SUSAN N. HERRINGER · KRYSTA RYZEWSKI · HASSINA Z. BILHEUX · JEAN-CHRISTOPHE BILHEUX
BRIAN W. SHELDON

THE APPLICATION OF NEUTRON IMAGING TO INVESTIGATE THE DESIGN AND MANUFACTURE OF A BRONZE OINOCHOE

The investigation of how ancient crafts were fabricated contributes to the study of material culture and its significance in constructing and mediating social relations and cultural values (Bourdieu 1977; Sillar/Tite 2000). In each step of the manufacturing process of ancient crafts, craftspeople make choices that influence the outcome of a particular object (Lemonnier 1986). These choices are influenced by social contexts and technological constraints – by tradition, technical innovation, and similarities across craft production processes (Killick 2004; Shimada 2007). In this paper, the fabrication of a Roman bronze oinochoe (wine pouring vessel) is examined and is related to traditional modes of formation.

Metallographic analysis has been used to study ancient manufacturing processes, but it often requires disturbing the object (i.e., sample removal) (Scott 1991; 2002). In the movement away from invasive and destructive methods of analysis to evaluate the manufacturing techniques utilized in craft production, cultural heritage research has embraced radiation-based techniques. Most recently, the field has drawn on neutron-based techniques as methods of analysis, such as diffraction (Siano et al. 2002; Kockelmann et al. 2006; van Langh et al. 2011), radiography (Lehmann et al. 2005), and tomography (van Langh et al. 2009; Peetermans et al. 2012). The majority of neutron computed tomography of cultural heritage materials has been undertaken by European spallation and pulsed neutron sources, such as NEUTRA/SINQ at the Paul Scherrer Institute (Peetermans et al. 2012), ISIS at the Rutherford Appleton Laboratory (Andreani/Gorini/Materna 2009) and FRM-II ANTARES at the Technische Universität München (Festa et al. 2009; Schulze et al. 2013). To our knowledge, the research presented here represents some of the earliest neutron imaging of cultural heritage materials to be completed in the United States (Ryzewski et al. 2013).

The advantage of using neutrons instead of X-rays for the investigation of metal objects such as bronze is the increased penetration depth of neutrons over X-rays (Heller/Brenizer 2009). Since X-rays interact with the electrons in the atomic shell, their interaction probability and therefore attenuation increases with greater atomic number. Neutrons, however, interact with nuclei and thus there is no direct correlation between atomic number and attenuation. Their ability to penetrate through layers of metal makes neutrons an ideal candidate in extracting otherwise invisible details about fabrication, such as material components and their compositional variance, modes of material joins, and internal structure.

After reviewing the principle of neutron imaging and the instrumentation utilized at the Oak Ridge National Laboratory (ORNL), neutron-imaging results of the bronze oinochoe will be presented. Measurements of the oinochoe were undertaken to determine how the oinochoe was assembled and what internal features exist. Building from the interpretation of these features, we hope to contribute to a broader archaeological understanding of oinochoe fabrication.

Methods

Neutron imaging

An incident neutron beam (I_o) is attenuated by the matter through which it passes. Assuming the object under investigation is homogeneous, the transmitted intensity (I) is given by the Beer-Lambert law:

$$I(\lambda) = I_o(\lambda) e^{-\mu(\lambda)\Delta x} \quad \textbf{Eq. 1}$$

where $\mu(\lambda)$ is the linear attenuation coefficient of the object at a given neutron wavelength λ and Δx is the thickness of the sample. Attenuation of the beam is a result of neutron scattering and absorption by the sample. The attenuation coefficient is wavelength dependent and is characteristic of a particular element. It is given by:

$$\mu(\lambda) = \sigma_t(\lambda) \frac{\rho N_A}{M} \quad \textbf{Eq. 2}$$

where $\sigma_t(\lambda)$ is an element's total cross section for neutrons of a wavelength λ, ρ is the object's density, M is its molar mass, and N_A is Avogadro's number.

The incident beam is attenuated by multiple layers of different atoms as it passes through the thickness of the sample, Δx. As a result, a single radiograph is a superposition of the attenuation through these various layers. The attenuation of the beam due to material at the front of the object cannot be distinguished from the attenuation due to material at the back of the object. Computed tomography allows for the three dimensional visualization of the attenuation. Computed tomography consists of taking a number projections, or radiographs, of the object at equally spaced rotational intervals. With a mathematical reconstruction algorithm, these projections can provide three-dimensional attenuation information.

