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Neutron tomography reveals extensive modern modification in Iron Age Iranian swords

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ABSTRACT

Early Iron Age Iranian bladed weaponry plays a significant role in discussions of metallurgical development in the ancient Near East. Due to its ubiquity in museum collections, as well as co-occurrence of bronze, iron, and bimetallic forms, it figures prominently in debates about the early ironworking techniques in the late 2nd and early 1st millennia BCE. However, dispersed collections, often lacking secure archaeological context, have made comprehensive assessment difficult. One major type of bladed weaponry, the so-called split-ear pommel swords have been the subject of much discussion, particularly around the presence of an iron core identified in many examples. Neutron tomography was applied to eight swords of this type to image their inner structure, assess the manufacturing process and determine possible recent modifications—the first time this technique has been applied to bronze Iranian weaponry of any period. The objects were recovered by the Border Force after being seized on entry to the UK and will be repatriated to Iran, providing an opportunity to investigate both ancient manufacture and modern (illicit) modifications. The results reveal extensive modern modification, namely the replacement of original blades—often made of iron—with different (but probably also ancient) bronze blades, conclusively showing that "iron cores" were not a technological feature in these bronze swords, but a result of modern tampering. Widespread iron blade replacement has masked the true extent of the production of bimetallic weapons and obscured the technological choices of early ironworkers. Given the centrality of unprovenanced objects in discussions of Iranian Iron Age metallurgy, these modifications have negative consequences for efforts to map the process of iron innovation.

1. Introduction

Iranian metal weaponry from the Iron Age (1250–550 BCE) is widely known, but poorly understood. Iranian Iron Age metalwork, best known from north-west and western Iran, was a popular item for museum acquisition in the 20th century, and as such is scattered throughout most major museums around the world. Its popularity began with discoveries made in the Luristan region from 1928 onwards (Moorey, 1971), quickly prompting dealers and museums to search for artifacts for their collections. Other objects were acquired from Iran by diplomats, scholars, museums, and universities (Maxwell-Hyslop and Hodges, 1966; Shizuma et al., 2017; Sokołowski, personal communication). Lacking secure provenance, the objects were purchased, and their status rarely questioned. The demand triggered illicit excavations, forgeries, and pastiches, understood as objects consisting of ancient elements which did not originally belong together. As a result, many of these Iranian bronzes in public and private collections are unprovenanced and loosely attributed to the regions or market towns where they first circulated, such as Amlash in Gilan province (Mahboubian, 1997; Meier-Arendt, 1984) or Kermanshah near Luristan. Graves and hoards were the main sources of these finds (Overlaet, 2003; Schmidt et al., 1989), as demonstrated by subsequent excavations and even the poorest male graves were equipped with a few weapons, as was the case in the cemeteries of Tepe Sialk, Marlik, and Khurvin (Moorey, 1971). The

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metalwork from the site of Hasanlu is a rare exception of excavated weaponry from a settlement site (Thornton and Pigott, 2011) while Sangtarashan is an example of a ritual site where large quantities of weapons were uncovered (Hashemi et al., 2023). Excavated samples are found in Iranian museums - though even domestic collections have significant quantities of illegally excavated confiscated material (Khorasani, 2006). While recent years have seen substantial work in archaeometallurgy by Iranian scholars that is beginning to shift this pattern of reliance on unexcavated metal objects (Hashemi et al., 2023; Oudbashi and Davami, 2014; Oudbashi and Hessari, 2017), there has yet to be a comprehensive analytical study of excavated, bimetallic bladed weaponry, i.e. multi-component weaponry combining both iron and copper-alloy parts, which figures so prominently in debates about early iron.

Due to the scattered distribution of these objects in museum collections, they are analysed piecemeal, in groups of just a couple of objects. If published, the results often appear in disparate journals, or as analytical notes attached to exhibition catalogues (Hopp et al., 1992; Marino-Hultman, 2000). The result is a lack of synthesis, which has made definite statements about bimetallic weaponry, and its significance to discussion of metallurgy during the early stages of iron adoption (specifically the Iron I and II periods) difficult. Bimetallic weapons are an important class of early Iron Age objects across the Near East. Although they are not exclusive to this period, they are much discussed in the context of early iron innovation and the Bronze Age-Iron Age transition (Erb-Satullo, 2019:566; Waldbaum, 1982). Bimetallic objects offer information about the early iron technology as they might represent the period of experimentation with the new material. Early iron swords mimic forms made in bronze while later examples belong to newly developed types. Adoption of iron, which appears only in very small quantities in the 13th-11th centuries BCE but became increasingly common by the 9th century BCE (Danti, 2013), cannot be fully understood without a detailed analysis of the bimetallic tradition (Pigott, 1981, 2004). In fact, the manufacture of bimetallic objects was deemed to be a marker of Iron Age II (Pigott, 1999). Bronze hilts were cast onto iron blades from about the 10th century BCE (Moorey, 1974) which is a plausible approximate date for the swords in the present study. As Iran lacks well-documented early iron smelting and smithing sites (a pattern that is true across the Near East), analysis of finished products is one of the few available means to investigate early ironworking techniques.

Neutron techniques are relatively new in the investigation of archaeological artifacts, and although the number of analyses has increased in recent years (Cazzaniga et al., 2021; O'Flynn et al., 2023; Park et al., 2022; Salvemini et al., 2020), their application is not yet routine. As these methods are completely non-invasive, they are particularly attractive for analysing complete, multi-component objects where sampling is discouraged or impossible. Conversely, the time and resource intensive nature of neutron techniques analyses means that investigation of large assemblages is often not feasible. In this context, their use is primarily focused on the analysis of select museum objects to address specific inquiries. Analyses of large assemblages can be conducted but they are limited by the complexity of data analysis. Furthermore, it is noteworthy that availability of these techniques is limited to a small number of facilities worldwide, so the techniques themselves are not yet widely established in the field of heritage science.

Imaging techniques have been useful in the past in identifying pastiches and modifications of objects. To date, the main such technique used for examining Iranian bladed weaponry has been X-ray imaging, but γ-ray radiography had been implemented as well (Kontani, 2005; Nojima et al., 2016; Shizuma et al., 2017). Neutron imaging is a complementary technique to X-ray imaging due to the nature of neutron interaction with matter, with several advantages over X-ray imaging relevant to the present study. As X-rays interact with electrons, their attenuation depends on the atomic number of each element and is not isotope specific. Conversely, neutrons interact directly with the nucleus of the atom, providing greater penetration power and different contrast mechanism. They are sensitive to hydrogen-rich materials and hence allow for the identification of organic matter such as wood or bone encased in metal, or corrosion phases (Fedrigo et al., 2018, 2023; Lehmann et al., 2010). Importantly, the technique is also effective for highlighting the presence of organic glues that could have been used in modern modifications or repairs (Fedrigo et al., 2023). This last feature is a crucial advantage of neutron tomography relative to more commonly applied X-ray imaging techniques from the perspective of identifying fakes, forgeries, and pastiches.

Swords discussed in this study (Fig. 1) belong to an assemblage



Fig. 1. Eight Iranian swords analysed in this study.

recently seized by the UK Border Force and subject to repatriation to Iran. They are currently held by the British Museum who have received permission from the Iranian authorities to investigate and analyse them prior to return. In tandem with a comprehensive synthesis and critical reassessment of prior research, the application of neutron tomography helps conclusively resolve persistent questions about the manufacture of these swords, providing a firmer foundation for wider assessments of innovation and adoption in bronze and ironworking techniques during a crucial transitional period in Near Eastern metallurgy.

