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X-ray-based examination of artworks by Cy Twombly: art technology and condition of the 'Original Sculptures'

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Abstract

What are Cy Twombly's sculptures made of? This article presents an overview of a non-destructive examination conducted on three sculptures by American artist Cy Twombly (1928–2011) as part of an art-technological research project at the Doerner Institut in Munich. The artworks are part of the collection of the Brandhorst Museum and belong to Twombly's series of so-called 'Original Sculptures': assemblages of individual found objects, which the artist covered and modified with layers of plaster and white paint. To develop a long-term preservation strategy, the research focused on understanding the materials and construction methods used in Twombly's sculptures. In collaboration with the Chair of Non-Destructive Testing at the Technical University of Munich, the artworks were inspected using X-ray radiography and computed tomography. The results showed that Cy Twombly used various everyday objects made from wood, plastics, metal, and paper/cardboard to build the assemblages. Unexpectedly, the examinations revealed that the individual parts are solely held together by the coating of plaster and paint, lacking additional mechanical connections. The overall structure thus proved to be very fragile and highly sensitive to physical stresses, whether due to handling, transport, or strains in the microstructure caused by climatic fluctuations. Since little was known about Cy Twombly´s choice of materials and manufacturing details, the results offer valuable insights into the overall artistic process and decision-making of one of the most influential artists of the 20th/twenty-first centuries. Conservators can use the art-technological findings to monitor the sculptures 'condition and develop or adapt long-term preservation strategies, including aspects such as ambient climatic conditions and handling storage and transport specifications. In addition, the knowledge generated can be used for further research on the specific materials and transferred to other artworks by Cy Twombly.

Keywords Applied non-destructive testing, Non-destructive testing of art, Radiography, Computed tomography, Modern and contemporary art, Sculptures, Cy Twombly, Art conservation, Art technology

Introduction

Especially in modern and contemporary art, artists often use inconsistent, rapidly degrading materials and unusual manufacturing methods [1–3]. Preserving these works of art for future generations presents a particular challenge since they involve various materials or combinations. These place specific demands on climatic conditions during exhibition or storage, as well as on general handling. Since preservation strategies must be worked out individually for each work of art, it is essential to understand

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as much as possible about an artwork's manufacturing, its construction, and the materials used by the artist. If no or few details about the manufacturing process are known, art-technological examination helps to define an artwork's essential properties and to determine its condition.

In this case, sculptures by the American artist Cy Twombly were examined. The sculptures of the Munich Brandhorst Collection are fragile material assemblages from mostly found objects covered in plaster and white paint. The high fragility of the works and limited knowledge about production and materials were the starting points for art-technological research. Therefore, a research project (2018–2021) was initiated and run by the Munich Doerner Institut, which is part of the Bayerische Staatsgemaeldesammlungen and is responsible for the conservation and art-technological research of the extensive holdings of the Munich Pinakothek Museums including the Brandhorst Collection.

In collaboration with the Chair of Non-Destructive Testing at the Technical University of Munich, as well as the Department of Corporate Technology (CT RDA IOT DPR-DE) at Siemens AG in Munich, a series of non-destructive imaging examination methods, such as X-ray radiography and computed tomography, infrared thermography, visual inspection including endoscopy, and X-ray-based methods, were carried out to better understand construction and condition of the artworks. Foremost, the research team wanted to differentiate the main components within the sculptures, determine their material, and reveal how the individual components inside the assemblages are interconnected. It was of great interest to locate potential weak areas or instabilities in the material structure, such as cracks, fissures, or corrosion, and to visualize them for conservation monitoring. This paper focuses on radiography (RT) and computed tomography (CT) since these examinations were critical in the research context and provided extensive insights into the artist's manufacturing process and the internal structure and condition of the artworks. With RT, two-dimensional radiographic images are generated; with CT, three-dimensional volume data is created and evaluated. The knowledge of morphological and physical characteristics of artworks is valuable for determining adequate strategies for their conservation. Applications of X-ray inspection of wooden cultural heritage objects are given in [4–7], and [8].

Cy Twombly's sculptures: art technology and conservation

Cy Twombly (1928–2011), one of the most important representatives of abstract expressionism, is best known for his paintings and works on paper. He also created remarkable sculptural work throughout the 60 years of his artistic career. The Munich Brandhorst collection preserves a significant and diverse group of artworks by the American artist, including critical works from Cy Twombly´s sculptural oeuvre [9].

The 'Original Sculptures'

This paper focuses on the so-called 'Original Sculptures' [10, 11], material assemblages that constitute the largest group within Twombly's sculptural oeuvre. In this context, the term 'Original' describes that some sculptures had a function beyond being a work of art since they served as models for bronze castings, the second largest group of sculptures in the artist´s work. The art technology of the bronzes and the strong relationship between the fragile 'Originals' and their durable counterparts in bronze was part of the research project at the Doerner Institut and is discussed in internal reports [12]. Twombly´s sculptural oeuvre comprises around 200 assemblages, 60 cast in bronze.