Neutron imaging at the Oak Ridge National Laboratory

Neutron tomography of a Roman period bronze oinochoe was performed at the Oak Ridge National Laboratory (ORNL) at the CG-1D neutron imaging beamline, at the High Flux Isotope Reactor. This beamline is part of the ORNL neutron scattering user program and is also utilized to prototype equipment and techniques for the ORNL's Versatile Neutron Imaging Instrument (VENUS), which is to be constructed at the laboratory's Spallation Neutron Source (SNS). The CG-1D beam currently provides wavelength-indiscriminate cold neutrons from 0.8 to 6 Å and has a neutron flux (with an 8 mm aperture and an L/D of 625) of 1×10^7 n/cm^2/s. CG-1D has a field of view of approximately 6.5×6.5 cm^2 and is capable of producing images with a resolution of ~50-75 µm in approximately 30-60 s. Recent upgrades of the CG-1D beamline are described by Santodonato and colleagues (2015).

Bronze oinochoe

Object description

The oinochoe was a common ceramic vessel form first produced in ancient Greece. As with other Greek pottery forms, it was later adopted by the Romans (1st century BC to 2nd century AD). The oinochoe is a pouring vessel used typically to dispense wine. Oinochoe forms range in size, mouth-opening (trefoil, rounded, or beaked spout), decoration, and material; they are typically taller than they are wide, have one handle, and are made of either ceramic or metal. Many early oinochoes were formed as two separate components (body and handle) in both the ceramic and bronze vessels (Schreiber 1999). Due to the long history of use of the vessel form, the oinochoe may be evaluated on changes to its manufacturing process.

The bronze oinochoe in this study, from the Wagner Collection of the Joukowsky Institute for Archaeology, was crafted in a Roman style (**fig. 1**). Similar forms have been observed in other circa 1st century AD bronze Roman oinochoe in the collections of the Walters Art Museum (2013, accession number 54.947) and at the Louvre (as cited in Richter 1956, pl. XVII c). The bronze oinochoe here rests on an ogee-form base and has a short beaked spout,

Fig. 1 Photographs of the bronze oinochoe from the Joukowsky Institute for Archaeology. – (S. N. Herringer).

which is directed towards a cylindrical neck and a pyriform body. The vine-decorated and side-incised, high-arching handle terminates with a stylized human face, while the upper part of the handle takes the form of an animal with its forelegs joined to the rim of the vessel. The vessel stands at 13 cm in height and is 6.5 cm at its greatest width. In the absence of provenience linking the oinochoe to an excavated context, questions exist about the object's authenticity (and will be addressed by future research). Nevertheless, the craftsmanship of the oinochoe is intricate and the procedure utilized in its manufacturing is not readily identifiable from exterior, surface features.

Computed tomography was used to examine the object's compositional variability, contents, and the

