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Rapid prototyping coded masks for X-ray backscatter imaging

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Abstract. Coded masks often lack a self-supporting structure that is difficult to manufacture without recourse to drilled holes in place of ideal square apertures, degrading imaging properties. An alternative approach is presented with 3D printed coded mask moulds cast with a radio-opaque material that allows square elements to be retained. Two methods are presented; hot casting a bismuth alloy (density 8.6 g cm^{-3}) and cold casting with tungsten powder/epoxy resin (densities 9.6 - 10.6 g cm^{-3}). A critical review of 3D printed coded mask fabrication along with some typical X-ray backscatter images is presented. Signal to noise ratio from both the machined tungsten and cold cast 3D printed mask were comparable, with the former having a slight advantage. Also, 3D printed cold cast masks were found to be more economical and easier to rapid prototype over traditional drilled tungsten masks.

Keywords: coded apertures, coded masks, X-ray backscatter, 3D printing.

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1 Introduction

In conventional imaging, a camera lens is used to form an image on a light sensitive detector. However, at X-ray energies the refractive index of materials is close to 1 and traditional lenses are rendered impractical, resulting in X-rays passing without significant focusing. Alternatively, a radio-opaque pinhole mask[1] can be used to form an image. A pinhole mask is a sheet of material placed in front of a detector, which attenuates radiation but contains a single aperture to allow some through put of light. The resolving capabilities of which are defined by the aperture size with smaller openings yielding a higher resolution yet dimmer image that requires a longer exposure time. To retain both a short exposure time and high resolution, multiple apertures can be used to increase the throughput of radiation. This encodes the image because the separate images from each pinhole overlap, and a coded mask (CM) or coded aperture is formed. The encoded image is then mathematically decoded to give the true image of the scene. CMs can be traced back to the

1960s with Mertz and Young (1961),[2] and are used for X-ray imaging in astronomy, the medical sector,[3] and defence and security.[4]

CMs are formed from 2D binary arrays of 1 and 0 elements that represent transparent and opaque regions. Transparent elements are essentially the apertures of the mask. When the binary array is converted into a CM each element in the array pattern is depicted as a perfect square. Fabricating a replica of this array pattern as a physical CM is challenging using square openings. Metal additive manufacturing, etching or laser cutting is an option;[5–7] however, the resulting masks lack a self-supporting structure and are mechanically weak. Alternatively, adding opaque rows and columns creates a version of the mask with self-supporting properties. This is known as a no two holes touching (NTHT) version of the mask[8] where apertures can easily be formed by drilling round holes in place of square elements. However, the self-supporting structure compromises the imaging properties of the original arrays pattern, because the perfect square elements are now circular.

This paper presents a solution to the above problem by 3D printing a radio-lucent CM mould into which a radioopaque material is cast to form the completed CM.[9,10] The mould material remains in place to serve as a support structure. This allows the original array pattern and its square elements to be retained, helping to preserve its original encoding properties. Such technique provides a quick and low-cost method of manufacturing CMs using an off the shelve polymer 3D printer. Also, 3D printing CMs would be particularly useful for constructing prototypes for experimental masks. This paper mainly focuses on the fabrication methods of 3D printed CMs using two different casting techniques and critically evaluating its use for X-ray backscatter imaging.

2 Mask Construction & Evaluation

2.1 Experimental Method

Fabricating the 3D printed CMs began with generating coordinates for open elements of the 2D binary array. These were imported as a ‘table-driven pattern’ into the computer-aided design (CAD) software SOLIDWORKS®[11] (see Munoz et al. on how to generate array patterns[12]). A simple $1 \times 1 \times 1$ mm cube was created within the CAD software to represent a single element of the array. The cube was then replicated based on coordinates of the open elements of the CM, and used to form a drawing of the CM pattern. This was then merged with a blank mould to create the completed CM mould (see Figure 1).

The CM mould was exported as a stereo lithography file, and 3D printed using an Ultimaker 2 Extended printer.[13] The type of print filament used depended on the casting temperature and included polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). Print settings for PLA and ABS were different and are presented in Table 1.