2. Background

Split-ear pommel swords are named after their bifurcated pommel shape, resembling an ear in cross-section. They are also characterised by long narrow blades and forked guards. Some of the first known examples of bimetallic swords of this type were found in the Chagoula Derre necropolis (Fig. 2) in the Talish region (de Morgan, 1927), currently in the Louvre (4370; 57,870). De Morgan attributes most tombs to the Iron Age and while such swords were dated to the 12th-11th centuries BCE (Maxwell-Hyslop and Hodges, 1962), more recently they have been dated to Iron Age II (1050–800 BCE) when a further example from the Talish region was excavated in a cemetery at Toul (Khalatbari, 2004:84). Such swords were excavated from 9th century BCE levels of Hasanlu in West Azerbaijan, with one example having an iron pommel as well as blade (Thornton and Pigott, 2011; Wever, 1969). Bronze and bimetallic examples of this type are also known from a number of sites in the South Caucasus (Kuftin, 1941; Gambaschidze et al., 2001:406). Unprovenanced examples can be found in the Cleveland Museum of Art (1942.550, 1942.552), the British Museum (1904,1202.1), the Ashmolean Museum, Oxford (AN 1966.554, AN 1967.1086), and Ruhr Museum, Essen (Hopp et al., 1992), among others.

Prior research of split-ear pommel swords has provided indications that recent modification and pastiche making is a concern. This poses serious issues for understanding early iron- and contemporary



Fig. 2. Map of sites with split-ear pommel swords, and other sites mentioned in the text.

bronzeworking techniques in this critical class of material. For example, the Penn Museum purchased a bronze sword in 1967, dated to the late second-early first millennium BCE. On examination, it was found that the hilt contained iron, and the 'corrosion' present in the joint between the hilt and the blade could be easily removed with organic solvents. Soft grey metal was revealed, deemed to be a modern lead solder. An original iron blade was replaced with a bronze one (Wever, 1969). During investigations conducted by the Department of Archaeology, Hiroshima University, in Iran in the 1970s, eight bronze swords were purchased in Tehran from an antiquities market. Eleven more were purchased and donated to the Okayama Orient Museum (Shizuma et al., 2017). The swords were analysed with γ-ray radiography at the Faculty of Engineering, Hiroshima University, and seven out of eight were discovered to be pastiches, of which five belong to the split-ear pommel type, with solder used to attach bronze blades to hilts containing iron tangs belonging to now-missing iron blades. Putty was used to obscure the joint area (Nojima et al., 2016). An iron core was discovered at the Okayama Orient Museum in eight out of eleven swords (one of which was a split-ear pommel type), previously assumed to be bronze. Iranian bronze swords, purchased on the art market in the 1960s, were x-rayed at the British Museum, and it was revealed that the hilts contained iron cores. Simpson and La Niece (2010) suggested that the swords originally had iron blades, which were subsequently replaced with bronze blades, while the original iron tangs remained inside. The bronze hilt was soldered onto the blade and a green paste used to conceal the attachment. More examples of similar forgeries are known in the UK; as early as 1962 Maxwell-Hyslop and Hodges revealed that among the collection at the Institute of Archaeology, UCL, there is a sword that originally had an iron blade, traces of which can be seen inside the hilt. It was replaced with a bronze one, cut to fit the hilt, which became apparent when the sword was dismantled (Maxwell-Hyslop and Hodges, 1962). The Ashmolean Museum houses a collection of ancient Iranian bronzes; two of the bronze swords (AN 1965.770 and AN 1968.61) were said to have iron cores, one of which could be seen through a hole in the hilt. At the time of writing his catalogue, Moorey (1971) claimed that they were a 'remarkable technical feature'. However, these swords have not been scientifically examined, and the integrity of the blades challenged by Simpson and La Niece (2010) on the basis of other analyses and the observation that the tip of an iron tang is visible at the top of the pommel, yet the blades are of bronze. The Ashmolean swords have been cited as proof of existence of bronze swords with iron cores (Kontani, 2005). Given all available data, it is possible these swords are well-made pastiches. Despite evidence of modification in some papers, the hypothesis of the iron core as a genuine technological feature continues to be proposed in the literature (Kontani, 2001, 2005). If so, the use of almost entirely hidden iron with unclear purpose in the context of its early appearance in the region would require explanation from either a technical or symbolic standpoint.

3. Methods

The present study was performed on the IMAT (Imaging and Materials Science & Engineering) beamline at the ISIS Neutron and Muon Source at the Rutherford Appleton Laboratory, Oxfordshire, UK. The instrument is used to record radiographies and tomographies of samples using pulsed neutron beam. While neutron tomography presents some limitations with respect to X-ray tomography in terms of resolution, it allows recording of features deriving from low atomic weight elements even in the presence of dense materials and may provide visual distinction between elements of similar atomic numbers because neutron attenuation is independent of the number of electrons. Due to their lack of charge, neutrons are generally a better probe than X-rays at penetrating dense matter, even though their energies are normally in the order of meV, as opposed to few hundred keV for X-rays. During neutron exposure some sample activation can occur, however, this depends on the elemental/isotopic composition of the material analysed, the intensity of the neutron beam, and exposure time, and is not an issue when analysing most bronzes, where the decay to a negligible dose can take mere hours. Presence of arsenic, however, can extend this time to a few weeks. The activation levels can be estimated if the composition and trace elements in the material are known (Postma and Schillebeeckx, 2009).

Neutron beam irradiates the object and is attenuated through absorption and scattering from the object. The attenuation of the incident neutron beam is dependent on the thickness and density of the sample, as well as its elemental composition. The energy of the neutrons comprising the beam is the only factor influencing the attenuation which can be controlled when imaging archaeological objects. The total transmission for a neutron beam follows the Beer-Lambert law:

$$\frac{I}{I_0} = e^{-\sum_i (N\sigma d)_i}$$

where I_0 is the intensity of the incident neutron beam, I is the intensity of the transmitted neutron beam, N is the atomic density (in atoms/cm^{-3}), d is the sample thickness (in cm) and σ is the total cross section (in barns) for each isotope i. The higher the transmission, the lower is the attenuation from the irradiated material.

Spatial resolution of the resulting imagery depends partly on the size of the pinhole (collimator) D and the length of the beam path L between the collimator and the sample position. The L/D ratio limits the resolution which can be achieved during the analysis and is partly determined by the instrumental setup. The distance between the sample and the detector l is dependent on the largest dimension of the sample perpendicular to the rotation axis, in this case the width of the pommel. The relationship between these parameters can be described as $d=l/(L/D)$, where d is the image blurring. The images were captured with a CMOS digital camera (2048 × 2048 pixels) which records the transmitted radiation through the sample, with the exposure time for each projection set at 30 s. The swords were aligned vertically and rotated 360° during the scan, where up to 766 images were captured. With a field of view of 21 × 21 cm^2, it was necessary to obtain multiple overlapping tomography scans to image the whole object. The beam path L between the pinhole and the sample was 10 m in all cases. Pinhole diameter was 40 mm. With the L/D ratio of 250 the resolution achieved was 200 μm.

Projection images without the sample (flat fields, I_0) and with the shutters closed (dark fields, DF) were acquired for normalisation, which can be described as:

$$T_n = \frac{I - DF}{I_0 - DF},$$

where T_n is the normalised projection. The process, also called flat fielding, reduces the fixed-pattern noise. It is performed after refining the projections by removing bright gamma spots.