The 'Original Sculptures' are assemblages of often banal, disused everyday objects, such as boxes, cardboard tubes, wooden crates, or funnels, which the artist then coated with plaster and painted white [13]. The structure is similar primarily: on a pedestal-like base—often wooden boxes—objects with a simple geometry are assembled on top of each other, mostly narrowing towards the top (see sculptures in Fig. 1). Cy Twombly was known for sourcing these objects from antique markets and backyard sales, and many photographs testify to his collection of odd findings [14, 15]. After assembling, the artist unified the different materials and surfaces with plaster and paint, drawing the composition together in a homogeneously light tone [16]. In some individual assembled objects, the initial use and materiality still can be seen—thick layers of white cover other objects and are not identifiable. From what can be derived from the surface and the underside of the sculptures, the individual parts are often wooden- or plastic-based, but cellulose or fabric material has also been used. To be able to determine the stability of the fragile structures, it is further essential to know if Twombly used nails, screws, or glue to join the individual pieces—or if they are fitted loosely and held together only by layers of paint and plaster, making any transport and handling of the plastics high risk, and the structure prone to fatigue damage due to material degradation.

Research project at the doerner institut—methodology and research objective

Since documentation from the artist himself barely exists and no art-technological research results on other of his sculptures were available, the conservators of the

Inv. No.:	UAB 650	UAB 657	UAB 656
Title:	Untitled	Untitled (´The Mathematical Dream of Ashurbanipal')	Untitled
Date:	2001	2000	2003
Material:	Wood, sheet metal, cellulose paper, printed paper, plaster, synthetic resin glue, synthetic resin paint, pencil	Wood, nails, staples, plaster, synthetic resin putty, synthetic resin paint, cellulose paper, cardboard, felt-tip pen	Wood, metal, nails, wire, plaster, synthetic resin putty, synthetic resin paint
Dim.:	39 x 40 x 29,8 cm (h/w/d)	104 x 53,2 x 52,9 cm (h/w/d)	110 x 38 x 40 cm (h/w/d)

Fig. 1 Artwork information of the three 'Original Sculptures' chosen for RT and CT inspection.Udo und Annette Brandhorst Sammlung © Cy Twombly Foundation. Photos: Johannes Haslinger (UAB 650), Jochen Littkemann (UAB 657), Haydar Koyupinar (UAB 656). Bayerische Staatsgemäldesammlungen, Museum Brandhorst, München

Doerner Institut examined the manufacturing technique and materiality of Twombly´s works as part of a research project. Of the 18 sculptures in the collection, ten were reviewed in more detail using different methods of analysis and investigation. In addition to a detailed visual inspection of all statues, the conservators not only analyzed the artist's documentation and artist-related literature and interviewed the artist´s longtime assistant and archivist but also conducted comparative visual examinations on sculptures from other collections on site. Part of the research consisted of collecting material-related information through analyses conducted by the scientific department of the Doerner Institut [17]: the binders of the paint and plaster coats on the assemblage sculptures were determined via Fourier transform infrared spectroscopy (FTIR-spectroscopy) and pyrolysis–gas chromatography-mass spectrometry (PyGCMS), and the elemental composition of the pigments and fillers in the white coatings was examined via energy dispersive X-ray spectroscopy (EDX) and X-ray fluorescence (XRF) testing. The results revealed that the artist mainly used products based on polyvinyl acetate or alkyd resins, pigmented with titanium or zinc white and with chalk or silicate as fillers. The findings suggest using relatively inexpensive and quick-drying products commonly used as a radiator or furniture paint and confirm the evaluation of photos from Twombly's studio, which sometimes show hardware store products in the background.

To gain information about the inner structure and the stability of the fragile works, the Munich chair for non-destructive testing, whose laboratories are equipped with various NDT analysis devices, was asked for assistance. Imaging examination methods such as X-ray-based inspection methods promised to be particularly insightful. In preparation for the RT and CT examination, a thoughtful selection of the sculptures was made. Among the selection criteria was that the questions and results of a work studied are transferable to other sculptures and thus have some significance for the artist's sculptural work. Another criterion was the size and transportability of the fragile sculptures. After conducting a benefit-risk assessment, the selected statues were transported in well-padded and cushioned isothermal crates within Munich.

Radiological examinations were carried out on four of the 18 sculptures created between 2000 and 2003 and are part of the artist's later work. Three sculptures that showed key results and, therefore are presented in this paper are described in Fig. 1.

Aim of the NDT examinations

Beyond the chemical analyses of binders and pigments/fillers conducted by the Doerner Institut, the physical properties of the structure and manufacturing details were of high interest, which could only be made visible by imaging examination methods such as X-ray-based inspection. With knowledge about materials and design, evaluating the Munich assemblages' mechanical stability and degradation behavior is an essential basis for the best possible preservation of fragile works.

