Campden BRI
Station Road
Chipping Campden
Gloucestershire
GL55 6LD, UK

Tel: +44 (0)1386 842000
Fax: +44 (0)1386 842100
www.campdenbri.co.uk

Non-destructive imaging of food and packaging using X-ray micro-CT

X-ray micro-CT is a technique that allows internal food and packaging structure to be investigated. These systems allow 3D objects to be visualised and measured without any destructive sample preparation.

Conventional imaging techniques generally produce 2D images of the surface, or a cross-section of a sample. Labour intensive methods, e.g. sectioning to produce thin slices, or chemical fixation to produce contrast, are frequently used to prepare samples for these 2D imaging procedures. However, these processes are usually destructive and the resulting 2D information is often insufficient to draw conclusions regarding the 3D structure. Moreover, these destructive techniques can introduce artefacts which confuse the interpretation of these measurements.

This white paper looks at some example applications of X-ray micro-CT to food structure and packaging analysis. To discuss potential projects using this technique, or to find out more please contact:

Alix Cornish:
alix.cornish@campdenbri.co.uk
+44(0)1386 842054

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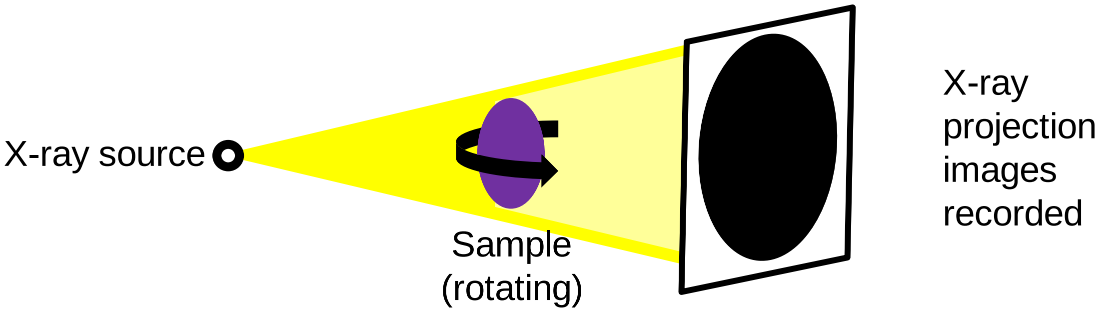
Campden BRI, Registered no. 510618, Incorporated in England & Wales
Registered Office: Station Road, Chipping Campden, Gloucestershire. GL55 6LD
Part of Campden BRI Group

Basic principle

Objects are placed within an X-ray beam and rotated. The X-rays are absorbed by the object. Dense regions cause more absorption than low-density regions, and thicker regions of the object cause more attenuation than thinner regions. A series of shadow projections are recorded. The shadow image produced at each angle provides information about the size and density of the object, in that orientation. Computer software is used to reconstruct the 3D shape from a series of shadow projection images, recorded over 180° (or more). A schematic of the instrumentation is shown in Figure 1.

Figure 1: Schematic of X-ray micro-CT instrumentation

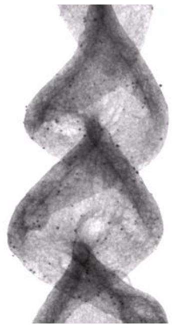
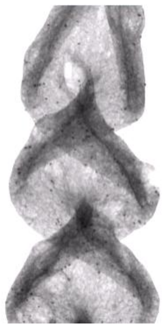


Photographs of the instrument at Campden BRI are shown in Figure 2. The image on the left shows the instrument with the sample compartment door open. The image on the right shows a sample mounted on a brass stub inside the sample compartment.

Figure 2: Photographs of the instrument at Campden BRI

Figure 3 shows X-ray projection images recorded from a twist snack product. Positions on the sample where the X-ray beam has penetrated just one layer show up bright and regions where the X-ray beam has penetrated a thicker region of the product show up darker. Dark spots are also visible on these images. These are caused by dense salt crystals and seasonings on the surface of the product, which attenuate the X-rays to a greater extent than the snack product itself.

