ADVANCES IN IMAGE FILTERING TECHNIQUES FOR QUANTITATIVE X-RAY COMPUTED TOMOGRAPHY BALLISTIC DAMAGE ANALYSES

Jeffrey R. Wheeler[1] and Herbert T. Miller[2]

[1]*Santa Cruz Institute for Particle Physics, University of California – Santa Cruz*
1156 High Street, Santa Cruz, CA, 95064-1077 USA
[2]*University of Maryland – Baltimore County*
1000 Hilltop Circle, Baltimore, MD, 21250-0002 USA

An analytical technique has been developed using LabView™ to quantify the volumetric ballistic damage in impacted material samples. This technique is a significant improvement over a previous, more labor intensive, method which used a variety of software applications to analyze and quantify the extent and morphology of 3D ballistic impact damage. This new software technique processes the digitized x-ray computed tomography (XCT) images and characterizes the amount of damage in a substantially more efficient manner than the previous method. The application of this technique greatly enhances our capability to quantify the volumetric meso-scale damage details of impacted targets.

BACKGROUND

The improved visualization and characterization of internal volumetric damage resulting from impacted metallic and ceramic ballistic targets has been demonstrated with the introduction of non-destructive x-ray computed tomography, XCT, damage assessment techniques [1-3]. While quite enlightening, the *qualitative* 3D virtual imaging of such damage, is necessary but insufficient to adequately characterize the technological details of such ballistic damage. A methodology previously developed [4] for the *quantification* of this damage in XCT ballistic impact analyses has been relatively inefficient and therefore not particularly cost effective. Our desire to speed up the quantitative analyses of ballistic meso-scale (>0.25 mm) damage in large quantities of XCT data has provided the motivation for the development of an improved analytical software approach.

Within LabView™, a program was written to import stacks of XCT images in the Portable Network Graphics (PNG) file format. Calculations were then made on these stacks and the outputs of these calculations, which are most relevant and useful for ballistic impact analyses and visualization, are the percentage damage in annular rings along the z-axis of penetration. Using these percentages, several calculations can be made such as the axisymmetric damage versus radius, cumulative damage, unit cumulative damage, and axisymmetric damage as a function of radius and depth. New techniques have been investigated to allow axisymmetric damage as a function of arc segment and depth to be plotted. Sample data is shown of a typical XCT slice in Figure 1.

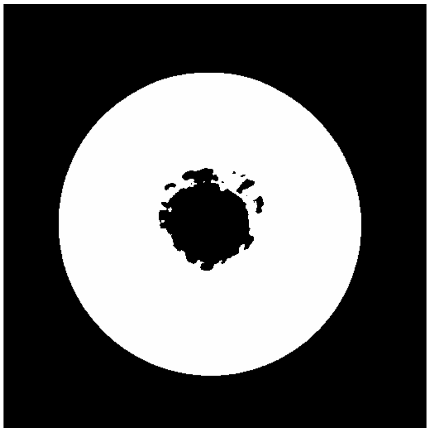

FIGURE 1: Ti-6Al-4V APM2 Sample 2, Image 10

PROBLEM

The task at hand was to create an efficient user friendly interface for analyzing stacks of XCT images in a reasonable time frame in order to quantify the discrete meso-scale damage. Previous methodologies created lacked user friendliness and required approximately eighty man-hours to analyze each XCT stack. The steps in obtaining an end result required the use of multiple software applications in order to produce data sets. The time and complexity issues associated with analyzing each XCT stack was not considered justified for continued use. However, it was an important starting point for our continuing research and development efforts.

SOLUTION

As defined, a *normalized binary square pixel array* is a binary image converted to a 2d array of pixels. The position in this array of pixels identifies the pixels (X,Y) coordinates in the PNG™ image. The pixel value of this coordinate position, either white or black in this case, identifies it as either a damaged or undamaged pixel. The header file of the raw ACTIS™ TIFF™ image contains the *X* and *Y* pixel and spatial resolutions. Application of these values in eq(1,2) is required in order to normalize output to a defined set of units.

$$X.pixels.per.UNIT = (X.pixel.resolution)/(X.spatial.resolution) \tag{1}$$

$$Y.pixels.per.UNIT = (Y.pixel.resolution)/(Y.spatial.resolution) \tag{2}$$

Input is required by the user in determining the X-offset, *user.input.X.offset*, and Y-offset, *user.input.Y.offset*. Applying these inputs to equation (3,4) one obtains the *X* and *Y* center.

$$\begin{gathered} X.real.center = \\ (user.input.X.offset * X.pixels.per.UNIT) + (0.5 * X.pixel.resolution) \end{gathered} \tag{3}$$

$$\begin{gathered} Y.real.center = \\ (user.input.Y.offset * Y.pixels.per.UNIT) + (0.5 * X.pixel.resolution) \end{gathered} \tag{4}$$

These centers are converted from floating point decimal to integer values. The integer, or rounded, values become the *X* and *Y* centers, along the Z-center axis of penetration. The calculations are performed as required within each slice. Within LabView™, routines were created to convert a binary PNG™ XCT slice into a *normalized binary square pixel array*. Using the array of slice data, calculations were made based on the criteria set forth in Figure 2. In this figure the use of arc segments, or wedges, was also considered but are not necessary unless obtaining wedge segment data.