Applied methods: radiography and X-ray computed tomography

Radiography units and CT scanners have been developed to provide resolutions on the order of micrometers or even in the sub-micrometer range [18]. Both methods are based on X-ray absorption through matter. At low scanning voltages, elements with high atomic numbers, such as iron or lead, absorb much X-ray energy compared to materials with low density, such as air or plastics. The differing absorption results in differing grey values in an X-ray image. A single-through transmission is called radiographic testing, and the resulting X-ray image is then a two-dimensional projection. Compared to RT, 3D CT scans require numerous 2D projections of 360 degrees around the object. Today's scanners often capture 1000–3000 projections per scan volume.

Cone-beam CT is the most widespread type of CT scanner in the industry. In Fig. 2, a CT scanner is schematically illustrated. For cone-beam CT, reconstruction algorithms such as the Feldkamp, Davis, and Kress (FDK) reconstruction convert the information from 2D projections into a 3D volume. The FDK algorithm [19] is a robust and easy-to-use algorithm characterized by its efficiency in handling large datasets. However, the FDK algorithm has limitations since it assumes certain conditions about the object being imaged, such as uniform attenuation properties. Those assumptions can lead to inaccurate reconstructed images. Its application should be considered in the context of the specific imaging goals and data characteristics [20–22]. The reconstructed 3D volume consists of small volume elements called voxels [18], which correspond to three-dimensional pixels. Volume analysis can be performed either by slice analysis or by particular 3D volume viewers. If the dimensions of the sculptures exceeded the CT scan volume, RT scans were taken—sometimes in addition to the rest of the sculpture, sometimes instead of the CT scans.

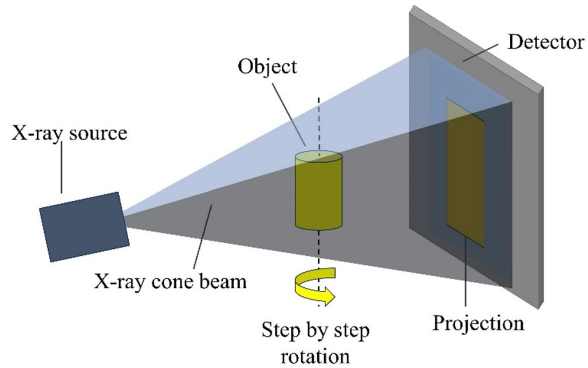


Fig. 2 Schematic illustration of a cone-beam CT scanner

Table 1 CT scan parameters for the investigated sculptures

Inv. No	Scanner	Voltage	Current	Voxel size
UAB 650	Siemens AG	180 kV	400 μA	256 μm
UAB 656	Yxlon	225 kV	190 μA	109 μm
UAB 657	Yxlon	300 kV	2.4 mA	127 μm

Today's industrial computed tomography scanners have voltages of up to 600 kV and resolutions of up to 500 nm and better. The presented CT data were acquired with either a custom-built CT scanner (at Siemens AG, pixel binning 2×2 for data transfer) or a Yxlon Precision scanner (at TUM, refurbished by Diondo). The detectors had 2048×2048 pixels with a 200 μm pixel pitch. As a pre-filter, 0.5 mm copper was used for all scans. Table 1 summarises the scan parameters for the investigated objects.

Results

A precise visual examination of the sculptures led to the respective research questions and, in the course, to determine the regions of interest for radiographic investigations. The presented inspections allowed not only to identify the individual found objects and the materials used by the artist in his assemblages but also to obtain information on the artistic process and the structural stability and condition of the sculptures.

Inv. No. UAB 650

The artwork with the Inv. No. UAB 650 (*Untitled*, 2001, see Figs. 1 and 3) consists of three parts (see Fig. 3: I, II, III). The base of the sculpture (I) is made of a wooden

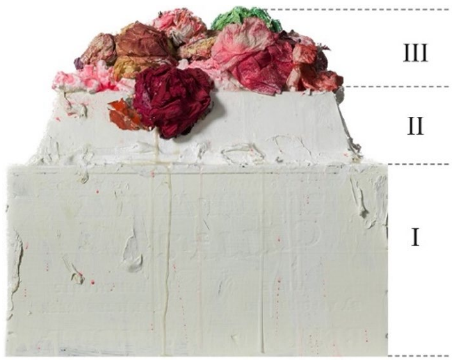


Fig. 3 UAB 650, different parts of the assemblage: I = cuboid bottom box, II = middle box, III = tissue paper 'roses' and plaster mass. Udo und Annette Brandhorst Sammlung. © Cy Twombly Foundation. Photo: see Fig. 1

box, which can be seen from the unpainted and opened underside but also as evidenced by the grain of wood that stands out through the paint layer in some areas. On all sides, lettering is embossed into the box's surface, but the white overpainting does not allow a complete transcription. The lettering is upside down, indicating that the box's actual bottom is now on top and serves as a base for the construction. Several other materials were used on the top of the sculpture, including another box element of an unknown material (II) and the decorative'roses' from colored tissue paper that are added on top of the sculpture (III) and that are both glued to the surface and embedded in a gypsum-like mass. The research team was particularly interested to learn more about the wording of the embossed lettering in the bottom box (I) and the object's materiality on the wooden base (II).