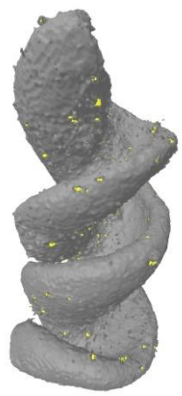
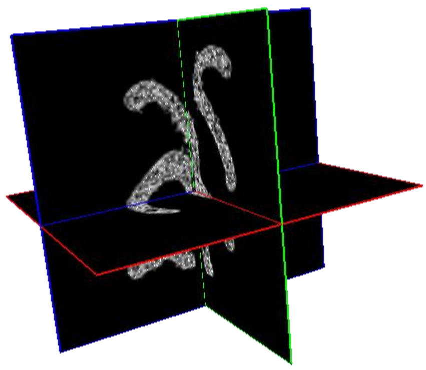
Figure 3: Example x-ray projection images at 3 angles of rotation

Photograph of sample	x-ray projection images		
	0°	120°	240°
			

These projection images are processed using computer software to generate a 3D model (Figure 4). The high density salt crystals are shown in yellow. Images of cross sections can be produced in any orientation that is desired. Measurements can be made from the 2D cross sections, or from the 3D model.

This white paper outlines some example applications for X-ray micro-CT: Characterisation of porous structures, multi-component products and packaging analysis.

Figure 4: 3D model and summary of cross sections showing 3 perpendicular cross sections

3D model	Cross sections
	

Characterisation of porous structures

Porous structures exist within many categories of food products, e.g. bakery produce, extruded cereals, and aerated confectionery and dairy products. The size and distribution of the bubbles is important for the size, shape and structure of the overall product. Bubble size distribution heavily influences the texture of products and is therefore an important sensory attribute. Consequently, it is vital to understand the size distribution of bubbles in porous foods. X-ray micro-CT offers a route to characterise this distribution without laborious preparation methods, which could damage the structure.

Figure 5: **Perpendicular 2D cross sections showing the internal structure of a piece of aerated chocolate**

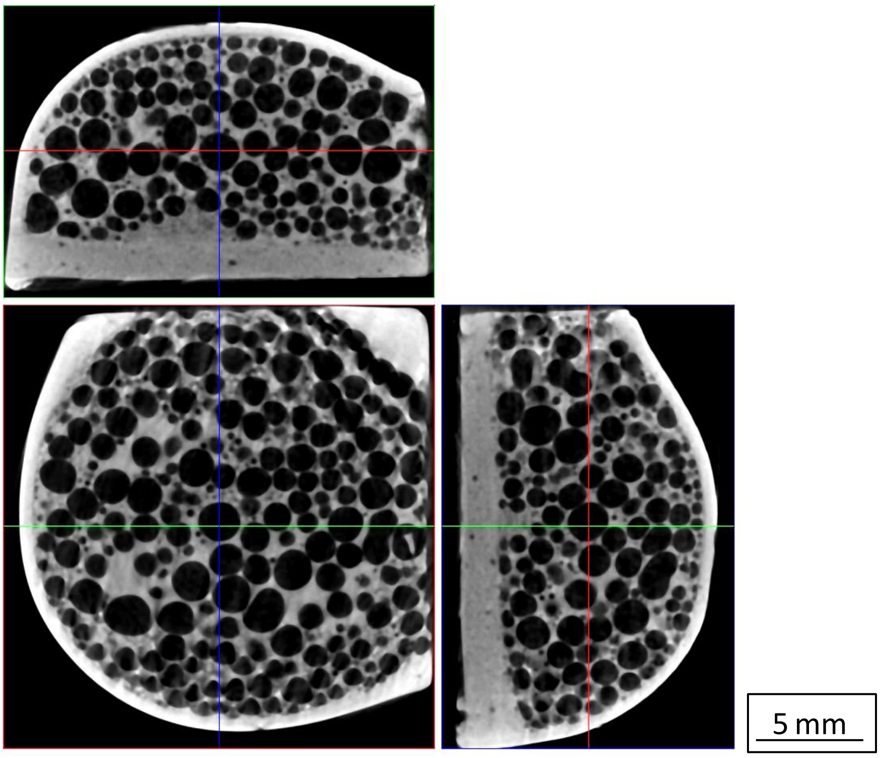
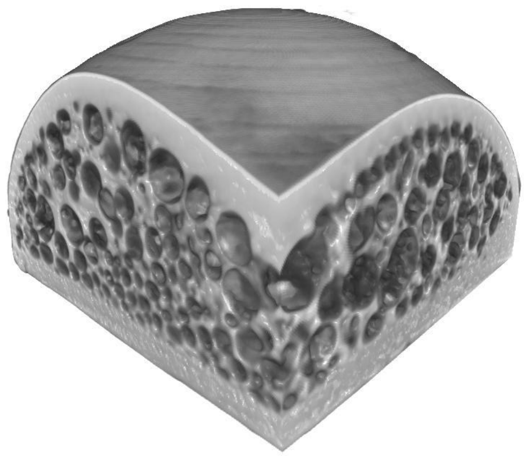
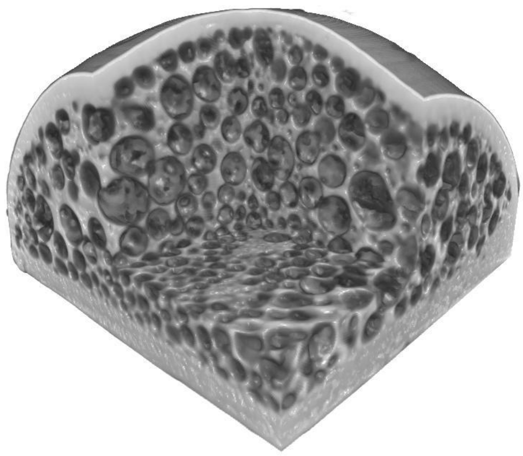