In Figure 2 the programming logic for the analyses of individual *normalized binary square pixel arrays* based on a Z-center axis of penetration is displayed. Assume the center value (X[n+2] , Y[n+2]) is this Z-center. For each slice, initial global values are set. These values are the unit increment between radii and the minimum and maximum radii of interest. Applying these inputs into equation (5) and rounding up to the nearest integer value determines how many times the program will iterate.

$$\begin{aligned}&Iterations.per.image=\\&(user.input.global.\max.radius-user.input.global.\min.radius)/\\&(user.input.radii.Increment)\end{aligned}\tag{5}$$

When obtaining wedge segment data, the need to input the angle theta increment and starting theta location is necessary. The *global minimum* and *maximum* radii being analyzed within are distinct from the *radii minimum* and *maximum* which is displayed in Figure 2.

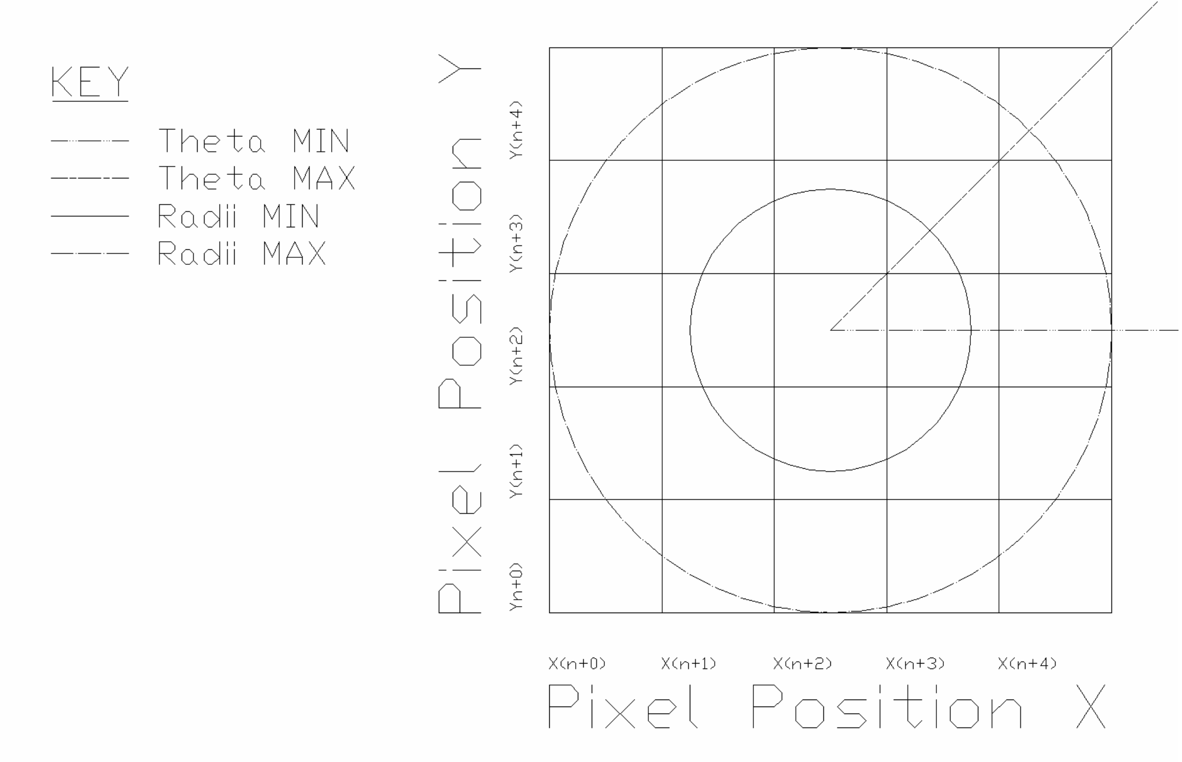

FIGURE 2: Normalized Binary Square Pixel Array

In analyzing images to obtain the axisymmetric damage versus radius, it is necessary to calculate the number of damaged and undamaged pixels within a particular *Radii MIN* and *MAX* (ring). Referring to Figure 2, this measurement is simply the area between the *Radii MIN* and *MAX*, or the area between the lesser and greater circle. For each iteration of the program the *Radii MIN* and *MAX* are incremented equally based on the *global increment*, as previously defined. The output of the program is determined by equation (6).

$$\%.Damage.within.Ring = (\#.Black.Pixels)/(\#.Black.Pixels{+}\#.White.Pixels)*100\% \quad (6)$$

The axisymmetric damage fraction is a measure of the percentage damage in annular rings from a given axis of penetration. Refer to Figure 3. In looking at this plot in comparison with Figure 1 and Figure 2, one can see the relation between the extracted data points as you move out from the center axis of penetration. The damage decreases from complete to zero, as would be expected. This plot is a quantitative visual representation of the graphical XCT™ data.