2.1.1 Hot Casting

The hot casting method involved using a ternary bismuth alloy (Bi 57 wt%, Sn 26 wt%, In 17 wt%) that had a eutectic temperature of 80 °C. This low temperature was critical for reliable casting, in order to avoid damage to the mould through heat transfer. The alloy manufacturing process began with melting the element with the highest melting point (bismuth), then adding all remaining elements to the molten liquid metal. This was cooled to 90 - 100 °C, high enough to remain in a liquid state, but lower than the 105 °C glass transition temperature (T_g) of the ABS mould to avoid its structural damage. Once the molten alloy was poured into the mould the cast was cooled for 3 - 4 hours before polishing to remove excess metal. The final solidified alloy had a measured density

(ρ_M) of 8.6 g cm^{-3}. Several tests were conducted, however it was noted that elements became loose due to the flexibility of ABS, and poor adhesion to the mould (see Figure 2). Because of this, along with the difficulties of working with the molten alloy and its comparably low density, work on hot casting was discontinued in favour of cold casting.

2.1.2 Cold Casting

The cold casting process was performed at room temperature with a 3D printed PLA mould. PLA has a T_g of around 60 °C and was generally easier to print than ABS. To complete the mask, a tungsten - epoxy resin composite (TEC) was used (Technon® poly kit[14]), which contained 100 mesh tungsten (maximum particle size of 149 microns) and two-part epoxy resin ($\mathrm{E_p}$). This was mixed according to the manufacturer's instructions with predicted densities (ρ) ranging from 9.6 - 10.6 g cm^{-3}. Following curing a polishing process was then used to finally complete the mask. Cold cast masks were found to be more robust than the hot cast masks with the epoxy resin firmly holding the radio-opaque elements in place. Examples of the final completed 3D printed cold cast CMs are presented in Figure 3 with (a) 19 MURA unit pattern and (b) 35×39 Singer set mosaic.

2.2 Analysis of Material used for 3D Printed CMs

When casting fine structures, such as the CMs, voids can be formed due to trapped air. To assess this, parts of the 3D printed CMs were examined to confirm their densities, and therefore confirm that their X-ray attenuation would be as expected. The densities of samples of both the TEC and bismuth alloy were measured using an Accupyc pycnometer.[15] The measured densities and those predicted were found to agree well, apart from the sample of the TEC with 94.9 wt% tungsten that was found to have a lower ρ_M than expected. The composition of the bismuth alloy was confirmed by X-ray fluorescence using an SII Nanotechnology Inc SEA6000VX X-ray fluorescence spectrometer (see Table 2).

2.2.1 Transmission

X-ray transmission (T)[16] was calculated for samples of pure tungsten ($\rho = 19.3$ g cm^{-3}), TEC ($\rho_M = 9.6$ g cm^{-3}) and bismuth alloy ($\rho_M = 8.6$ g cm^{-3}) using Equations 1 and 2, where, μ/ρ is the mass attenuation coefficient and w is the weight fraction of element i, and x is the mass thickness.

$$\mu/\rho = \sum_i w_i \left(\mu/\rho\right)_i \tag{1}$$

$$T = e^{-(\mu/\rho)x} \tag{2}$$

Figure 6 presents calculated X-ray transmissions at energies of up to 200 keV. Those for 2 mm thick TEC and Bi alloy are very similar with both generally transmitting < 1 % up to around 120 keV. However, the K absorption edge for Bi (87 keV) introduces leakage through the alloy that increases transmission to about 4 % in that region. The transmission of the 2 mm thick tungsten can be seen to be virtually identical to that for 4 mm thick TEC, because the density of the TEC is half that of tungsten. Both were predicted to have a transmission < 1 % to about 160 keV.

2.2.2 Structural Analysis

A transmission radiograph of a cold cast TEC CM is presented in Figure 4 and shows three types of defect. As a result, errors are introduced into the mask pattern. Further refinement of the printing/casting process may be able to address these problems.