Since the dimensions of the sculpture are comparatively small, a full CT scan could be performed, illustrated in Fig. 4. The wood structure of the bottom box (I) is shown in Fig. 4a, c, and d: annual growth rings and knotholes are visible. The individual boards of the box were interconnected with nails (16 horizontally and nine vertically arranged nails, see Fig. 4b). Additional glue between the panels cannot be observed. Figure 4a shows that the plaster-coated and painted object (II) on the box (I) appears brighter than wood or plaster. On top of part II, CT identifies a highly X-ray absorptive gypsum-like material underneath the colorful 'roses' (III).

Using CT, letters became visible at the surface of the sides (see Fig. 4c) and the facing up bottom of the wooden box (see Fig. 4d). Especially the latter writing, which is usually hidden under object II, was of great interest to the researchers. Since not all letters were visible in a single x–y cross-section of the CT scans, the images were stitched together to reconstruct the writing (see Fig. 4c, d). The writing shown in Fig. 4c—embossed into one of the sides of the wooden box—is separated into four lines. The top line reads 'B. C.' and the middle line 'NEW YORK,' then 'B.C. STATE SEALS / ARE AFFIXED TO BOTTLES.' At the top of the wooden box –the bottom that points upwards—another branding is visible (see Fig. 4d for the digital reconstruction of the lettering): amongst other words, which cannot be identified, the writing indicates 'BERRY BRO^{S} & RUDD L.^{TD}.'

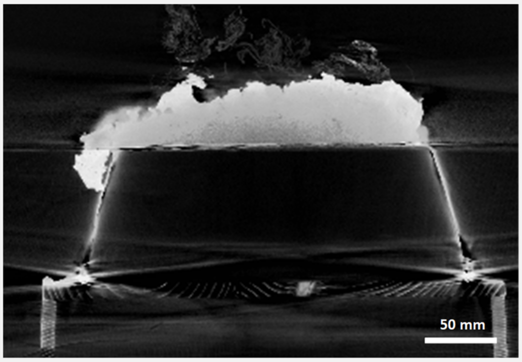
Inv. No UAB 656

Inv. No. UAB 656 (*Untitled*, 2003, see Figs. 1 and 5) is composed of four structural components (see Fig. 5: I–IV): A presumably wooden cuboid (I) forms the base of the sculpture, with a cylindrical object (II) on top of it. The upper part of the sculpture consists of two objects: a cone-like object (III), with a rod that protrudes vertically upwards, and a slat (object IV) with a nailed application of several thin cables, shrink tubing, or similar. The slat sits on the cone and also points vertically upwards. The construction has been reworked with white paint and a plaster-like mass, especially the cone-shaped object III. Of particular interest were the nature and origin of the cone-object (III) as well as—given the high fragility of the structure—the connection between the individual elements.

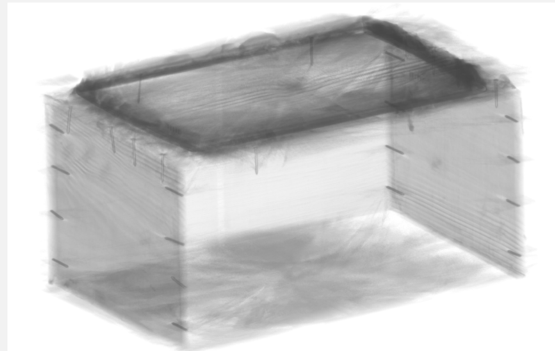
CT and RT confirmed the assumption that objects I and II are wooden boxes, see Figure 6a. The cone-shaped component showed a high X-ray absorption and is, therefore, most likely made of sheet metal, the round wooden rod attached to it. Figure 6b shows a segmentation of the cone-shaped element and allows us to identify the inscription 'HELPMATE VACUUM WASHER.' Moreover, the CT scan showed that the vertical element IV is a wooden slat with plaster attached to the side of the metal cone. The application comprises coated metal wire pieces painted and nailed to the wood (see Figure 6a, detail).