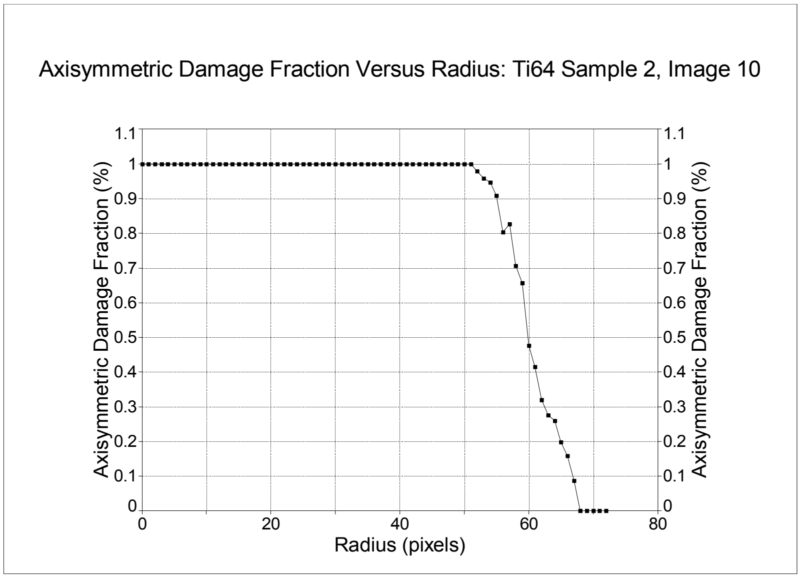

FIGURE 3: Axisymmetric Damage Versus Radius: Ti64 Sample 2, Image 10

In analyzing stacks of slices, it is possible to create a 3d quantitative graphical representation of the damage caused by a projectile using the axisymmetric damage fraction versus radius, and simply adding to that an image number. This gives depth dependence.

Figure 4 displays a sample of the capabilities of this software and spatial relations one can obtain in applying these simple calculations to stacks of slices.

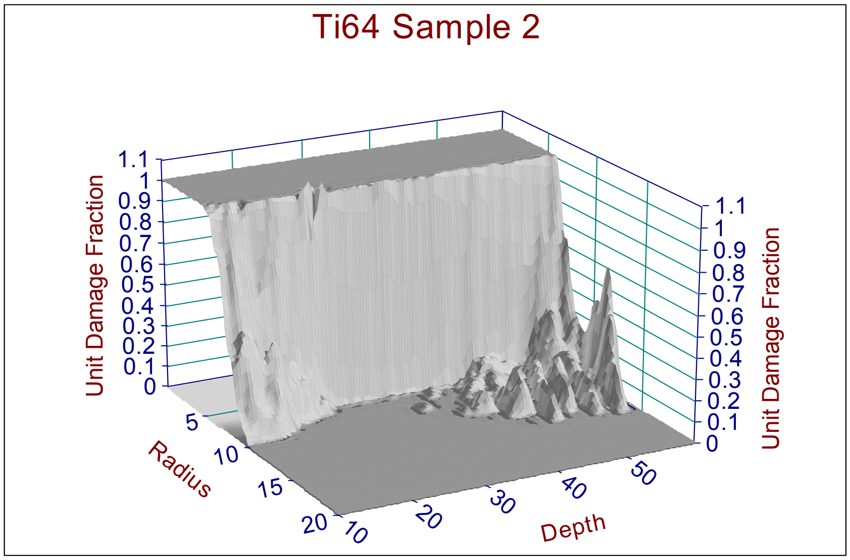

FIGURE 4: Axisymmetric Unit Damage Fraction versus Depth

Axisymmetric Unit Damage Fraction versus Arc Segment: Discussion

Due to the fact that no two XCT™ images are alike and that different techniques to analyze XCT™ images describe damage in their own unique ways, it was decided that different algorithms needed to be developed to describe damage based on the data presented. Discussions on this topic led to the idea displayed in Figure 5. In creating and implementing the use of *wedges*, more accurate representation of the types and causes of ballistic damage will become possible.

