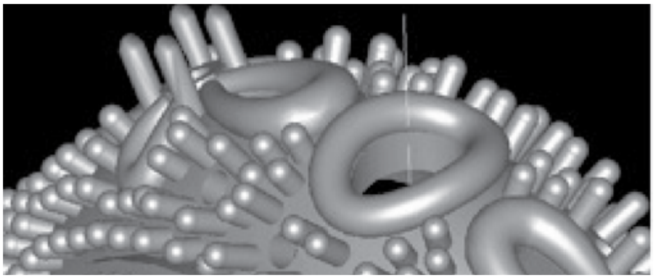

Figure 8 — Rhinoceros STL Export 34 MB

refining a polygonal surface. These programs were intended for the engineering community serving the aerospace and automobile industries where product size made laser and photometric scanning a viable source for design. These programs have developed a broader appeal in medical, dental and some fine jewelry applications. Each software program reviewed has grown from a focused conversion utility into a fully modular application with some capable of complete CAD functionality. Conversely, there are CAD programs like Rhinoceros that have modified their software to accept mesh objects and can perform a variety of CAD operations directly on the STL mesh. The test design was modeled in Rhinoceros using a multitude of points, curves and surfaces to define the native 3D. These components were combined and exported into a 34 MB STL file. This study contrasts and compares the original Rhinoceros STL file with the results from both micro-CT scanners and the associated decimation software required to create a file with this file size constraint.

Werth Scanning Test

The Werth scanning process used 400 rotary positions to cover the entire 360-degree range while recording X-ray projections at each position. Using their proprietary reconstruction software, we generated a 3D data point cloud of our ring. Additionally, a low-force touch trigger probe mounted on a different axis was used to measure several reference points on the ring in order to use the multi-sensor metrology software. It took about 80 minutes to do a four-section scan and assemble the data. The reconstruction software was running on a three-computer cluster and provided a point cloud data file of 9 GB. This file was decimated further and output to a 42 MB STL file. Since CAD technology is not able to process this amount of data in an acceptable time frame, an intelligent process was used to reduce the number of points. Using this "thining out" process with a tolerance value of 10 microns, the file was reduced from 42 MB to 11 MB without losing too much valuable data.

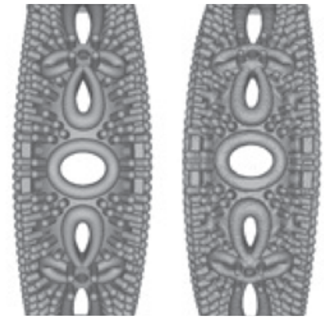

Figure 9 — Werth Tomoscope 42 MB / Rhinoceros STL File

Both the Envisiontec Perfactory pattern and the Werth STL output, showed a taper and an inconsistent surface finish present in the pattern that was scanned. The expected "stair step" effect seen across a rounded surface was accurately represented in the Werth output indicating a highly accurate result. To quantify these results, I used the Werth best-fit color map software to compare the two files. The findings indicate the variation of the Rhinoceros file and the Werth file were accurate in a range from 0.03 through -0.03 mm on the critical prong, hole and mill grain features. This indicates a high degree of accuracy for both the Envisiontec Perfactory pattern and the Werth Tomoscope scan output.

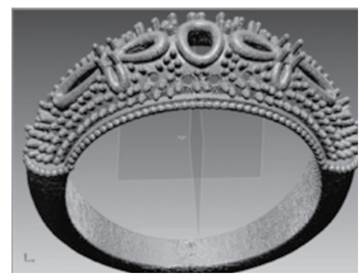

Figure 10 — Skyscan 1172, 28 micron, lower resolution, Baseline 225 MB

Skyscan 1172 Scanning Test

The Skyscan 1172 provided an STL polygonal mesh file generated from their proprietary reconstruction and point cloud conversion software. The 14-micron pixel,

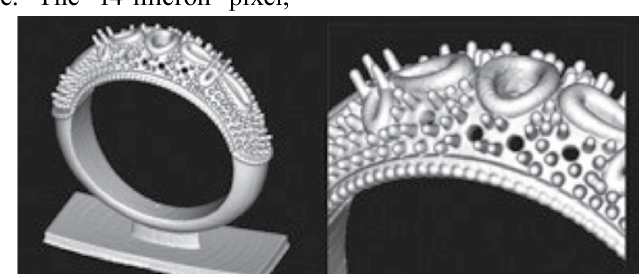

Figure 11 — Werth Tomoscope Scan 42 MB

FILE DECIMATION ANALYSIS I

Software Manufacturer	Start STL Size	End STL Size	CPU Time HH:MM:SS	CPU Specs
PolyWorks, Innovmetric Saint Foy, QC	124 MB	34.1 MB	0:07:06	3 GB RAM Dual Xeon 3GHz 64-bit Windows
Rapidform Inus Technology Seoul, South Korea	124 MB	34.1 MB	0:01:40	3 GB RAM Dual Xeon 3GHz 64-bit Windows
Geomagic, RTP, NC	124 MB	34.1 MB	0:07:40	3 GB RAM Dual Xeon 3GHz 64-bit Windows
Claytools Sensable Technologies Burlington, MA	124 MB	34.1 MB	0:11:46	2 GB RAM Intel Xeon 3GHz Windows 2000 Nvidia Quadro FX
Magics RP Materialise Leuven, Belgium	124 MB	34.1 MB	0:01:40	3 GB RAM Dual Xeon 3GHz 64-bit Windows Nvidia Quadro Fx 3400/4400

Each program achieved the target file size with a range of qualities in output. The results varied based on the skill level of the operator and familiarity with the programs.