Inv. No. UAB 657

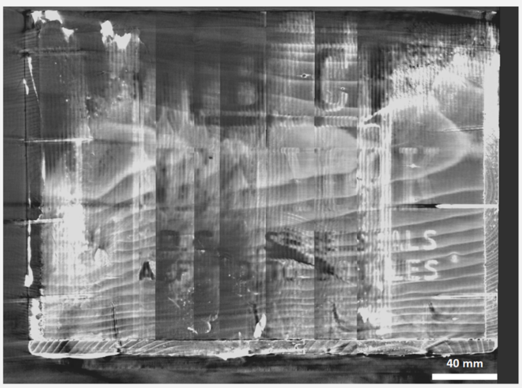
Through visual inspection, the sculpture with the Inv. No. UAB 657 (*Untitled*, 'The Mathematical Dream of Ashurbanipal, '2000, see Figs. 1 and 7) was found to be made out of four individual components (see Fig. 7: I–IV): The base (I) is a square box made from wood, which can be viewed from the unpainted underside. The box is open at the bottom and was used upside down, which is why the actual base of the box serves as a support surface for the further construction of the assemblage: Stacked in the middle of the wooden box are three almost cylindrical shapes (II-IV) that taper towards the top. Since the materiality and condition of the internal construction could not be reconstructed due to the thick layers of plaster, the researchers focused mainly on the three cylinders. According to the outer shape of object II, a hat



(**a**) Cross-section in the x-z plane of parts II and III, lighter colors represent higher material densities.



(**b**) 3D visualization of the box I with 27 visible nails.



(**c**) Stitched cross-sections in the x-y plane of the side of the wooden box I reveal lettering, which is unreadable due to the paint layer: "B. C. / NEW YORK / B. C. STAT SEALS / AFFIXED TO BOTTLES"

(**d**) Stitched cross-sections in the x-y plane of the CT volume at the hidden top of the wooden box I, digital reconstruction of the lettering.

Fig. 4 Results of the CT inspection on UAB 650

box made of solid cardboard or another cylindrical box was suspected under the plaster layer. A primary concern was that the horizontal surface of the cylindrical-shaped object II appeared to be somewhat concavely deformed, which made the cake-like construction appear unstable.

The CT scans in Fig. 8 indicate that all three cylinders are corrugated cardboard. The characteristic corrugated sandwich structure becomes visible through the differences in X-ray absorption between air and cardboard and identifies the present cardboard as a thin, single-wall corrugated board. Figure 8a is a cross-section in the x–y plane where objects IV and III meet and shows cardboard structures and an uneven surface that cannot be recognized as uneven from the outside due to the thick plaster layer. The three-piece system of objects II–IV was found to be not a stack of three individual objects, but rather the CT scans indicate the three-piece construction was formed as a whole – assembled from various pieces of thin cardboard with staples as connecting elements (see Fig. 8b, c and d).

Discussion

The key benefits of RT and CT are that these imaging examination methods facilitate not only non-destructive but also—given the fragility of the sculptures—non-contact examination, combined with highly informative value in terms of material and structure. Since the 'Original Sculptures ' were mainly assembled of wooden objects like crates or slats and cellulose material like cardboard or paper, then coated with plaster and paint—all in all, materials with a low material density—the testing methods were well suited for the artworks. However, Twombly sometimes used metal pieces in his work, and these can cause metal artifacts. The artifacts impair the

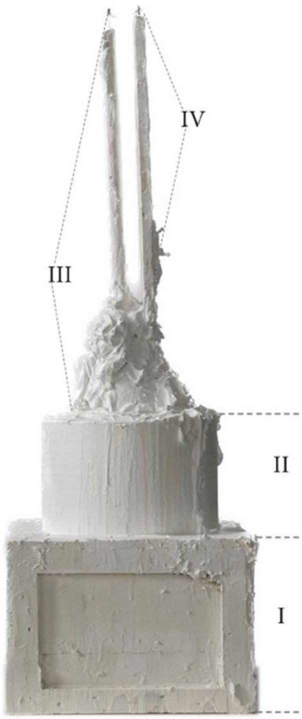


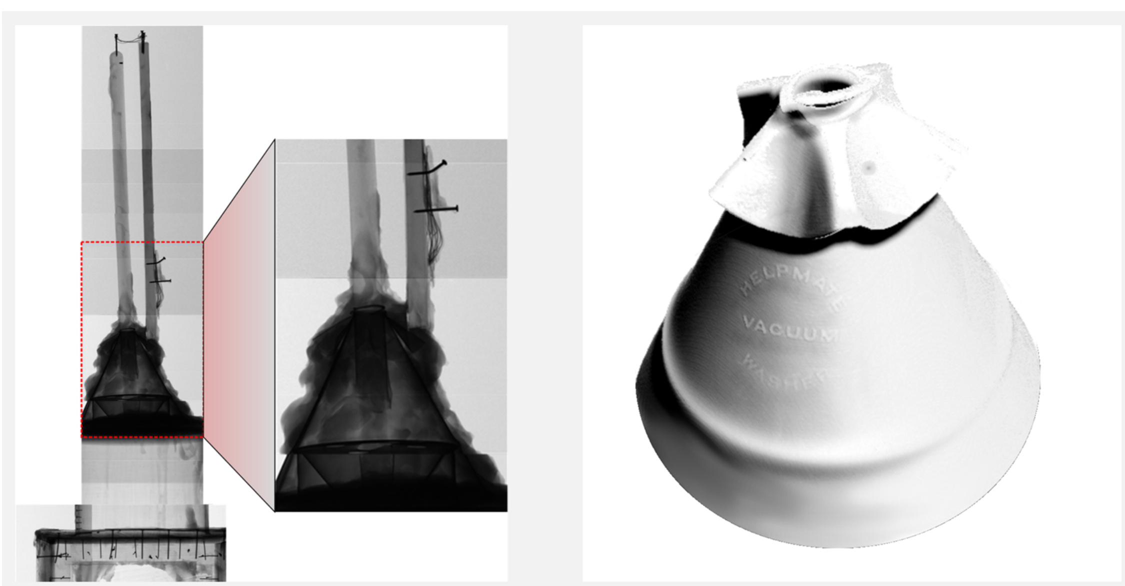
Fig. 5 UAB 656, different parts of the assemblage: I = cuboid base box, II = cylindrical box, III = cone-shaped object, IV = lath with application. Udo und Annette Brandhorst Sammlung © Cy Twombly Foundation. Photo: see Fig. 1