Figure 5 shows three perpendicular cross sectional images of a piece of aerated chocolate. The chocolate shows up bright and the internal pores (and surrounding air) are dark.
Figure 6 shows 3D rendered images of the same piece of aerated chocolate. The image on the right has a cutaway to reveal the internal structure.

Figure 6: **3D rendered images showing the structure of a piece of aerated chocolate**

3D rendered image of the external surfaces	**3D rendered image with a cutaway**
	

In addition to non-destructive imaging, X-ray micro-CT enables quantitative analysis of porous structures. The volume occupied by the whole structure and the volume occupied by each individual bubble can be measured. Several structural parameters can then be calculated based on this information. Some values calculated for this piece of aerated chocolate are shown in Table 1.

Table 1: **Table of parameters**

Volume of chocolate piece:	5696 mm^3
Total volume of bubbles:	1348 mm^3
Porosity:	23.7 %
Total number of bubbles:	6848 bubbles
Bubble density:	1.2 bubbles per mm^3

Figure 7: **Pore size distribution plot and corresponding 3D models showing a piece of aerated chocolate. The 3D models show the bubbles in 7 size classifications.**

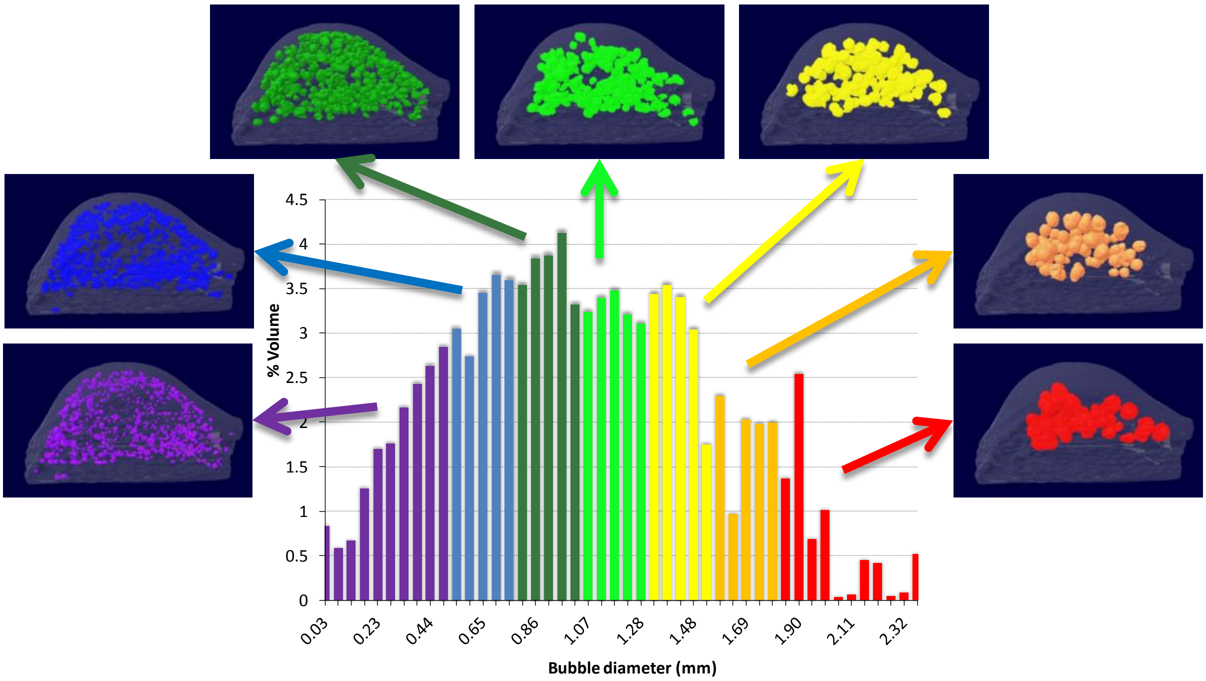
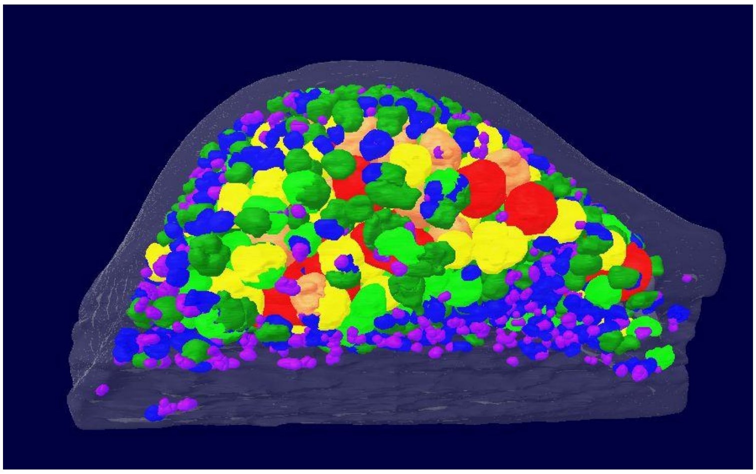