- A void within one of the radiopaque elements, caused by trapped air.
- Leakage of the TEC at the edge of one of the radiolucent elements, due to surface porosity of the 3D printed mould
- Some rounded corners, due to the resolution of the 3D printer.

Samples from each CM were sliced and polished to view their internal structures. The image in Figure 5a shows that the hot cast Bi alloy produced a good cast with no air pockets. Small air pockets were revealed in the cold cast TEC cured mixture at $\rho_M = 9.6$ and 10.6 g cm^{-3} (Figure 5b - c). Also, air pockets appeared to be more frequent at higher tungsten contents. Figure 5d shows a scanning electron microscope images taken using a HITACHI SU5000[17] and further illustrates this with air pockets in the TEC around 200 - 250 μm in diameter.

3 Testing 3D Printed Coded Masks

X-ray backscatter images were captured with a variety of CMs that were fabricated using the 3D printed method described above. These were compared to conventional drilled tungsten sheet CMs. This section details the experimental procedure and equipment used to obtain all exposures within this paper.

3.1 *Experimental Method*

3.1.1 *X-ray Imaging Test Procedure*

The experimental setup (see Figure7a) consisted of a VJ Technology[18] X-ray generator operating at 100 kV and 5 mA. X-ray backscatter exposures were captured from a quadrant of blocks with aluminium, paraffin wax, PVC cylinder and copper blocks (see Figure7b). These were chosen to give a contrast range in the resulting X-ray backscatter images. A 1.4 mega-pixel Gemstar ICCD camera[19] was used with the CMs to capture X-ray images.

The CMs used for imaging had radio-opaque material that was 2 mm thick. Four 3D printed cold cast CMs with $\rho_M = 9.6$ g cm^{-3} were used for the experiment. The smallest feature or element size for each mask was 2×2 mm. These CMs consisted of a 19 modified uniformly redundant array (MURA),[20] a 13 dilute uniformly redundant array (DURA),[12,21] a 19 random array (RANDA) and a 17×21 Singer set.[22] Machined NTHT versions were manufactured from a Wolfmet HA190 tungsten alloy ($\rho_M = 17.1$ g cm^{-3})[23] with 2 mm apertures. All CMs were subject to a 2×2 mosaic of the unit or base pattern, minus one row and one column to reduce the effects of partially coded field of view.[24,25]

3.1.2 *Encoding and Decoding*

The first process of encoding the image during an exposure (D) followed Equation 3, where the encoding array or CM (A) was correlated with object (O), plus some noise term (N).[26] The encoding process was performed twice with the CM at 0 and rotated 90 degrees.[10,12,27] Each exposure was set for 5 s ensuring enough photons were collected to form a resolvable image free from saturation.

$$D = (O \otimes A) + N \tag{3}$$

The decoding process began by cropping out the mosaic from the encoded exposure. Failing to do so presented artefacts from the mosaic in the final reconstructed image.[25] Due to imaging at close range (1 m from the camera), near-field magnification (N_m) was applied (see Equation 4) where, a was the distance from the CM to object and b, CM to the detector plane. N_m ensured that the final encoded exposure was the same size as the decoding array (G), thus ready for the correlation process.

$$N_m = \frac{a+b}{a} \tag{4}$$

The decoding array was the original array pattern with its open and closed binary elements of 1 and 0 balanced for optimum results, as in Equation 5, where χ is the open fraction[28] (see Table 3 for open fraction of CMs).

$$G_{i,j} = \left\{ \begin{matrix} 1, & A_{i,j} = 1 \\ \\ \eta, & A_{i,j} = 0 \end{matrix} \right\} \text{ where, } \eta = -\frac{\chi}{1-\chi} \tag{5}$$

A normalised cross-correlation function inbuilt into MATLAB®[29,30] was used to mathematically decode and reconstruct the final exposures (R), where the bar over D and G indicate their mean values (see Equation 6). Reconstructed exposures subject to 0 and 90-degree rotation were summed to reduce noise within the final imaged.[10,27]

$$R(u,v) = \frac{\sum\limits_{x,y} [G(x,y) - \bar{G}_{u,v}][D(x-u, y-v) - \bar{D}]}{\sqrt{\sum\limits_{x,y} [G(x,y) - \bar{G}_{u,v}]^2 \sum\limits_{x,y} [D(x-u, y-v) - \bar{D}]^2}} \tag{6}$$