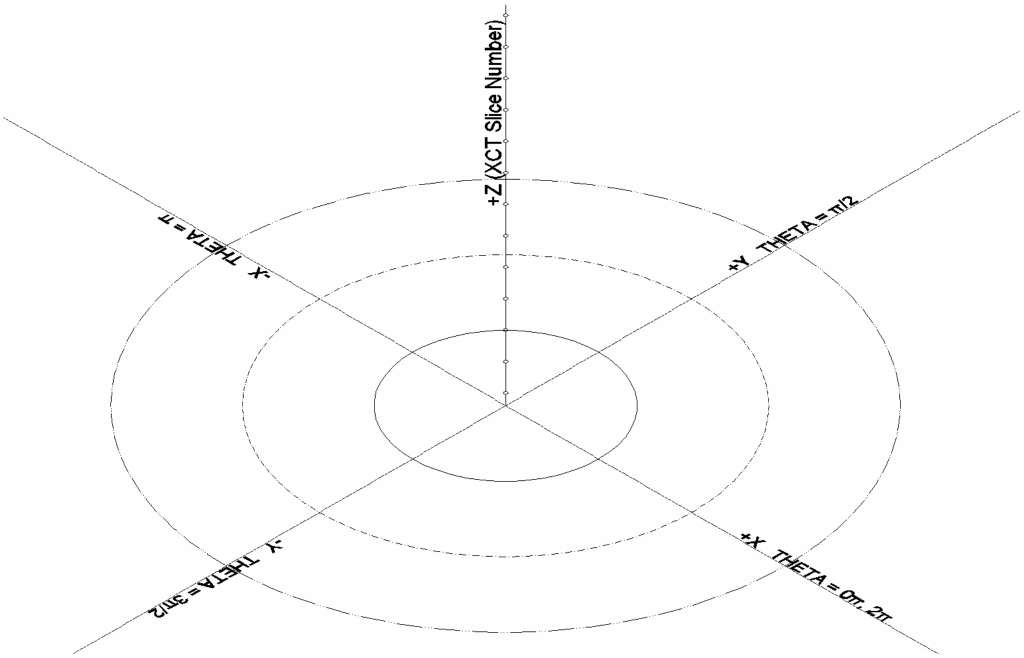

FIGURE 5 Axisymmetric Unit Damage Fraction versus Arc Segment Polar Plot Configuration

In determining an appropriate sampling volume size, the ratios of the dimensions of angularly sample volumes must be considered. That is, thickness, delta-r, and arc length, based on delta-r and delta-theta, of the sampled volumes should be chosen such that their ratios are within predetermined limits. It is desirable to use cubic or reasonably close to cubic volumes in the application of this methodology to XCT™ data. With this in mind the ratio of any one dimension to each of the two others must be between one-third (1/3) and three (3). This is to ensure that calculations are based on sampled volumes with moderate aspect ratios so as to avoid possible geometrically skewing results. Volumes with relatively large aspect ratios would encompass relatively large regions in the physical field-of-view of XCT™ scans, thus failing to provide relatively local annular data as a function or radius.

SUMMARY

Using LabView™, a program was written to import stacks of digitized XCT image data to allow fast processing and analyses of the volumetric meso-scale damage details of impacted targets. Current efforts are focused on databasing of XCT image data in order to allow for the real-time analyses and comparison of large amounts of information and the 3D visualizations hereof. In creating this architecture, it provides one a system to compare ballistic physics modeling data with quantitative expiremental results. This allows for more effective ballistics testing expirements and thefore more accurate ballistic physics models.

ACKNOWLEDGEMENTS:

The authors wish to acknowledge the helpful technical direction and guidance of William Green, Nevin Rupert, Dr. Joseph Wells, Dr. Terry Shalk, and Dr. Robert Johnson.

REFERENCES

1. J.M. Wells, W.H. Green, and N.L.Rupert, "Non-destructive 3-D Visualization of Ballistic Impact Damage in a TiC Ceramic Target Material", *Proceedings MSMS2001, 2nd International Conference on Mechanics of Structures*, University of Wollongong, Wollongong, NSW, Australia, 159-165,2001
2. J.M. Wells, N.L.Rupert, and W.H. Green, "Progress in the 3-D Visualization of Interior Ballistic Damage in Armor Ceramics", *Proceedings of ACERS PacRim IV Conference*, Maui, Hawaii, 441-448, 2001
3. J.M. Wells, W.H. Green, N.L. Rupert, A. Cole, S.J. Alkemade, S.J. Cimpoeru and M. Szymczak, "Ballistic Damage Visualization in Monolithic Ti-6AL-4V with X-ray Computed Tomography", *20th International Symposium on Ballistics*, Orlando, Fl, ADPA, Vol. 2, 1112-1120, 2002
4. J.R. Wheeler, C. Delgado, and H.T. Miller, "Development and Application of Image Filters for Quantitative XCT Analyses", Presentation at ASNT 2003 Spring Research Symposium, Orlando, FL, March 2003