analyzable image area and can hide additional information. Due to the size of the sculptures and limited test space, not all works could be investigated with a holistic CT scan. In some cases, individual radiographic images were taken and stitched together. Instead, the sculpture's parts and materials of interest had to be determined in advance using visual inspection. When investigating Cy Twombly's sculptures with CT and RT, it was possible to identify most of the artist's materials and draw conclusions about the working method.

Inv. No. UAB 650

This study revealed the inscription on the horizontal bottom of the wooden box I (Fig. 4d), which is hidden from the viewer. The probably burned-in letters could be identified, revealing the box's previous use as a transport container for Whisky from 'Berry Bros. & Rudd Ltd., a Scottish wine and spirits company founded in the seventeenth century [23]. At the beginning of the twentieth century, Berry Bros. & Rudd´s scotch whisky named 'Cutty Sark' became hugely popular in the American market. After the box was used for its intended purpose, it came into the hands of Cy Twombly and was then processed in the artwork.

According to the CT scans, object II (see Figs. 3 and 4a) has a high X-ray absorption and could therefore be identified as a sheet metal part. This information was new to the research team, as they had previously assumed



(a) Radiographic images stitched together; the enlarged image shows the washer with its rod to object IV on the right.

(b) Segmented metallic artifact inside the sculpture with the company´s branding 'HELPMATE / VACUUM / WASHER.'

Fig. 6 Results of the X-ray CT and RT of UAB 656

Fig. 7 UAB 657, different parts of the assemblage: I = cuboid bottom box, II-IV = cylindrical shapes. Udo und Annette Brandhorst Sammlung © Cy Twombly Foundation. Photo: see Fig. 1

a plastic object. Metal elements such as nails or sheet metal require special monitoring, as metal can be susceptible to oxidation and corrosion processes and destabilize the structure. These findings must be considered in future adjustments of the ambient climate conditions.

Inv. No. UAB 656

With computed tomography, it was possible to confirm the assumption from visual inspection, namely that Inv. No. UAB 656 comprises four structural components (Fig. 5: I–IV). The discovery of the metal, cone-shaped artifact, identified by the embossed writing as a vacuum washer from a company called "Helpmate" (see Fig. 6b), was an unexpected finding for the research team. Hand-operated vacuum washers like the one Twombly used in the assemblage were used up to the mid-1900s to clean clothes, acting like a plunger when moved up and down in a tub of water with dirty laundry. Figure 6a also allows conclusions to be drawn about the inner workings of the washer: a water flow controlled by various built-in metal sheets creates a vacuum when moved up and down, gently cleaning the textiles. The finding of the vacuum washer artifact supports the observation that Twombly liked to use found objects that were previously collected at antique markets and backyard sales. With the knowledge of the vacuum washer used by Twombly, the catalog raisonné for the artist's sculptural oeuvre was re-evaluated—in the case of the 1992 made sculpture 'Madame D`O' [10, pp 268–269], which also has a similar, cone-shaped object with a round rod as a central element, a vacuum washer could have been used.

In addition to a visualization of the other elements used in the sculpture—the application on the wooden slat IV turned out to be a metallic wire in plastic insulation (see Fig. 6a)—it was also shown that this wooden slat IV only sits on the funnel of the vacuum washer and is fixed there only by applied plaster and paint, without any mechanical connection element. The observation that the individual objects of the assemblages were, for the more significant part, not mechanically joined together using nails or screws applies to all Twombly sculptures examined. This led to a reassessment of the fragility of the sculptures, especially about handling the works, transport, and storage conditions.