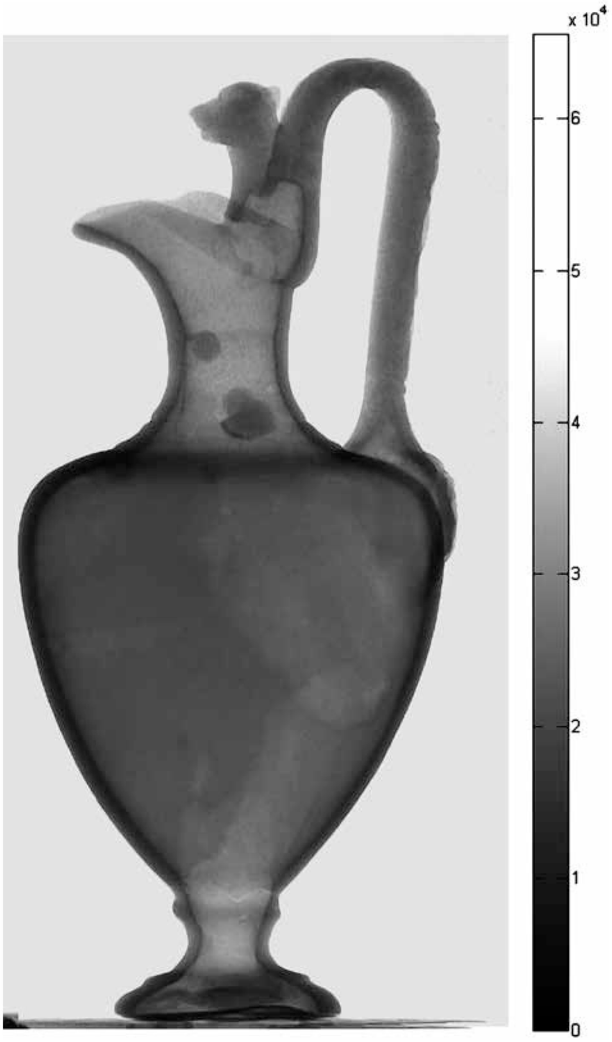


Fig. 2 A neutron radiograph of the oinochoe. The transmission scale displayed for the oinochoe's 2D neutron data is an illustration of the true gray values obtained from the CCD, which produces 16 bit or 2^{16} = 65535 gray scale values. – (S. N. Herringer).

material effects of joining. With a long tradition of oinochoe formation, the researchers are interested in changes, if any, to its fabrication process. The vessel may represent a continuation or adaptation of a tradition, or marked change in assembly altogether. Tomography results highlight an adaptation to the attachment of handles to bronze oinochoe.

Due to the restrictions imposed by the CG-1D's field of view, the top and bottom sections of the oinochoe were imaged separately. Normalization was performed using the Octopus software (Dierick 2005). The two halves of the oinochoe tomographic images were rejoined post-processing with Photoshop. This is done by using the automatic layer alignment option (stitching procedure) that is capable of aligning and blending radiographs as long as there is enough overlap between images. For these measurements, we chose to use ~1 cm overlap, which corresponds to 15 % of the radiograph. **Figure 2** shows one of the merged projections used for the tomographic reconstruction of the oinochoe. While care was taken in positioning the oinochoe in the beam, the human face side of the vessel rotated out of the field of view and therefore some data is missing from the volume as will be seen in the reconstruction *vide infra*.

Reconstruction, volume rendering, and visualization

Reconstruction of the data was performed using commercial software called Octopus (Dierick 2005). The volume rendering (a way to display a 2D projection of a 3D data set) and visualization of the oinochoe were performed using a 2D transfer function custom-built in ImageVis3D (Fogal/Krüger 2010). Often, straightforward histogram-based segmentation techniques are utilized to identify areas of interest in the object. A histogram is a plot of all pixels gray scale values (which is based on the attenuation of the beam) as a function of the number of pixels having these values. The peaks and valleys in the histogram are used to locate the different areas of interest. In the case of the oinochoe, these peaks overlap (as seen in **fig. 3**), making it difficult to segment the 3D reconstruction of the oinochoe from the background. Digital segmentation, a means to isolate different parts in the image (in this case, the oinochoe from the background), was based on a 2D transfer function (**fig. 4a**). Transfer functions are a way to visualize a volume by mapping pixels using opacity and one or more colors (Zou et al. 2010; Kniss/Kindlmann/Hansen 2005). They can be used to enhance an area inside a complicated 3D structure. The data enclosed in the quadrilateral in the 2D transfer function was used to render the oinochoe's volume (**fig. 4b**).

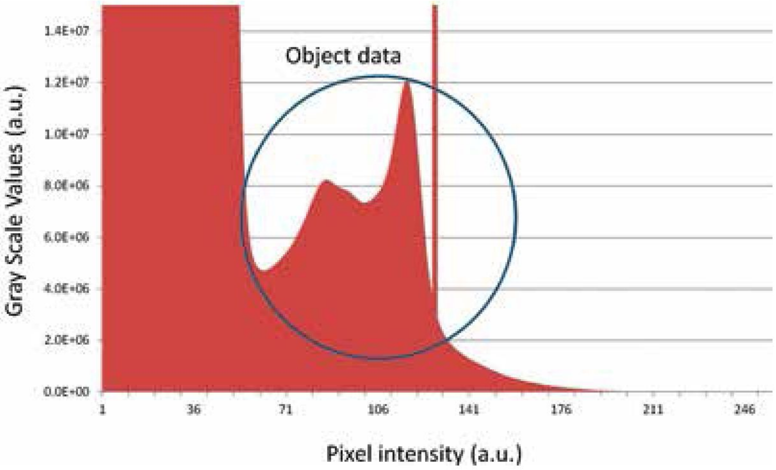
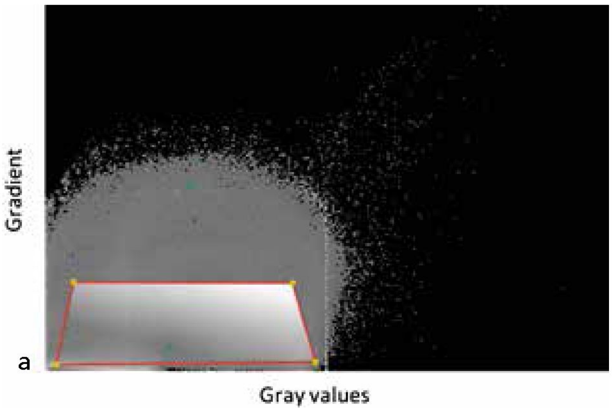