Image quantification was performed by calculating signal-to-noise ratio (SNR) (see Equation 7) from the mean sample of the object (μ_S), within the summed reconstructed exposures.[3] The lead backdrop in Figure7b formed the background, where the standard deviation was taken (σ_B).

$$\text{SNR}_{\text{dB}} = 10 \log_{10} \left(\frac{\mu_S}{\sigma_B} \right) \tag{7}$$

4 Results

4.1 X-Ray Backscatter Images

Reconstructed X-ray backscatter CM exposures of the quadrant in Figure7b are presented in Figure 8. The different field of view or image sizes in Figure 8 are reflected by the different array unit or base pattern size. It is also noticeable that the NTHT images are larger than those from 3D printed CMs. This is because NTHTs inherently introduce extra rows and columns in the original array, increasing the overall pattern size. The corresponding SNR are given in Table 3. The results meet the Rose criterion[31] with a minimum value of 5 or 7 dB (using Equation 7) for the scene to be distinguishable (see Table 3). The results were rather comparable with the Wolfmet HA190 NTHTs slightly outperforming 3D printed CMs, except for the 3D printed 13 DURA which had 0.2 dBs greater in SNR than the machined tungsten.

5 Discussion

The SNR results in Table 3 were lower than those from our previous work using radioactive source exposures[10] that were 15.7 dB for a 3D printed TEC 19 MURA CM and 15.2 dB for a Wolfmet HA190 NTHT. This could be caused by the following three reasons. During our previous work the radiation received from the background of the scene was much lower than for the exposures presented in this study, because a radioactive source was used as the test object. For the exposures presented in this paper, this was replaced by the quadrant of blocks placed in front of a lead screen (see Figure 7b) and the whole field of view was irradiated with X-rays. Consequently, the backscattered X-rays received by the camera originated from both the test object and the lead screen background, whereas previously it was only from the radioactive source. Although the ill posed nature of the decoding process was the same for both experiments, the X-rays scattered from the lead background, combined with the larger physical size of the quadrant of blocks, meant that the geometry was closer to an extended scene than the ideal point source presented by the radioactive source. In this case X-rays received from the edges will have only been partially coded, introducing errors in during image reconstruction.[7,27,33,34] Lastly, the CMs used in this study possess a range of open fractions (shown in Table 3) with a variation of different patterns, which has been revealed to have an effect on the image quality during CM imaging.[7,12]

With regards to the construction of CMs machining tungsten, NTHTs is a costly process, usually requiring specialist equipment such as a computer numeric control machine and trained operators. Conversely, we have found 3D printed CMs are much lower in cost and can be easily made in-house using relatively inexpensive equipment. Results are comparable to machined tungsten NTHTs. The cold casting method contained numerous advantages over hot casting which include, lower cost, higher densities, ease of manufacturing and greater structural stability. Evidence of structural instability in the hot cast CA can be seen in Figure 2.

Figure 5 shows a possible increase in air pockets at higher densities for the TEC. This may be the cause of an increase in uncertainty for the confirmed sample densities, explaining the larger gap between calculated and measured results (see Table 2). The greater uncertainty at larger densities may also occur from the increase in viscosity of the liquid mixture. Mixing at high viscosity would require more energy, thus introducing trapped air that would find more difficulty in escaping to the surface. The solution to reducing air pockets may be provided by spin casting or casting in a vacuum.