Reconstructing the images creates a 3D matrix of attenuation values which correspond to the total cross-section σ of the material in that area. The 3D images were normalised and reconstructed with Mantid Imaging software (Tygier et al., 2023; Arnold et al., 2014) using Filtered Back Projection algorithm and stitched using the Fiji distribution of ImageJ software package (Schindelin et al., 2012) where applicable. Segmentation and volume rendering of the tomography datasets were performed using Dragonfly (ORS), version 2022.2.0.1399 for Windows.

Swords were mounted in aluminium cylinders for the measurements because aluminium is almost transparent to neutrons and as such is an ideal material for neutron imaging experiments. All weapons were initially imaged with X-ray radiography at 90–95 kV with MeX+40BT Hybrid Portable X-Ray with a CXDI – 410C detector at Cranfield University. It was possible to see some internal features in the hilts of the bronze swords, but the swords believed to be bimetallic were impenetrable with X-rays at the power available to us. Moreover, corrosion products would be impossible to see with X-rays regardless of the power,

due to the high levels of hydrogen present in them. On the other hand, neutron imaging reveals such features easily as they are highly attenuating.

4. Results

Careful macroscopic investigation provided some indications of object modification and blade replacement. For example, objects AR1, AR2, AR3, and AR4 have blades which stylistically are unusual for the split-ear pommel sword type (Hajitabar and Haji, 2022). Some inconsistencies in corrosion were noticed as well (AR1, AR2), alongside evidence of iron, which was either visible as corroded reddish metal (AR8, AR9) or discovered with the use of a magnet. As all bronze blades are corroded and bear evidence of having been buried, they are believed to be ancient, rather than modern copies. Dimensions of objects and their weights are provided in Table 1.

Table 1
Swords analysed in the study.

sword number	total length (cm)	blade length (cm)	weight (kg)	magnetic response in the hilt
AR1	58.5	42	1.23	yes
AR2	55	38.5	0.78	yes
AR3	55.5	38	0.98	yes
AR4	56	40	0.78	no
AR5	64.5	50	0.90	no
AR6	61	45	0.86	no
AR8	89	72.5	1.05	yes
AR9	82	65.5	1.28	yes

With neutron tomography the evidence of corrosion is visible on the surface of the hilt in many examples, as the high attenuation of the neutron beam is caused by the hydrogen-rich corrosion products, which appear white. Similarly, hydrogen-rich glues or similar modern materials will appear white but can be differentiated both by their location (for example, where corrosion is not expected, away from exposed surfaces), morphology, and texture, which appears more porous (Fig. 4).

4.1. Sword AR1

The shape of the blade is unusual for this type of weapon (Fig. 3) (Hajitabar and Haji, 2022) and a corrosion pattern along the shoulder of the blade suggested that a penannular grip was previously cast onto it (Fig. 5 in blue).

The bottom of the hilt does not possess a forked guard, which is expected in this type of weapon, but rather ends in a straight line. The blood channel decoration ends abruptly, leaving a gap between the blade and the hilt which seems to be filled with material (Fig. 5 in red). Moreover, the hilt contains metallic iron while the blade does not (see Table 1). While x-raying the sword proved unsuccessful and no internal features could be distinguished, neutron tomography revealed the presence of an iron tang belonging to the original blade. It is rectangular in cross-section (Fig. 4a–d) and while it starts in the centre of the pommel, it curves slightly and is largely off-centre in the hilt itself (Fig. 4a–c). In the middle of the thick band below the pommel, there is a large bubble in the centre of the hilt (Fig. 4a) and the tang is more corroded there as it is not enveloped by bronze. Corrosion at the interface between the bronze and iron is visible as a fine, bright line, indicative of the presence of hydrogen-rich products.

As the tang starts to widen into a blade (Fig. 4d), an amorphous hole



Fig. 3. Sword AR1.

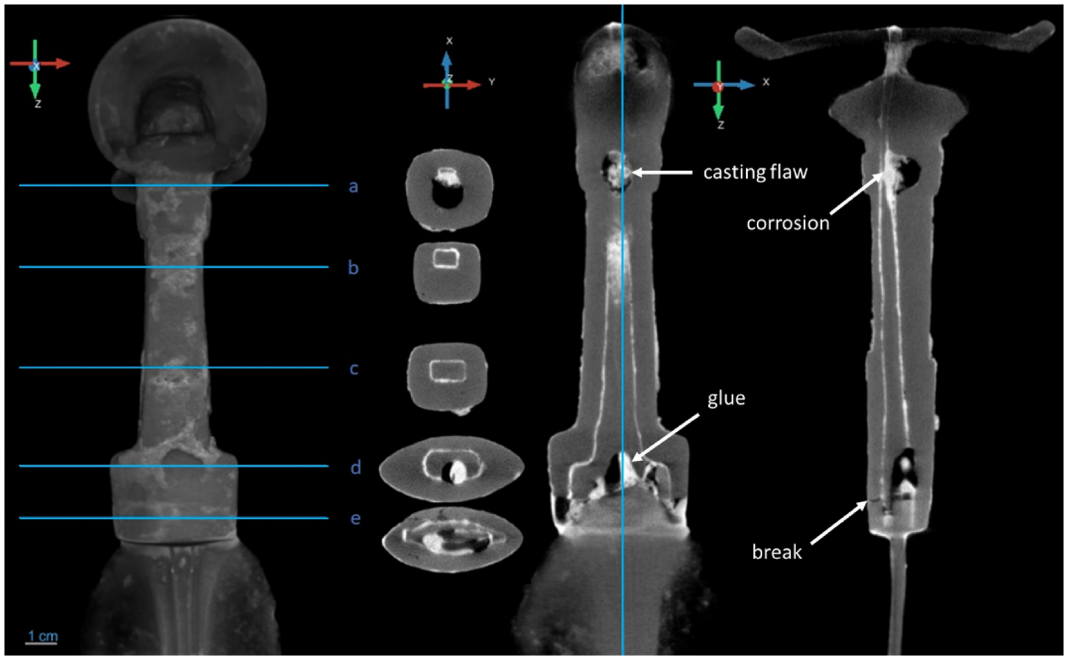


Fig. 4. Sword AR1 – NT slices through the hilt. Corroding iron tang of the original blade can be seen, and glue or resin used to attach a bronze blade.

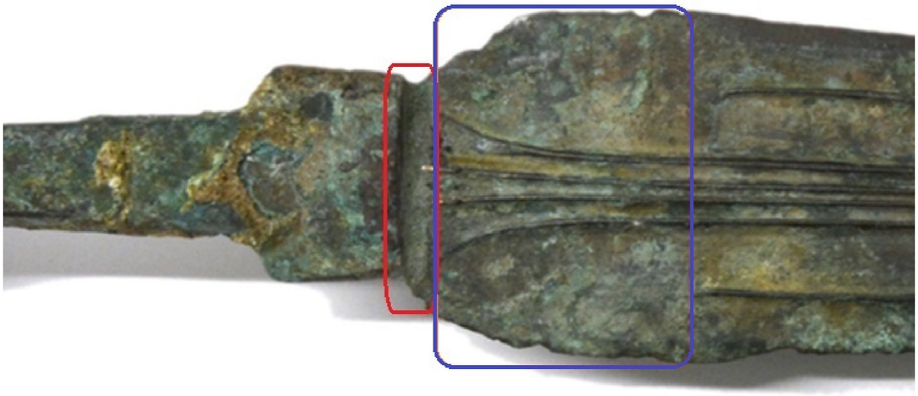


Fig. 5. Sword AR1 – close up on the different corrosion pattern around the shoulder of the blade (blue), missing forked guard and the gap between the blade and the guard (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

is present, as if the metal was melted as opposed to drilled into, which would create a uniform drill hole (compare with other swords in this study, Figs. 15 and 17). Thus created void does not exhibit a fine white line of corrosion, suggesting that it was formed recently, and not enough time has elapsed for the corrosion to appear. Compare that with the layer of corrosion on the remaining surfaces of the iron tang (Fig. 4a–e). The highly attenuating white substance in Fig. 4 d-e can be identified as hydrogen-rich glue, the only visible means of attaching a new bronze blade. Its amorphous appearance is consistent with being used in a liquid state. Finally, a crack in the guard of the sword can be seen (Fig. 4), which could be a result of recent manipulation when inserting a different blade, as there is no evidence of corrosion in the crack.