Fig. 3 A histogram of the oinochoe, following 3D reconstruction, shows strong overlaps between the different areas inside the object (encircled). – (S. N. Herringer).



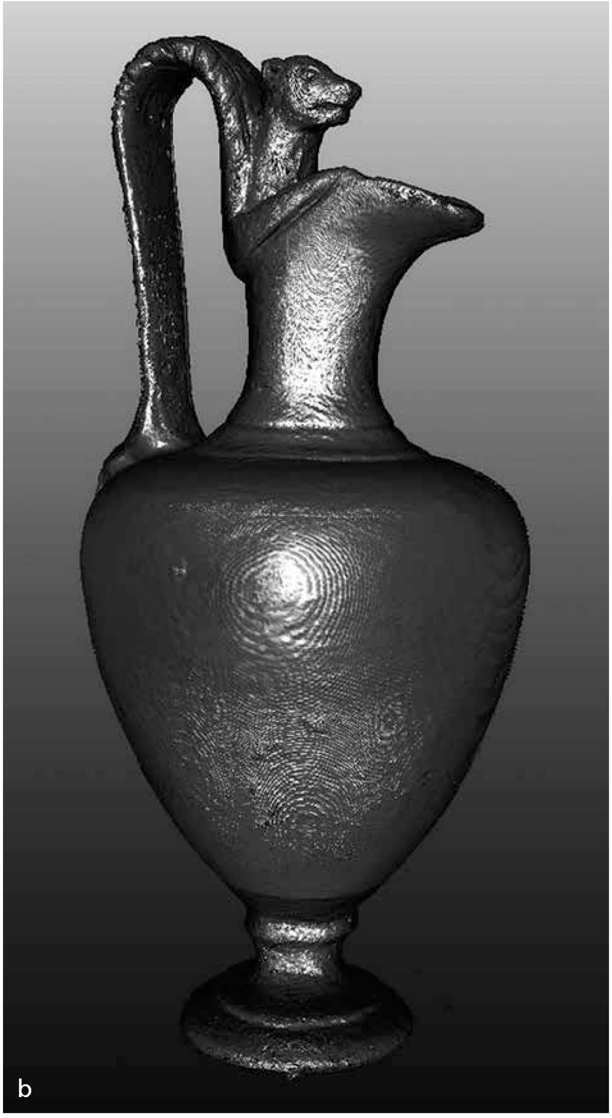


Fig. 4 **a** 2D transfer function applied to the volume rendering of the oinochoe. The data within the quadrilateral was used to render the vessel's volume seen in **fig. 4b**. – **b** volume rendering based on the 2D transfer function provided in **fig. 4a**. – (S. N. Herringer).

Results of tomography investigation

Volume rendering analysis led us to question whether the oinochoe vessel was cast as a whole or in two pieces – a body and a handle. A slice through the volume rendering of the oinochoe in **figure 4b**, where the zoomorphic handle attaches to the spout (**fig. 5**), illustrates the nature of the join between the handle and the vessel body. In addition, the join of the handle to the body can be seen in the contours

Fig. 5 Detail of a cross-sectional view of the oinochoe where the zoomorphic figure at the top end of the handle attaches to the spout (**a**) and where the anthropomorphic end of the handle attaches to the body of the vessel (**b**). – (S. N. Herringer).