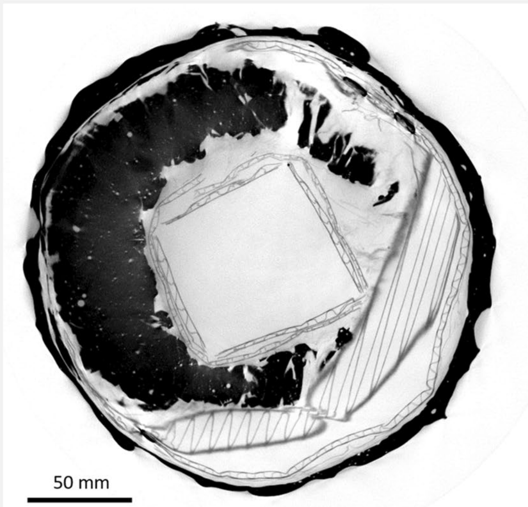
Inv. No. UAB 657

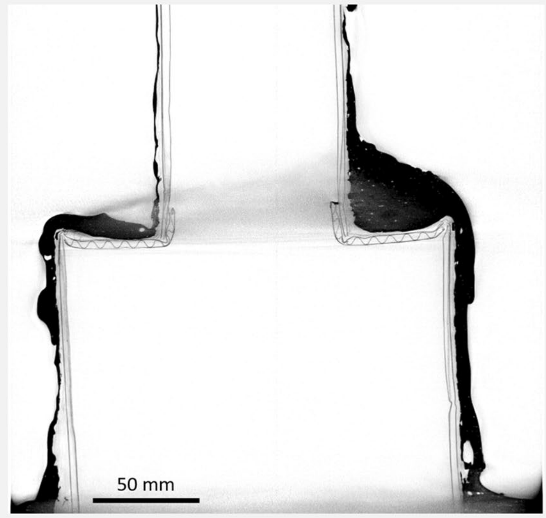
In the CT scans of UAB 657, it was possible to identify the materials of the sculpture parts II–IV (see Fig. 7): the construction is made from a single-wall corrugated board, fixed with metal staples, and then coated with plaster. Due to contrast adaptation, the cardboard appears dark in Fig. 8. The plaster is characterized by high X-ray absorption compared to cardboard and air (see Fig. 8b and d).

Single-wall corrugated board is a cheap, rapidly aging, and pliable material commonly used to wrap fragile items. The CT scans suggest that Twombly assembled the corrugated cardboard himself, formed it into a cylindrical, cake-like shape that gradually tapers upwards, and fixed it in places with metal staples (see Fig. 8a–d). This was a surprising finding, as the construction was assumed to be three individual objects stacked onto each other and not an entirely self-made structure. From a conservation perspective, it is both astonishing and challenging that Twombly did not use a supporting internal form to construct the shape and that the weight of the plaster rests directly on the unstable corrugated cardboard material (see Fig. 8b and d). The concave deformation, which can be seen in Fig. 8b, is probably due to the weight of the plaster coating and very likely happened already during the drying phase of the plaster in which the corrugated board was exposed to moisture from the hardening plaster material. Learning more about the inner construction and the state of preservation of the sculpture—especially of its upper part—was a central result for the conservators.

Advantages and limitations of RT/CT and alternative methods

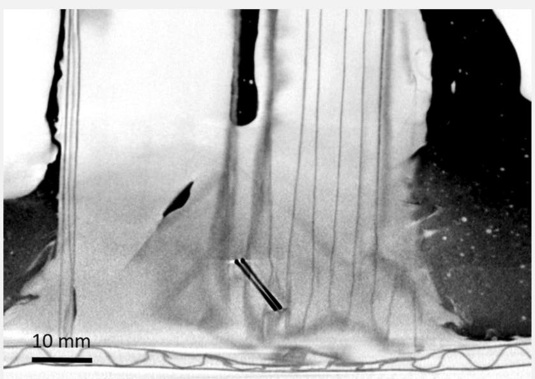
Twombly's assemblages are composed of different parts with a wide range of materials. When materials of strongly differing atomic numbers are inspected with low energetic X-rays, artifacts can occur in CT scans. This can be seen in Figs. 4a, d, where the physical principle





(a) Cross section in the x-y plane between objects III and IV: irregularly composed corrugated cardboard structure, black area depicts plaster material

(b) Cross section in the x-z plane of the two upper objects III and IV: a structure built from thin corrugated cardboard without supporting internal structure, coated with plaster material



(c) Zoomed cross section in the x-y plane between objects II and III, staples connect and compress the corrugated cardboard

(d) Cross section in the x-z plane: the detailed image of two staples interconnecting individual cardboard pieces where objects III and IV meet

Fig. 8 Results of the X-ray CT measurements on UAB 657

of photo absorption from iron nails and sheet metal led to cross-shaped metal artifacts. Those artifacts affect image quality and impair the evaluation. Using acceleration voltages higher than 1 MeV reduces the impact of photo absorption and allows low disturbed resolution of materials with varying densities, as presented in the 3-D scanning of sea freight containers [24]. However, such so-called XXL-CT scanners are subject to the highest radiation protection requirements. Therefore, the scans are costly and require long lead times. For high-density materials like metals, neutron tomography could substitute CT. Previous research [25] showed promising results applying neutron tomography to dense metals in cultural heritage objects. However, neutron tomography is very expensive since a nuclear reactor is needed, and the dimension of the applicable objects is restricted due to the setup.