4.2. *Sword AR2*

As with AR1, the shape of the blade is unusual for this type of weapon and a corrosion pattern along the shoulder of the blade is inconsistent with a forked guard (Fig. 6). Moreover, the presence of iron was detected in the bronze hilt. The sword was x-rayed but beyond some damage on the side of the forked guard no detail could be seen inside. With neutron tomography it was possible to examine the internal structure of the object (Fig. 7). A thick iron tang was revealed, irregular in cross-section and rotated in respect to the hilt (Fig. 7b and c). It possesses some elongated voids, perhaps suggesting that the iron was not forged very well. Starting at the top of the pommel, it ends abruptly in the middle of



Fig. 6. Sword AR2.

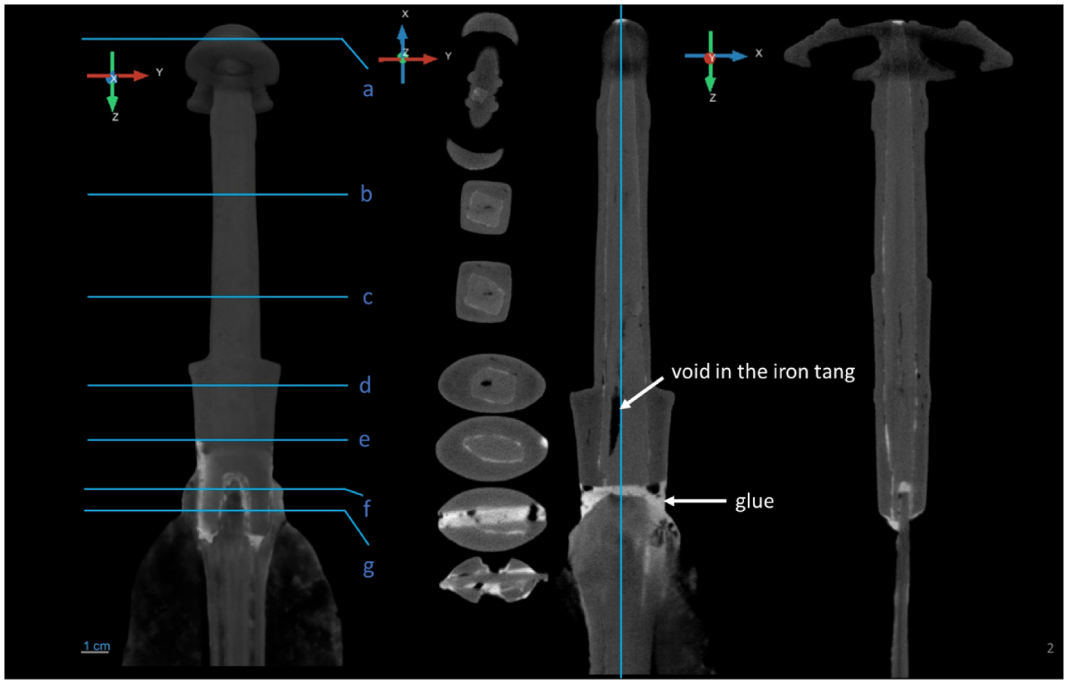


Fig. 7. Sword AR2 - NT slices through the hilt. Iron tang of the original blade can be seen, and glue or resin used to attach a bronze blade.

the guard. While the guard appears intact on the surface, it is truncated straight across its centre (Fig. 7f). Hydrogen-rich material fills the resulting void (Fig. 7f and g), and the bronze blade seems to be embedded in it similarly to AR1 (Fig. 4). It does not have a tang, which might have been removed to make the blade fit inside the hilt.

4.3. Sword AR3

Neutron tomography revealed the internal structure of the sword AR3 (Fig. 8). A narrow iron tang, rectangular in cross-section, is heavily corroded, particularly where voids are present in the bronze hilt (Fig. 9b and c). The tang starts at the raised ring below the pommel (Fig. 9a) and widens into a round-shouldered blade, where a very thin white layer of corrosion is also present (Fig. 9f). This blade was drilled into, based on the uniform circular cross-section of the hole (Fig. 9e and f), and further truncated in a straight line (Fig. 9h). The resulting void was filled with a hydrogen-rich material, into which the tang of replacement blade was inserted. The presence of many small bubbles in that matrix (Fig. 9h), suggests it is a glue used in a liquid state, which needed to fill the large gap between the shoulders of the new blade and the truncated original blade. The replacement blade has a long tang, approximately round in cross section (Fig. 9f and g), which appears to have broken at the rivet hole.

4.4. Sword AR4

Neutron tomography (Fig. 12) clarified that the lower attenuation was a result of the guard being truncated inside in a straight line across its width, while the forks on the surface appear undamaged, similarly to swords AR2 and AR3. A gap between the shoulder of the blade and the guard can be seen; the tang was inserted into a perfectly round hole in the hilt and attached with a hydrogen-rich substance, probably glue or other adhesive, identified by its high attenuation coefficient.

There is no evidence of an original blade or tang onto which the hilt was subsequently cast, it is therefore most likely that the hilt was cast together with a blade, and the sword was made entirely of bronze.

4.5. Sword AR5

The guard appears damaged, as if the fork present in some other examples was broken off (Fig. 13). Additionally, an iron rivet could be seen, which was unusual for this class of object. The sword was x-rayed, and it was revealed that the guard loses thickness just above the rivet, which suggested that it had been tampered with in a similar fashion to the examples discussed previously (Fig. 14).

Neutron tomography revealed the true extent of the modifications. A



Fig. 8. Sword AR3.