Figure 7 shows a bubble size distribution plot for the aerated chocolate piece. The distribution has been plotted using 46 size classification bins, approximately 0.05 mm apart. 3D models showing bubbles in seven broader size classifications are displayed around the distribution plot. A 3D model showing all the bubbles (colour coded by size) is shown in Figure 8.

Figure 8: 3D model showing the bubbles inside a piece of aerated chocolate colour coded to correspond with size – where purple represents the smallest and red represents the largest bubbles.



These images reveal that the larger bubbles are only located in the centre of the chocolate and that the smaller bubbles are evenly distributed throughout the aerated interior. Some small bubbles are also present in the surrounding chocolate, towards the base of the product.

Characterisation of multi-component products

Many food products contain more than one component, for example bran in wholemeal bread, the pastry and filling in pies, and enrobed confectionery products. It is often challenging to separate out these components to measure them individually. Micro-CT analysis enables different components within a structure to be measured non-destructively, without manual separation.
It is possible digitally to separate (segment) two components that show differences in contrast, or are spatially separated. In this case, the shell and the nut of an almond have been segmented.

Figure 9 shows the nut before segmentation. It is possible to see a gap between the shell and the nut. Figure 10 shows images from the same sample after the segmentation process. Two separate 3D models have been generated, one for the shell and one for the nut.
Table 2 shows volume measurements for both components.

Figure 9: **3D rendered images showing an almond. The image on the left shows the outer shell and the image on the right has a cutaway to reveal the almond nut inside.**