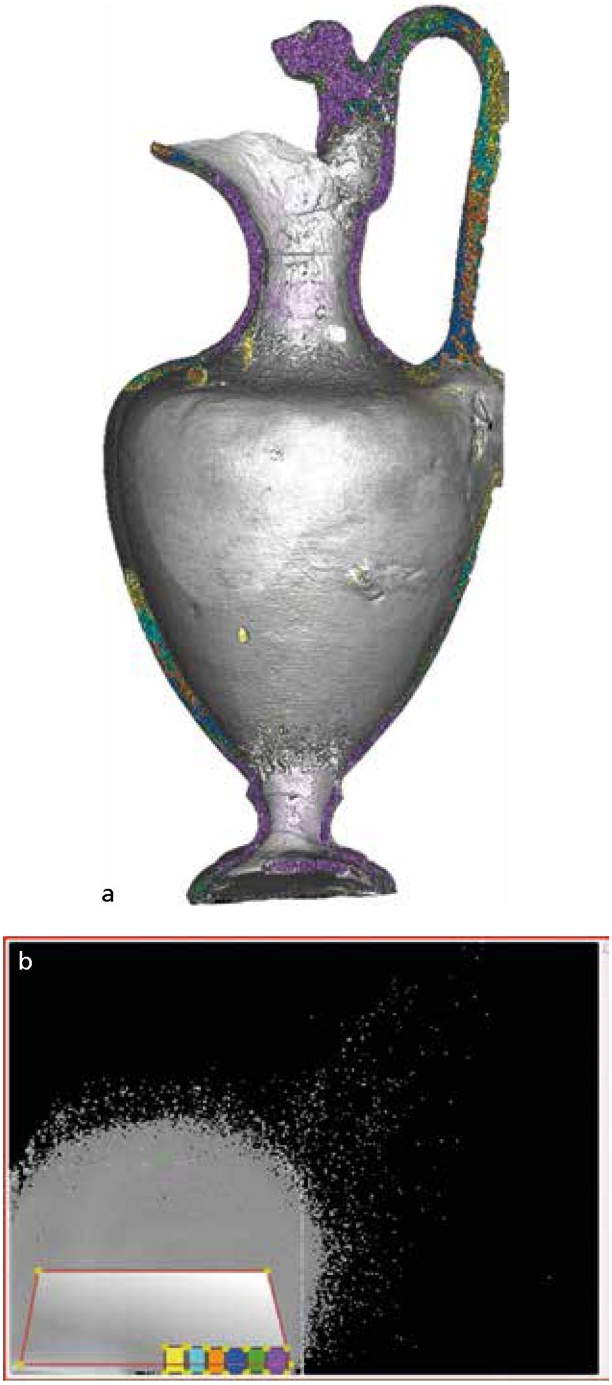


Fig. 6 **a** an adaptation to the 2D transfer function to highlight the gradual transition of the attenuation throughout the vessel. Arbitrary regions of varying attenuation were selected. – **b** volume rendering with the transfer function in **fig. 6a** applied. – (S. N. Herringer).

on the interior surface that surround the human face end of the handle.

From initial inspection of the volume rendering, it appeared that the porosity of the handle and the body were quite different. Upon further inspection, it was revealed that the attenuation of the vessel – both the handle and the body – varied. The attenuation changes gradually throughout the body and along the handle. By selecting arbitrary regions within the 2D transfer function (**fig. 6a**), the gradual transition of the attenuation throughout the vessel can be seen (**fig. 6b**). Since attenuation is both element and density dependent as seen in **equation 2**, these differences in attenuation may be related to either compositional or density differences within the vessel. While there are no stark changes in attenuation within the vessel, the gradual variation in attenuation throughout the vessel is intriguing and may offer further insight into the manufacturing process. The homogenization of the attenuation at the joining regions may allude to the application of heat used to attach the handle to the vessel body. The variation along the handle and through the thickness of the body wall and handle may be indicative of elemental segregation or density variation developed during casting. Future experimental work will investigate these ideas.

In addition, it was discovered that the oinochoe is not hollow, as was assumed prior to imaging the object. The secondary material that fills the majority of the cavity of the oinochoe is difficult to visualize in the volume rendering due to its low attenuation value and thus is not easily distinguished from the background with the 2D transfer function. However, more attenuating inclusions, as seen in the radiograph (**fig. 2**), rest in the interior mass and are not floating within the vessel. **Figure 7** is a tomographic slice of the oinochoe through the center of the vessel body, which shows the low-attenuating interior mass with more highly attenuating inclusions. Eventual preservation work will explore this interior mass and its inclusions.