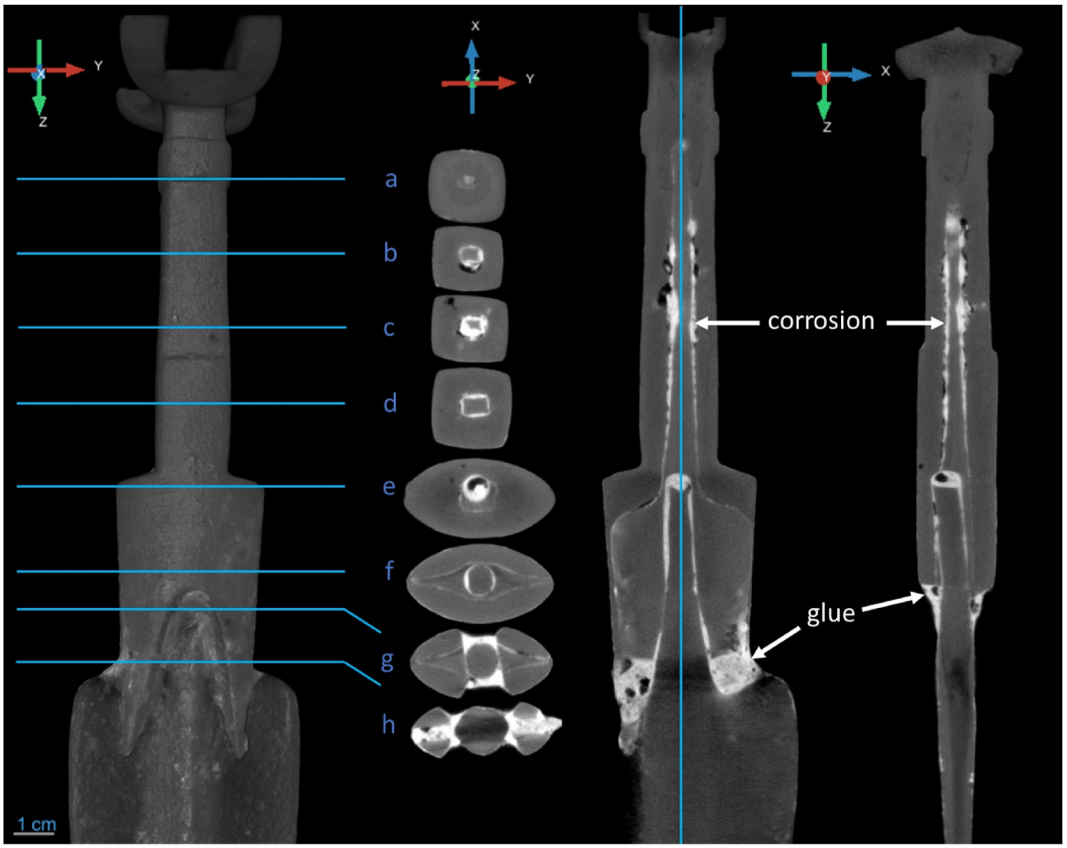


Fig. 9. Sword AR3 – NT slices through the hilt. Corroding iron tang of the original blade can be seen, and glue used to attach a bronze blade.



Fig. 10. Sword AR4 The sword (Fig. 10) possesses an unusual waisted blade. It was x-rayed and a suspicious line resulting from lower attenuation became visible across the forked guard (Fig. 11).

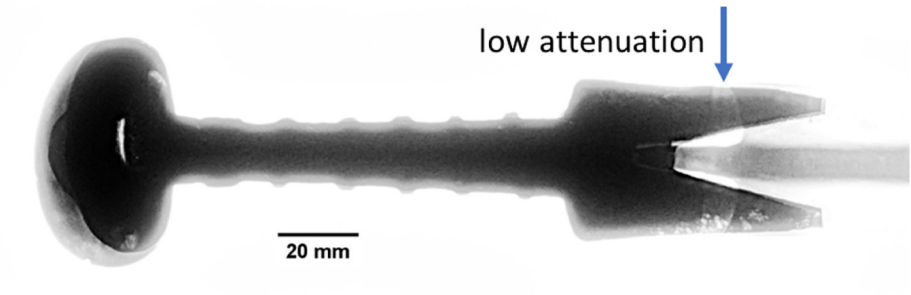


Fig. 11. X-ray radiograph of AR4 showing the suspicious lowering of attenuation in the guard. In radiography high attenuation is shown in black while low attenuation is shown in white, unlike tomography.

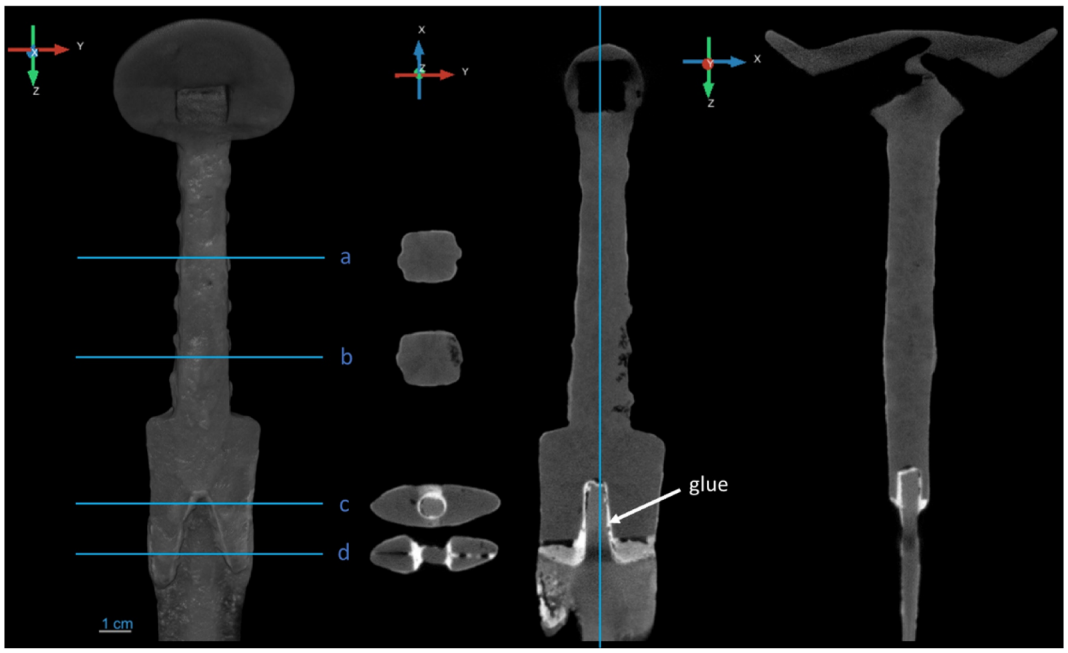


Fig. 12. Sword AR4 – Neutron tomography slices through the hilt. The bronze blade is attached with a hydrogen-based compound such as glue or resin.



Fig. 13. Sword AR5.

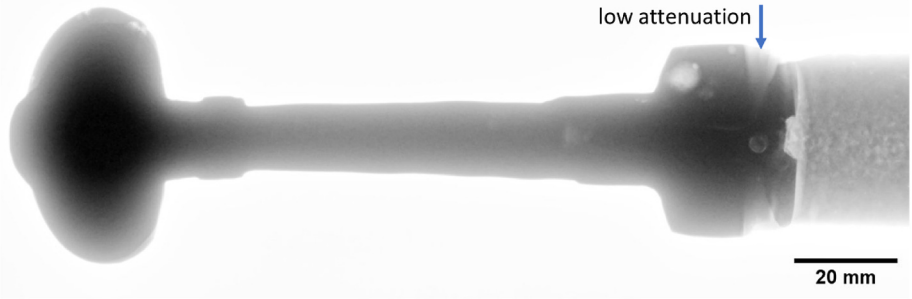


Fig. 14. X-ray radiograph of AR5 showing lower attenuation in the guard due to partial removal of original metal and a less dense material being used to attach the two parts.