3D rendered image of the external surfaces	3D rendered image with a cutaway

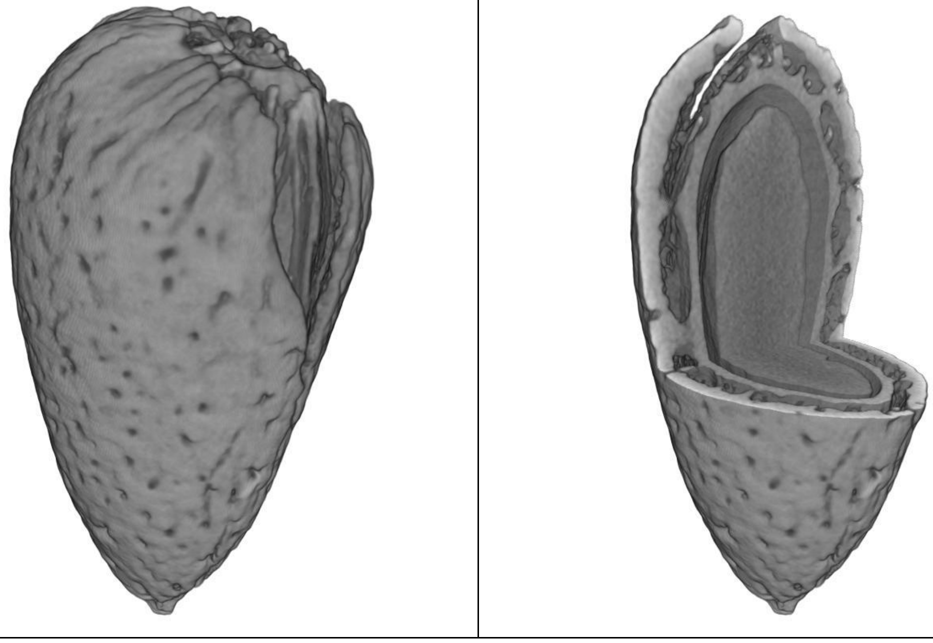
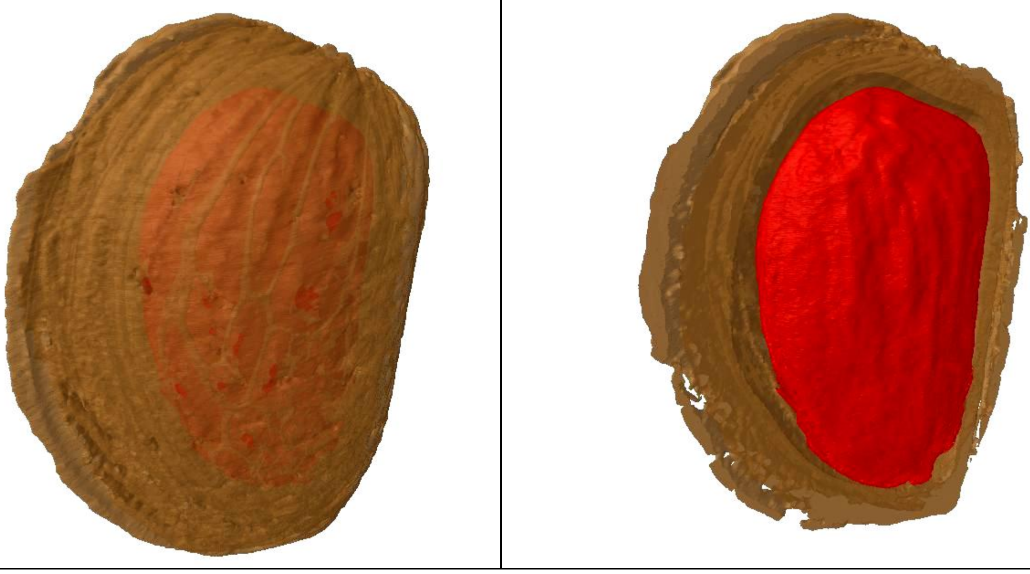


Table 2: **Values for the volume of the shell and the nut**

	Shell	Nut
Volume (mm^3)	1713	3424

Figure 10: **3D rendered images showing an almond nut in its shell. The image on the right shows the nut inside the shell (the shell has been shown semi-transparent). The image on the right shows the shell cut away to reveal the nut inside.**

Semi transparent shell revealing nut	Shell cutaway to show nut



Measurement of packaging

Packaging materials are often manufactured to strict tolerances. If the packaging dimensions fall outside these tolerances, the packaging may fail, spoiling the product inside and potentially leaking and spoiling surrounding products.

Measuring packaging dimensions using traditional manual techniques can be time consuming. These methods are destructive and the process of preparing the material for measurement may change the shape or size of the material, making the measurements useless. X-ray micro-CT allows packaging materials to be imaged and measured non-destructively.

Figure 11 shows 3D rendered images of a bottle cap from a pouch drink product. The image on the left shows the outer surface and the image of the right has been cut to reveal the internal structure. The cap seal is intact. i.e. the cap has not been unscrewed from the pouch.

Figure 12 shows four 2D cross sectional images. The central image shows a cross section through the centre of the bottle cap. Three perpendicular cross sections are shown around this image. The coloured borders correspond to the positions at which these cross sections were taken. A 3D rendered image with a cutaway is shown on the left for clarity.

Several features can be seen within these images including the seal between the pouch and the cap, and the interlocking threads.

In addition to qualitative observations from the images, dimensions of the packaging material can be measured. Measurements of any dimension can be made, including of the gaps between the cap and the pouch or thickness of the cap.
Figure 13 shows thickness measurements from the threads in the cap. Measurements of thread thickness were taken in 20 positions. The distribution of thicknesses is shown in Figure 14.