To further investigate the series of the 'Original Sculptures,' another conceivable method would be air-coupled ultrasonic testing. Compared to other ultrasonic inspection methods, air-coupled ultrasound is contact-free and does not thermally influence the part. It enables transmission through materials, detecting boundary layers as material or density changes, e.g., delamination, inclusions or cracks, and their location. Additional benefits include its rapid scanning capability and the absence of the need for costly equipment or radiation protection [21]. [26] and [27] used air-coupled ultrasound to detect delamination and cracks in wooden panel paintings, [28] performed in situ studies of bricks hidden beneath a wall painting, and [29] could authenticate wooden panel paintings. However, current setups for air-coupled ultrasonic testing are often stationary and demand two-sided access to the object. Further, interpreting the received ultrasonic signal requires either homogeneous material or a reference signal from a reference sample. Therefore, air-coupled ultrasound could be used for other objects of Cy Twombly's sculptures. Unfortunately, the presented objects are unsuited for this method due to the necessary two-sided access and geometry restrictions.

For further inspection of the 'Original Sculptures,' in case the single coating layers are of interest, pulsed or lock-in thermography could be used as in previous research [30, 31]. These methods can visualize single coating layers and their specific structure, allowing conclusions about Cy Twombly's painting technique and individual working steps.

Since not every sculpture is transportable or fits inside a stationary RT or CT system, a portable RT system, as described in [4], could extend the investigations of the 'Original Sculptures.' Given the high fragility of the sculptures, a portable system would be desirable for further studies.

Conclusions

This paper presents the first radiographic examination of selected sculptures of the American artist Cy Twombly (1928—2011), conducted in the context of an art-technological research project. The sculptures, assemblages of mostly found objects covered with plaster and white paint, were created between 2000 and 2003.

The applied testing methods were radiographic testing and computed tomography to learn more about the construction, the used material, and the state of preservation of the fragile assemblages.

Before the RT and CT examinations, conservators could approach the materiality and inner structure of the sculptures only via visual inspection and merely rely on art-historic publications, which describe the manufacturing with often incomplete material and marginal technical information. In this context, the radiographic investigations provided vital information and confirmed or challenged assumptions about Twombly's working method or choice of materials. For example, the computed tomography scans proved that Twombly created his sculptures mainly with randomly found objects but also showed that the artist simultaneously built up parts of the sculptures himself, such as the cake-shaped structure made of thin corrugated cardboard found inside the sculpture UAB 657. In addition, previously unknown materials and structural elements could be identified, and statements could be made about the condition or particularly fragile areas. The stored image data allows monitoring of the condition of the sculptures and is a crucial aspect when it comes to deriving appropriate conservation methods. In summary, it can be said that all the knowledge generated is of great importance for the long-term preservation of the works: The understanding of material and manufacturing enables conservators to develop artwork-specific strategies for storage, exhibition, and transport—they can now determine what the optimal climatic conditions for the works of art are, which areas must not be touched or need exceptional support during storage or transport, and also which artworks should not be exposed to the vibrations caused by transportation at all. In addition, the results enable targeted research on material aging and degradation. Finally, the CT and RT examinations gave insight into the working methods of one of the most influential artists of the 20th/twenty-first centuries.

However, in the CT inspections, the sculptures' size and material were limiting factors, and not every sculpture or every part of a sculpture could be examined. These technical issues could be approached using portable RT systems, XXL-CT scanners, or neutron tomography.

The examinations contributed to the research landscape of the appropriate use of NDT methods for artworks and specifically to the knowledge about the art technology of Cy Twombly's sculptures. Future studies of these and other Cy Twombly artworks can be based on these findings.

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Author contributions

JR, MT, and SS produced the first draft of the manuscript and contributed to several edits. The writers contributed text and figures to the manuscript and edited the script before submission. MT and EB examined the sculptures' materials, structure, and condition and carried out broad research into the artist's sculptural oeuvre and his working methods. SS, JK, and RB performed the radiographic testing of the sculptures. SS analyzed and interpreted the data with Juliana Reinhardt's help, who also performed infrared thermography on selected sculptures. PJ undertook endoscopy examinations and eddy current measurements together with JK. The research project was led by EB, who provided substantial guidance and equipment together with MG and Prof. CUG for the conception and design of the work. All authors reviewed the final manuscript critically and approved publishing this version. All authors agree to be accountable for the aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Availability of data and materials
Raw data are available from the authors with the permission of Doerner Institut, Bayerische Staatsgemäldesammlungen Munich. The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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