6 Conclusion

3D printed CMs using the cold casting technique offers a low-cost and convenient alternative to the traditional method of drilling solid tungsten. This is particularly useful for constructing experimental mask prototypes. Fabrication is less labour intensive with most of the manufacturing time taken up by 3D printing and curing the TEC epoxy resin. A wide range of masks, including a single aperture or pinhole, can be manufactured using this method. Although the SNR taken from images using machined tungsten were on average marginally higher (1 dB) than those from 3D printing results were comparable. It was noted that some structual defects were introduced during the cold cast process and fabricating 3D printed CMs at higher densities appeared to be prone to air pockets within the cast. Thus, all 3D printed CMs used for acquiring the images in this paper contained a density of 9.6 g cm^{-3}. Further refinement of the casting process would require a more detailed understanding of these defects, which could be obtained by microCT. Further work on the hot casting method was discontinued because its advantages were greatly outweighed from those from cold casting. Also, 3D printing CMs would be particularly useful for constructing prototypes for experimental masks. Findings from this research may be used for further development in CM imaging, medical imaging or applied to defence and security. A convenient method for quickly manufacturing prototype CMs in the laboratory has been described. Future work would include investigating scatter produced by low atomic material within the mask.

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8 Acknowledgments

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Table 1: **3D Printer Settings**

Group	Settings	PLA	ABS
Quality (mm)	Layer Height	0.1	0.1
	Thickness	0.8	0.8
	Initial Layer Thickness	0.3	0.3
Speed (mm s^{-1})	Travel	150	150
	Bottom Layer	30	20
	Infill	100	50
	Outer Shell	40	50
	Inner Shell	80	50
Temperature (°C)	Nozzle	215	245
	Build plate	60	100
Fill (%)	Infill	20	20

Table 2: **Material Density**

Attenuating Material	Concentration (wt%)	ρ g cm^{-3}	ρ_M g cm^{-3}
TEC	W 93.5, Ep 6.5	9.6	9.57 ± 0.02
TEC	W 94.6, Ep 5.4	10.5	10.63 ± 0.06
TEC	W 94.9, Ep 5.1	10.8	10.09 ± 0.08
Bi alloy	Bi57, Sn26, In17	8.5	8.61 ± 0.02

Table 3: **SNR of X-Ray Backscatter Images in descending order.**

CM Type	χ	Material	SNR (dB)
19 MURA NTHT	0.16	Tungsten HA190	12.7
19 MURA	0.50	3D Printed TEC/PLA	12.1
17×21 Singer NTHT	0.15	Tungsten HA190	11.8
19 RANDA NTHT	0.14	Tungsten HA190	10.9
17×21 Singer	0.33	3D Printed TEC/PLA	10.8
13 DURA	0.43	3D Printed TEC/PLA	10.2
13 DURA NTHT	0.18	Tungsten HA190	10.0
19 RANDA	0.33	3D Printed TEC/PLA	9.4

Fig 1: SOLIDWORKS® drawing of (a) array pattern, (b) blank mould and (c) merged together to fom the CM mould.

Fig 2: (a) hot cast with the white bar as a scale indicator, measuring 50 mm. (b) loose element in the CM.

Fig 3: Example 3D printed cold cast coded masks of (a) 19 MURA and (b) 35×39 Singer set. The white bar in all images are scale indicators measuring 50 mm.

Fig 4: (a) X-ray transmission radio-graphs of a 4 mm thick, $\rho_M = 9.6$ g cm^{-3} cold cast CM. (b) magnification of the region in the orange box in Figure 4a, with the red arrows showing defects in the mask.

Fig 5: (a) Optical micro-graphs of sampled regions of hot cast CM and (b) showing air pockets in cold cast CM at $\rho_M = 9.6$ g cm^{-3} (c) and 10.6 g cm^{-3} (bar length 1 mm). (d) SEM of a cured TEC sample.

Fig 6: Theoretical X-ray transition 2 and 4 mm thick samples.

Fig 7: (a) Experimental setup with the Photonic-Science® Gemstar camera on the left and the VJ Technology® X-ray generator on the right. (b) Quadrant of blocks forming the test object, with the white bar as a scale indicator, measuring 100 mm (upper left: aluminium, upper right: paraffin wax, lower left: PVC cylinder, lower right: copper).

Fig 8: (a - d) show the reconstructed backscatter exposures of the quadrant test object in Figure7b, using 3D printed cold cast CMs (e - h) are the equivalent images for the Wolfmet® HA190 NTHTs.