Figure 11: 3D rendered images showing the external surface of a pouch drink cap (left) and the same cap with a cutaway to reveal the internal structure (right).

3D rendered image of the external surface of a pouch drink cap	3D rendered image showing a pouch drink cap with a cutaway revealing the internal structure
	

Figure 12: **2D cross sections of a bottle cap from a pouch drink. The images on the right are from perpendicular planes – colour coded to correspond to the border colour.**

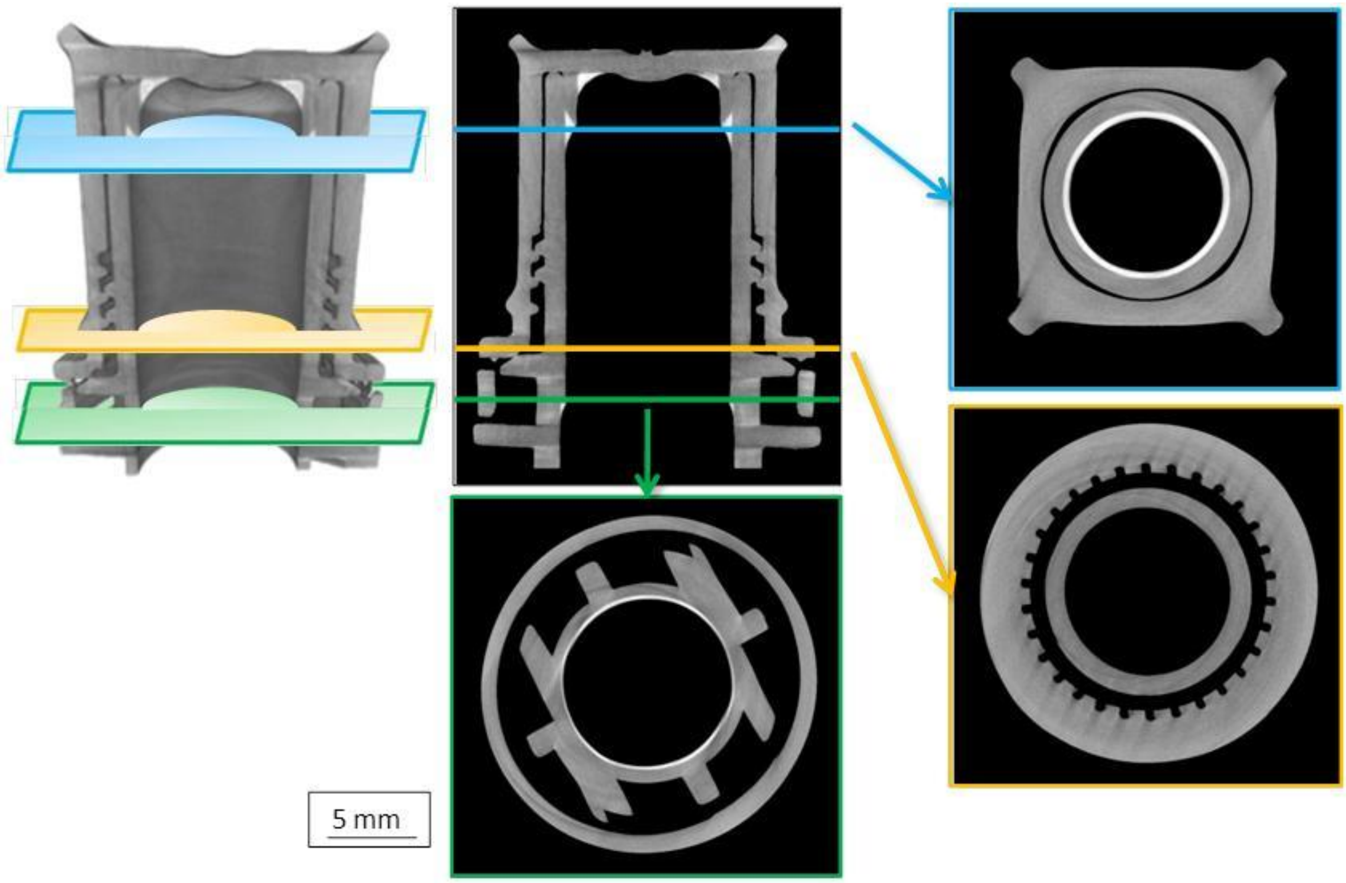


Figure 13: 2D cross section taken through the wall of the cap to intersect the threads. The region inside the red box has been enlarged to show the location where measurements were made.