FILE DECIMATION ANALYSIS II			
Software Manufacturer	Human Time HH:MM:SS (*)	Skill Level Require (1-10)	Quality Score (1-10)
PolyWorks, Innovmetric Saint Foy, QC	00:10:00 Straight forward process	6	9 ***Comparable to the remeshed file
Rapidform Inus Technology Seoul, South Korea	0:04:00 Relatively easy process once the model is activated so it can be decimated	6	9 ***Comparable to the remeshed file
Geomagic, RTP, NC	0:09:00 Possibly the most straight forward process	6	9 ***Comparable to the remeshed file
Claytools Sensable Technologies Burlington, MA	0:15:00 Fairly smooth to reference the triangle size already present in order to get the correct triangulation.	8	7 There were some connections created in between the cylinders through the voxelization process of Claytools. ***Comparable to the remeshed file.
Magics RP Materialise Leuven, Belgium	00:20:00 – 00:30:00 Triangles from the "smallest detail, max angle, and # of iterations" required training	8	9 ***Comparable to the remeshed file

high resolution file size was approximately 1.41 GB. Upon inspection we found it was not formatted as a valid STL file and could not be opened by any computer. The 28-micron pixel, lower resolution, scan file size was a 218 MB file with bad triangulation. This file was imported into Rapidform XOR and the STL mesh was *re-meshed* to provide a better starting point. This process took 7.5 minutes to complete. The file was then decimated in Rapidform and the process took 1.25 minutes. The end result of this process was a data file that was more correctly triangulated. The file size also went from 218 MB to 124 MB. At this stage of decimation the file would still be four times the 34 MB starting size of our original STL file generated from Rhinoceros. Using this file as a new starting point the following software programs were then compared through the selected import and decimation processes.

Each program achieved the target file size with a range of qualities in output. The results varied based on the skill level of the operator and familiarity with the programs.

Figure 12 — PolyWorks Decimation, 34 MB

Figure 13 — Rapidform Decimation, 34 MB

Conclusions

It is apparent from the results of these tests that the use of micro-tomography will be a viable method for reverse engineering of fine jewelry designs over the next decade. Given the significant financial investment in both hardware and software required at this time, this technology is expected to begin as an outsourcing option for most fine jewelry manufacturers. This trend will probably mimic the implementation rates of CAD software, 3D printing and CNC milling for jewelry applications over the past five years. I believe that we will see common in-house use of scanning devices by 2010 including micro-tomography.

Steven Adler is the owner of A3DM. This article has been developed from May 2008, 22nd Santa Fe Symposium on Jewelry Manufacturing presentation.

For more information contact A3DM, visit *www.a3dm.com*

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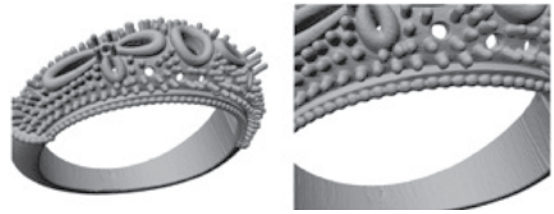

Figure 14 — Geomagic Decimation, 34 MB

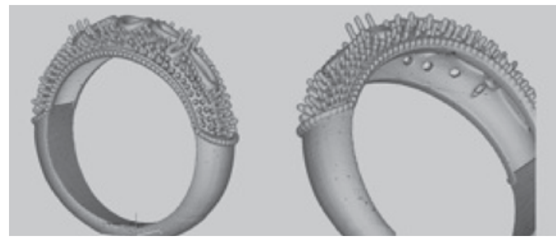

Figure 15 — Freeform Decimation, 34 MB

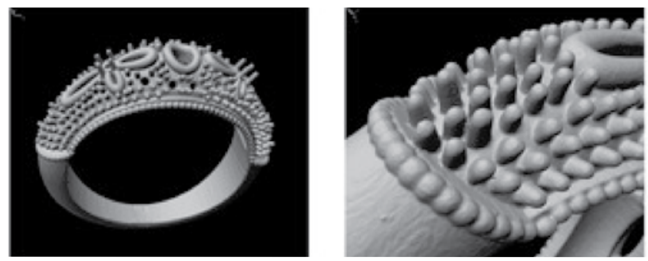

Figure 16 — Magics RP Decimation, 34 MB