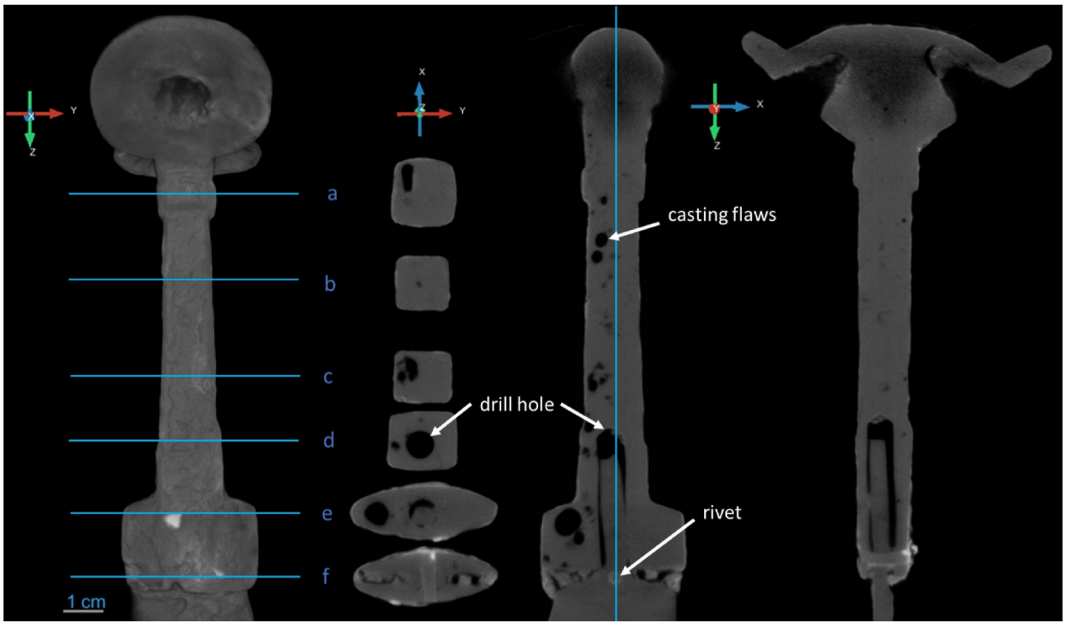


Fig. 15. Sword AR5 – Neutron tomography slices through the hilt showing casting flaws and modern modifications. The blade is inserted into a drill hole (d) and attached with a rivet (f).

drill hole reaching 43 mm into the hilt can be seen, 7 mm in diameter (Fig. 15d). The replacement blade was inserted and secured with a rivet only (Fig. 15f), as the drill hole appears empty otherwise, with no lead or hydrogen-rich filling material in the gap. Numerous casting flaws in the hilt are visible, and they seem to be responsible for the imperfect shape of the drill hole. The results suggest that the sword was made entirely of bronze.

4.6. Sword AR6

The brown marks below the forks of the hilt were suspected to be glue (Fig. 16). The sword was x-rayed revealing a gap between the tang of the blade and the forked guard. Moreover, there seemed to be a lower attenuation in the area around the tang and continuing up the hilt. Neutron tomography clarified that it was a large drill hole, clearly modern due to its perfectly uniform cross-section, and its crisp, obtuse-angled tip (Fig. 17b). The blade was inserted halfway through that hole and attached using hydrogen-rich glue, identified by its high attenuation. Similarly to previous examples, the forked guard, while appearing complete on the outside, was truncated straight across its width below the surface (Fig. 17e, which is not immediately obvious due to the many casting flaws in the bronze.

There is no evidence for another blade or tang inside, therefore it can be determined that the sword was originally cast together with a blade and was made entirely of bronze.

4.7. Sword AR8

The end of a corroded iron tang could be seen through the hole of the pommel, while the rest of the sword appeared to be made of a copper alloy. Additionally, when viewed longitudinally along the length of the blade, the blade is oriented in the same plane as the pommel (Fig. 18). All other known examples of split-ear pommel swords have blades



Fig. 16. Sword AR6.

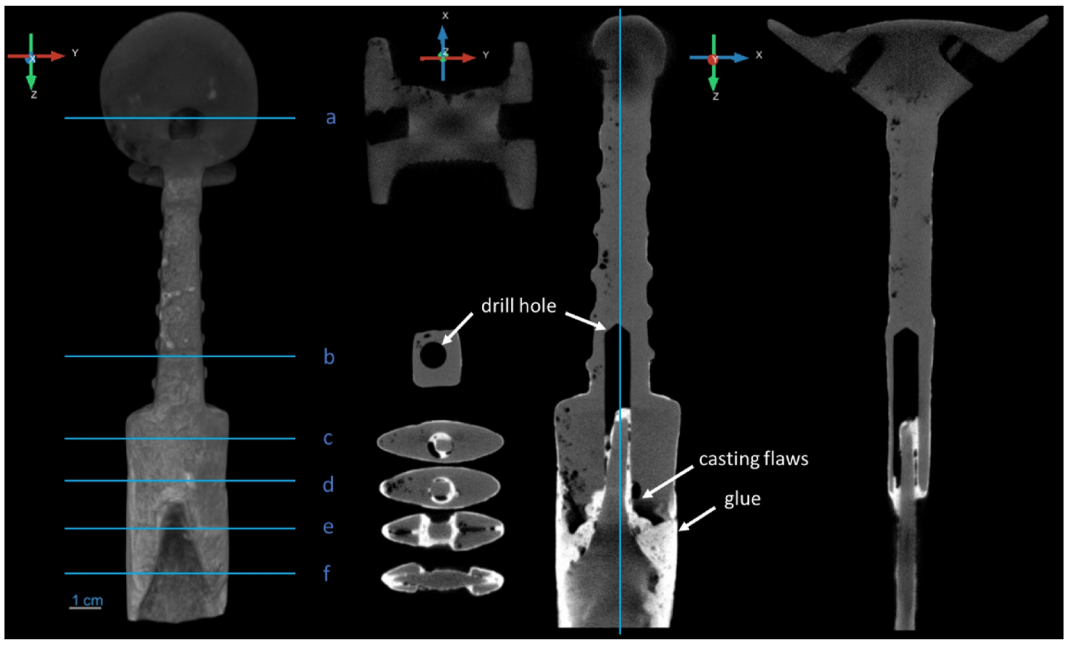


Fig. 17. Sword AR6 – Neutron tomography slices through the hilt. The blade is attached with a hydrogen-based glue (c–f) and inserted into a large drill hole (b).



Fig. 18. Sword AR8.

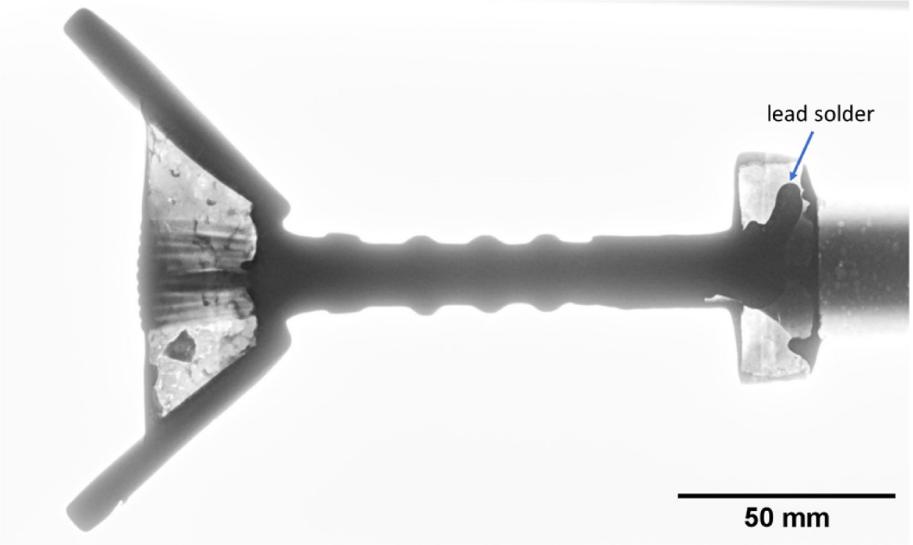


Fig. 19. X-ray radiograph of AR8 showing a highly attenuating material (lead) used as solder in the hollow guard.

orthogonal to the pommel. The sword was x-rayed which revealed that the guard was hollow, unlike the rest of the hilt, and that solder is present inside, based on the liquid appearance and its high attenuation (Fig. 19, black on a radiograph and marked with a blue arrow).