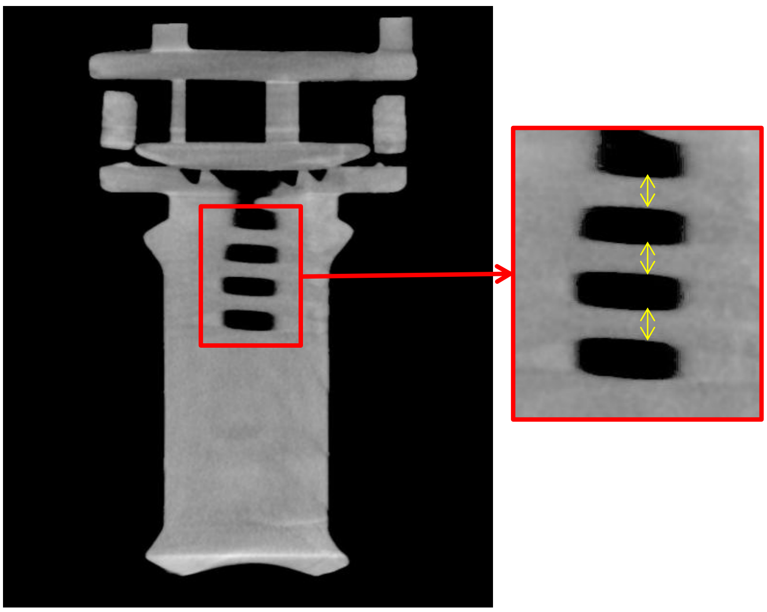
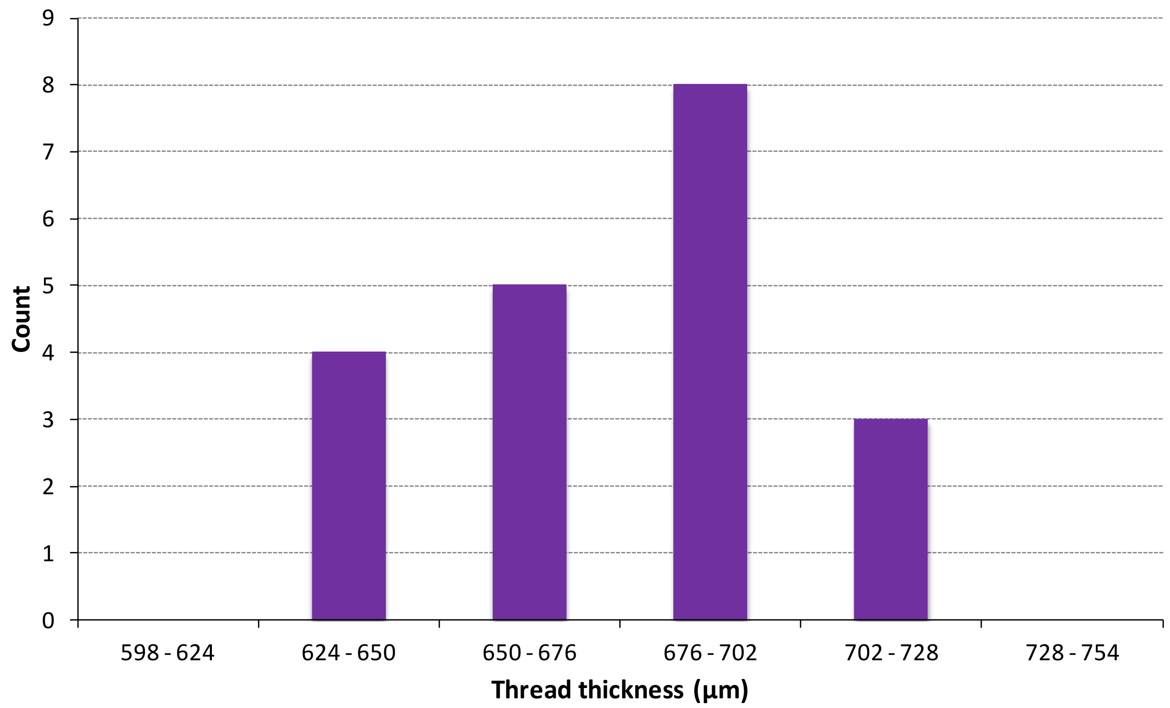


