Nuclear Instruments and Methods in Physics Research A 605 (2009) 167–170

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Archaeology benefits from neutron tomography investigations in South Africa

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ARTICLE INFO

Available online 12 February 2009

Keywords:
Neutron tomography
Archaeology
Necsa
SAFARI-1
Cultural heritage

ABSTRACT

This paper describes the neutron tomography investigation on archaeological artifacts from museums in South Africa. While X-rays fail to penetrate the brass matrix of the samples, neutrons can easily reveal, on a non-invasive manner, the content and structure of these precious samples. The South African Neutron Radiography (SANRAD) facility, located at the SAFARI-1 nuclear research reactor, operated by Necsa near Pretoria, South Africa, was utilized in a tomography mode during the investigations. For the 3D tomographical reconstruction of the sample, 375 projections were collected while the sample was rotated around a defined axis through 360° rotation interval. The results show that the technique is able to reconstruct structural features very well and in particular, highly absorbing zones and the presence of defects in the bulk. The samples originate from collections at museums in South Africa and these investigations were the first of its kind performed in the country.

1. Introduction

It is currently common practice, due to the availability of neutron radiography (NR) sources at European neutron imaging research facilities in France, Switzerland, Germany, Slovenia and Italy, for them to take part in archaeological excavation programs where unique and important artifacts, found at Roman, Greek and other European excavation sites, are investigated [1–3]. The benefits of thermal neutron transport through metals such as brass and copper were earlier enhanced and explored, as reported by Rant and Kardjilov. Schillinger [4], however, was the first to report that through the neutron non-destructive, tomography scanning and investigation of artifacts, hidden features within as well as reparations previously performed where other non-invasive techniques such as X-ray- and gamma-ray-imaging fail, could be revealed.

The power of NR imaging as non-destructive and complementary technique to X-ray- and gamma-ray-imaging, enhances the knowledge obtained about ancient cultures through the investigation of artifacts being discovered. It is important to make the community of archaeologists, conservationists and restorers aware of the opportunities of NR and tomography in their field of research and applications. The possibility of investigating relatively large samples (up to several hundred square centimeters) as well as thick samples of geological material in reasonably short time, makes neutron tomography a very attractive method for addressing important archaeologically related problems such as characterisation and multi-component analysis of archaeological objects and intact artifacts (fossils, metals, ceramics, composites, organic materials), conservation assessment and treatment, treatment of wood with resins, etc.

The following main neutron imaging advantages were demonstrated in this work: (a) neutrons are attenuated by some light elements like H, Li, B, where X-rays do not provide a good contrast and (b) neutrons easily penetrate relatively thick layers of metals like Pb, Fe and Cu where X-rays even with energies of several hundred keV fail.

The 125 kV X-ray and neutron attenuation coefficients of some metals, which are of high relevance for archaeological investigations, are listed in Table 1 [5].

This paper describes similar neutron tomography investigations being performed in South Africa at the South Africana Neutron Radiography (SANRAD) facility, located at beam port-2 of the SAFARI-1 nuclear research reactor near Pretoria, operated by Necsa.

Two bronze Egyptian artifacts, a bronze falcon (Fig. 1) as part of a rare collection found in collections located at the Groote Schuur Official Residence in Cape Town and a "Horus the child" statue (Fig. 2), located at the National Cultural History Museum in Pretoria were investigated.

The tomography scans were used to aid further sampling for XRF and XRD analysis which confirmed the existence of previous

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doi:10.1016/j.nima.2009.01.213

Table 1
Linear attenuation coefficients of some metals for thermal neutrons and 125 kV X-rays.

Material	μ (cm^{-1})							
	Au	Ag	Cu	Sn	Bronze	Pb	Zn	Fe
Thermal neutrons	6.28	3.99	0.99	0.20	0.87	0.37	0.34	1.20
X-rays	35,9	5.67	1.97	3.98	~2.5	22.8	1.64	1.57

Fig. 1. Photo of bronze falcon.