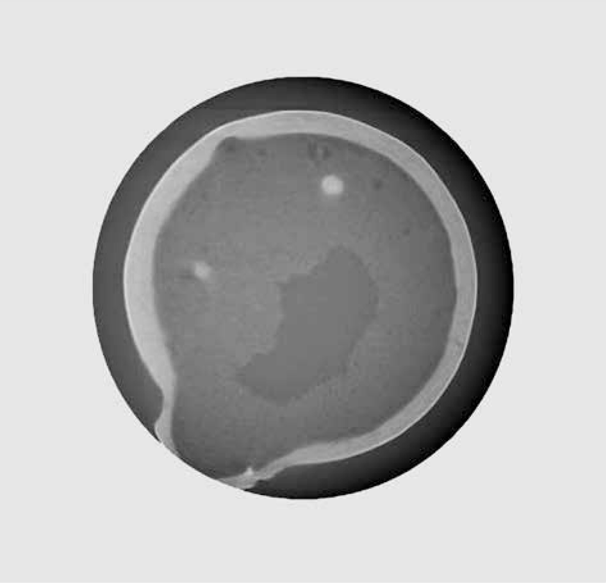


Fig. 7 Tomographic slice of the oinochoe through the center of the vessel body, which shows the low-attenuating interior mass with more highly attenuating inclusions. – (S. N. Herringer).

Conclusions and future analysis

Neutron tomography allowed for the examination of the oinochoe. From the volume rendering and visualization of the vessel, it is apparent that the handle and body were formed separately and later joined together. As mentioned previously, many earlier ceramic and bronze oinochoes were also formed as two separate components. However, the attachment of handles of other bronze oinochoe is often visible; the handles are removable or attached to the vessel via rivets. The significance of the join, visible with neutron tomography, marks an adaptation in the construction process. The handle is still formed separately, as it is in earlier metal and ceramic oinochoe, but a different way of attaching the handle is utilized.

Future work at Oak Ridge National Laboratory at the commissioned VENUS beam will allow for compositional information to be collected in three dimensions through the application of energy-dispersive neutron imaging.

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Summary / Zusammenfassung

The Application of Neutron Imaging to Investigate the Design and Manufacture of a Bronze Oinochoe

Neutron imaging is a non-destructive and non-invasive method for analyzing ancient materials and their construction. This paper demonstrates the utility of neutron tomography for investigating a bronze Roman oinochoe (a wine pouring vessel) to better understand the methods of its fabrication. Adaptations to traditional modes of formation may be explored due to the long history of use of this vessel form. The neutron imaging results allowed researchers from both archaeological and materials science disciplines to evaluate steps in the manufacturing process, as well as to view the interior constituents of the bronze vessel for future preservation measures. The results highlight how neutron imaging may provide otherwise inaccessible details of the fabrication of the bronze oinochoe. This study was performed on the CG-1D neutron imaging beamline at the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory in Tennessee, USA.

Die Anwendung von Neutronenbildgebung (Neutron Imaging) zur Untersuchung von Design und Herstellung einer bronzenen Oinochoe

Neutron Imaging ist eine zerstörungsfreie und nicht-invasive Methode zur Untersuchung von historischen Materialien und ihres Aufbaus. Dieser Beitrag zeigt die Nutzung der Neutronentomographie, um die Herstellungstechniken einer bronzenen römischen Oinochoe (ein Ausschankgefäß für Wein) besser zu verstehen. Außerdem lässt sich aufgrund des langen Zeitraums, in dem diese Gefäßform Verwendung fand, die Adaption an traditionelle Formgebung studieren. Die Ergebnisse der Neutronenbildgebung erlaubten sowohl Archäologen als auch Materialwissenschaftlern, die einzelnen Schritte des Produktionsprozesses zu beurteilen, und auch die inneren Bestandteile des Bronzegefäßes für künftige Konservierungsmaßnahmen zu betrachten. Die Ergebnisse verdeutlichen, wie Neutron Imaging sonst nicht sichtbare Details zur Herstellung der bronzenen Oinochoe liefern kann. Die Untersuchung wurde an dem CG-1D Neutron Imaging-Strahlplatz am High Flux Isotope Reactor (HFIR) am Oak Ridge National Laboratory in Tennessee, USA, durchgeführt.

Keywords

neutron imaging / oinochoe / manufacturing process / Oak Ridge National Laboratory