Figure 14: Distribution plot showing the thread thickness measured in 20 positions



Sample requirements for X-ray micro-CT scanning

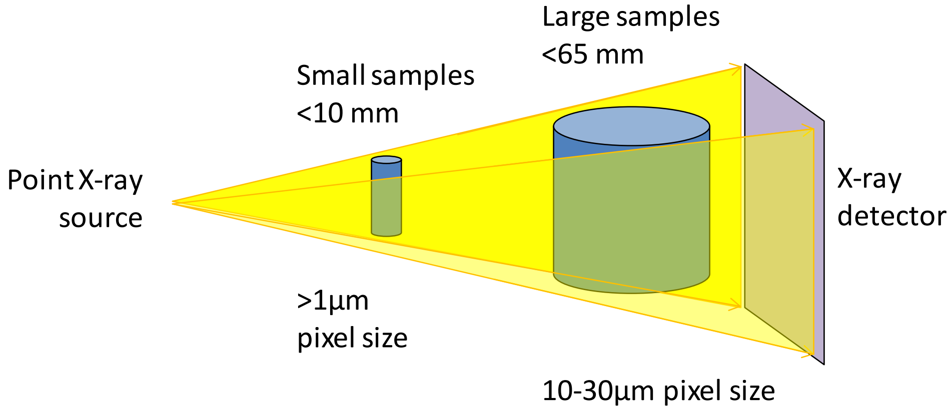
For samples to be suitable for analysis by X-ray micro-CT, they must be:

- below a certain size
- below a certain density
- motionless for the duration of the scan

The maximum sample size depends on the geometry of the particular instrument being used. Microtomography refers to methods where image data is in the micrometre range. Typical sample sizes can be up to a few 10s of centimetres. These instruments tend to be laboratory based systems. Tomography is an identical technique, but on a larger scale, with a lower resolution, such as medical X-ray CT scanners.

Campden BRI has a Bruker 1174 instrument which is capable of scanning samples with dimensions of up to 65mm diameter. The maximum resolution that can be achieved is around 1µm (pixel size) for very small samples (up to a few mm in diameter). Figure 15 illustrates this trade off between sample size and resolution. The sample must be contained inside the X-ray cone at all times during the scan. It is not possible to scan a small region inside a larger object. However, it may be possible to prepare a subsample for measurement without damage to region of interest. Smaller samples can be positioned nearer the X-ray source and still remain inside the X-ray cone, enabling higher magnification and better resolution to be achieved.

Figure 15: **Schematic of X-ray cone geometry inside an X-ray micro-CT instrument illustrating the trade off between sample size and resolution**



The maximum sample density depends on the X-ray conditions being used. The instrument at Campden BRI enables a range of X-ray energies and exposure times to be used to suit the requirements of different materials. However, if the X-rays are completely blocked by the sample, there will be insufficient information for the reconstruction process to work properly and the resulting images will contain strong artefacts. The extent to which X-rays are attenuated is based on the atomic mass of the atoms within the sample. Most food products are composed of water, carbohydrates, protein and fats, so have a high proportion of carbon and oxygen atoms and few heavier elements. Plastic packaging materials are primarily composed of carbon based polymers. These food and packaging materials can be measured using the instrument at Campden BRI. Packaging containing thin layers of aluminium can also be analysed, but steel packaging cannot. As illustrated for the twist snack, salt particles can be clearly discriminated due to the relatively high atomic mass of sodium and chlorine.

Most laboratory based X-ray micro-CT systems do not allow dynamic measurements - it is not possible to monitor processes during a scan (e.g. foam stability over a short time). However, it is possible to perform a time series if the samples are stable for the scan duration. Samples can be scanned, modified, then re-scanned several times. Some specialised laboratory X-ray micro-CT instruments contain controlled heating and compression stages to allow samples to be measured at a series of different temperatures, or under differing amounts of compression. The instrument at Campden BRI can be used to measure ambient or frozen samples. For the latter, a specially designed sample holder with dry ice compartments is used to keep the sample frozen throughout the scan.

Contact us

X-ray micro-CT offers solutions for a diverse range of problems. This white paper showcases example data for a few selected applications, but this technique has many further potential applications. Please contact us if you think we can help you. More information, including a video is available on the Campden BRI website:

http://www.campdenbri.co.uk/videos/x-ray-micro-ct-scanner.php

Dr Alix Cornish
+44(0)1386842054 alix.cornish@campdenbri.co.uk