Fig. 2. Photo of bronze "Horus" statue.

restoration materials. In conjunction with the tomography, the conservator, student and curator are able to take account of the location and extent of previous conservation.

2. Experimental method

The layout of the SANRAD has been described and published elsewhere [6]. For the purpose of these experiments, the bronze samples were positioned in the neutron beam as close to the scintillator screen as possible to minimize geometric unsharpness and enhance the geometric resolution of the tomography system to 0.088 mm/slice. (Fig. 3) Neutron transmission projections of the sample at every 0.96° through 360° (that is 375 projections as standard practice) to minimize artifacts were being generated in the reconstructed image during the reconstruction phase and were saved on hard disk. The exposure time for each projection was 25 s at $\frac{1}{2}$ dynamic range (30 K grey levels) of the 16-bit ANDOR CCD imaging system. Through Octopus [7] reconstruction software, a number of axial slices were generated that describe the

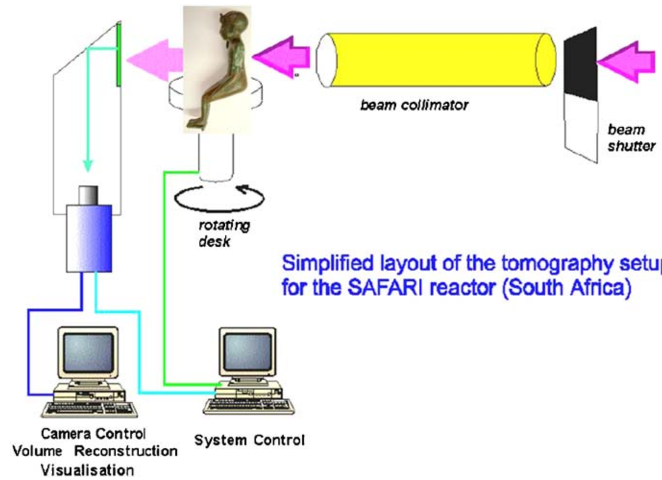

Fig. 3. Schematic layout of experimental setup of bronze samples at the SANRAD facility in front of the neutron scintilator screen.

total sample—these slices were imported into VGStudioMax [8] imaging software to visualize a virtual 3D image of the sample. Analysis was performed on slices in the *yx*-, *yz*- and *xz*-planes as well as in the 3D reconstructed tomograph through segmentation and image enhancement functions. Certain voxels were pseudo-colored to enhance high attenuation areas. Radioactivity buildup in the bronze samples, over the period of approximately 3 h in the thermal neutron beam, as a result of thermal neutron bombardment and neutron capture, was anticipated and was also observed after the scanning. The samples were thus kept in a shielded save environment until full radioactivity decay (~7 days) before they were released for visual inspection and correlation with generated neutron tomograms.

3. Analysis of an Egyptian bronze falcon

The neutron tomography scanning of this artifact was initiated by interest in determining its process of manufacture, as well as by earlier discoveries at the Walters Art Gallery (Baltimore, USA) [9] where bone remnants and mummified remains of actual falcons were found in six of the nine similar bronze falcons [9]. A single sculpture of this collection, however, indisputably contained only an "earthy" material. Neutron tomography investigation aims to obtain information on the inner core content, state of corrosion of the outer shell, previous reparation areas and casting methods.

3.1. Core material

It is being revealed by neutron tomography investigations that, where animal/bird remains could potentially have resided as indicated by previous investigations on similar falcon artifacts in USA, only core material was shown to be present (Fig. 4).

3.2. Casting—chaplets

In the neutron tomography results, the layered structure of the bronze casting is revealed quite clearly, together with pins (darker spots known as chaplets)—indicative of a lost wax casting process, which was clearly used to produce the sculpture. The tomography slices generated by VGStudioMax software also provide revealing insight into the effects of the casting procedure on the metal structure.