Neutron tomography confirmed that the sword was heavily modified (Fig. 20). An iron tang of the original blade can be seen inside the bronze hilt but as it starts to widen into a blade the hilt abruptly ends, and a wedge is cut into the iron blade (Fig. 20 in a red circle). Similarly to the guard, the lower part of the hilt is hollow as well (Fig. 20e and f). Bronze blade is soldered in the centre, with its tang slotted into the original iron blade at a 90-degree angle. The solder can be identified through its low attenuation coefficient, which results in a very dark grey colour in the image, coloured in green in the 3D rendering in Fig. 20 for clarity. As there is no evidence of hydrogen-rich corrosion products on the surface of the sword, the area of high attenuation on the join between the two parts of the hilt (Fig. 20 in red circle) most likely corresponds to paint or

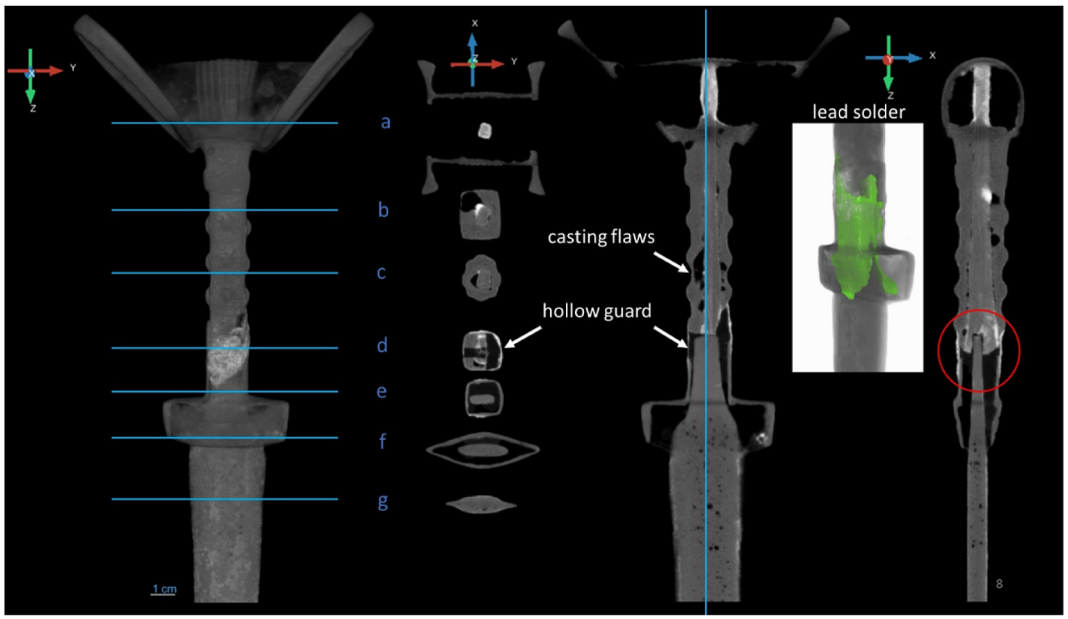


Fig. 20. Sword AR8 – Neutron tomography slices through the hilt and a 3D rendering of the hilt and guard with lead solder coloured in green. The iron hilt of the original blade can be seen, and a bronze blade inserted at a 90-degree angle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

putty used to cover up the joint. The tang of the replacement blade appears to have been cut straight across to fit inside the hilt.

The difference between the attenuation levels of the exposed end of the iron tang seen through the pommel (Fig. 20a) and its part embedded in bronze (Fig. 20b and c) is due to the hydrogen-rich corrosion products where the iron was not protected from oxygen.

4.8. Sword AR9

As with previous examples, initial macroscopic examination provided some indications of modern modification (Fig. 21). The end of a corroded iron tang could be seen through the hole of the pommel. The sword was first x-rayed which revealed that the blade did not continue into the hilt and was attached in a way which rendered the weapon non-functional (Fig. 22). It appeared to have been attached with pins and the blade was cut into a fork shape, with what might have been the remnants of the original blade slotted in-between.

Neutron tomography revealed the full extent of the modifications (Fig. 23), with one of the pins identified as a modern drill bit, ca. 2.3 mm in diameter (Fig. 23). The twist of the drill bit is readily apparent in transverse and radial sections. The original tanged iron blade can be seen inside the hilt, matching in shape the forked guard. It appears to have been cut to fit in the other blade, and the gaps between were filled with a hydrogen-containing material, most likely glue, or synthetic putty, owing to the high attenuation registered in the image (Fig. 23e–h). The iron tang of the original blade is circular in cross-section in the top part of the hilt (Fig. 23e) and rectangular closer to the blade (Fig. 23c).



Fig. 21. Sword AR9.

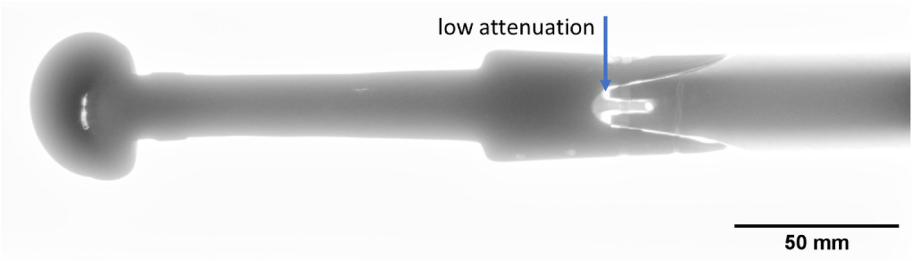


Fig. 22. Sword AR9 - X-ray radiography with darker areas corresponding to higher attenuation. The hilt shows extensive modifications.

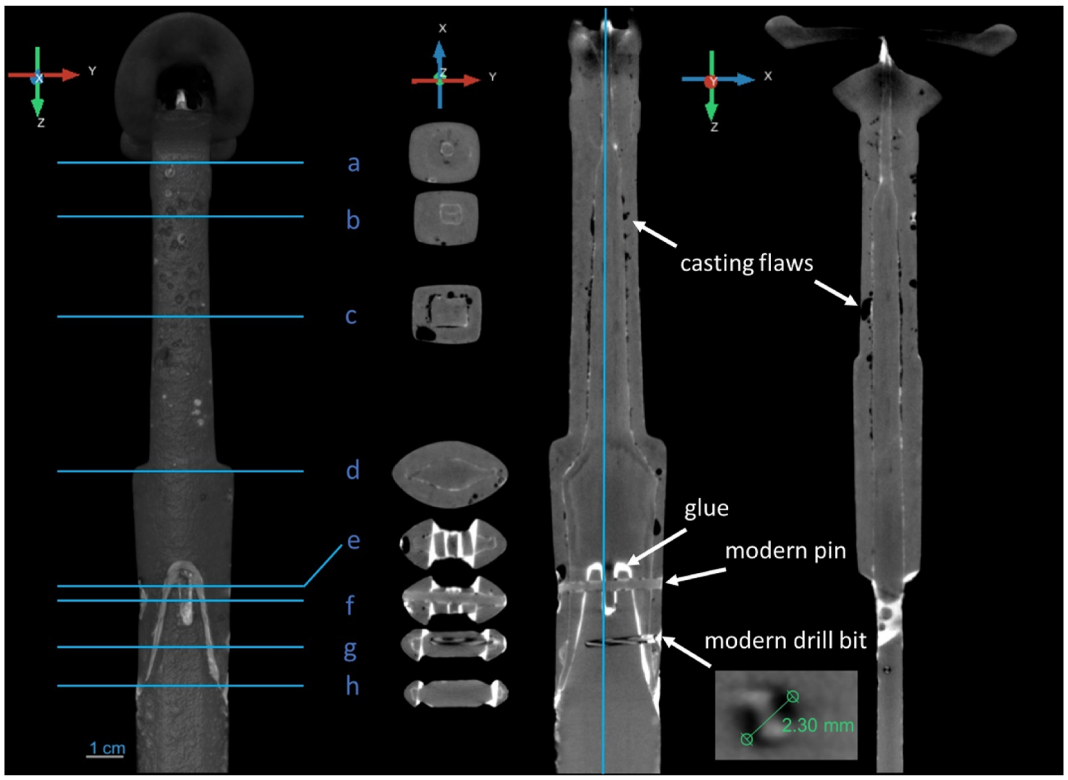


Fig. 23. Sword AR9 – Neutron tomography slices through the hilt. The original iron hilt and blade can be seen, and a bronze blade attached with a pin (f), a modern drill bit (g), and glue (e–h).

5. Discussion

Macroscopic observation, neutron tomography, and X-ray radiography revealed widespread blade replacement and other modifications to these objects. While bladed weapons were no doubt repaired in antiquity, numerous features indicate that the modifications identified in this assemblage are modern attempts to increase the marketability of these objects. Bimetallic weapons are especially vulnerable to modern modifications, as iron blades are likely to heavily corrode and be replaced with bronze counterparts to render the object complete and increase its value on the antiquities market.

The combination of macroscopic observation and neutron tomography allows us to define a kind of *chaîne opératoire* of modern tampering. The first observable feature in these swords is the almost complete lack of stylistic consistency. Split-ear pommel swords are characterised by long narrow blades which harmonise well with narrow forked guards and the only diagonal line is that of the split-ear pommel. Swords discussed here, however, except for AR8 and AR9, possess blades vastly different. In the case of AR1 and AR2 it appears the blades were chosen based on their attractive appearance achieved with midrib decoration. Resulting pastiches appear unbalanced as the blade is too wide for the narrow hilt it was attached to. It is also possible that the blades used for modification were the only ones available, either looted or purchased, and there was no conscious choice to be made. Some of the blades used for replacement may have originally belonged to swords with wooden hilts, whose decomposition would render them available. It is impossible to know if some of the blades originally had rivet holes as the blades themselves were modified to fit the swords – one tang appears to have been shortened (AR8), another seems to be broken at the rivet hole (AR3) which is common as it is the most delicate part of the blade. Blade of AR9 was cut into a fork shape to insert it within the original iron blade remaining in the hilt. Blades of AR1 and AR2 do not have tangs, which suggest that they were either removed, broken off or never existed in the first place. If they originally belonged to swords with large grips cast onto them, a tang could be obsolete, as these types of grips were intended as means of securing the blade firmly in place. The most likely explanation seems to be that the tangs were removed to make the blades fit better inside the hilt, as the replacement blades of AR1 and AR2 do not at all match the hilt shape they were forced into. The one commonality in all swords in this study with a forked guard, the fact that the inner part of the fork was cut out to facilitate the insertion of the new blade, seems to corroborate that.

All previously published Iranian pastiches mentioned above used solder to attach new blades to hilts (Nojima et al., 2016; Shizuma et al., 2017; Simpson and La Niece, 2010; Wever, 1969). In this study, only one sword (AR8) was modified in this way. Since most of these earlier analyses relied on X-ray radiography, which is not sensitive to light elements, it would be impossible to detect the presence of glue with this technique only. Given the dates of acquisition, the earlier analysed examples were modified in the 1970s at the latest, while the pastiches in this study were seized on recent entry to the UK. Hence, it is plausible that the swords in the present study were modified recently, and so we are seeing a new generation of pastiches with a different *chaîne opératoire* of illicit modification where glue, rather than solder, was used. Whether this is indeed a chronological shift, or simply an indication of inter-group variation between contemporaneous forgery traditions, remains to be seen.

Modifications to the swords were extensive, and often carried out with modern materials, clearly distinguishing them from ancient repairs. While it is understandable that the bimetallic weapons (i.e. with heavily corroded iron blades) would be modified if the goal were to sell them for a higher price as complete objects, it is not immediately obvious why the blades of bronze swords (AR4, AR5 and AR6) would be replaced. Since it appears that they were cast as one with the hilt there is no possibility of them having fallen off or being detached from the hilt. It also seems inconceivable that a complete weapon would be modified in such an invasive way. Therefore, it might be assumed that the original bronze blades of the swords in this study were damaged or broken,

perhaps during excavation or as part of the depositional process.

It is difficult to determine how the modifications were executed in the case of sword AR1. It is apparent that the metal was melted in some way, possibly by heat or by chemical means. It could be beneficial to sample and analyse the glue used, although this would necessitate further damage to the sword. AR9 is one of the examples modified most heavily. As one pin was used and it had penetrated the entire width of the hilt, while the drill had not, it seems likely that it was not the intention of the person who made this modification to use the drill as a pin but rather the drill broke and was left in place. This suggests a considerable lack of skill on the part of the forger. Finally, it appears that the reason why the hilt truncation of AR8 is uneven is the large voids in the metal which were not anticipated by the modifier. For this reason, the hollow part of the hilt does not perfectly match the shape of the original hilt.

6. Conclusions

Extensive modern modifications of the swords presented in this study obscure the fact that several of them are bimetallic. It is likely that the relative proportion of bimetallic swords from Iran is underrepresented - in this study alone, five swords which appeared to have bronze blades were revealed to originally have had iron blades. This discovery has significant consequences for efforts to track both the spread of iron in absolute terms, but also for understanding how metalworkers adapted bronzeworking techniques to the new metal (see early work on the latter in Maxwell-Hyslop and Hodges, 1966). Iran is a crucial region for understanding the movement of iron technologies eastward from the Near East, where there have been recent advances in the study of early iron (see— Erb-Satullo, 2019 and references therein), and Central Asia, where patterns of iron innovation remain quite unclear.

Of particular importance is establishing if there are more examples of bimetallic weapons which had been modified, hiding the degree to which the technological practice of combining bronze and iron was a routine feature of early Iron Age metalworking. Our investigations show that, unless they came from controlled excavations, the possibility of illicit modifications cannot be excluded. Indeed, given the rates of modification indicated in this study and others, the probability of modification seems high. Recognising these pastiches calls into question the authenticity of Iranian swords purchased by museums or donated to them, as many have never undergone scientific analyses. Numerous objects displayed in Iranian museums have been confiscated from looters (Khorasani, 2006) and as such should also be treated with caution, even though they did not leave their country of origin. While this study focuses on one major type of Iranian Iron Age sword, there are other known examples of modified types, such as cotton-reel pommel swords (Kontani and Tanaka, 2002; Simpson and La Niece, 2010), and the extent to which others might have been modified is unknown.

Finally, the analyses provide further evidence that the presence of iron in the hilts of Iranian bronze swords is not a technological feature of bronze swords, but rather remains of a tang from the original iron blade removed during tampering. Indeed, with our expanded assemblage of analysed objects and a synthesis of prior research, we are now in a position to exclude this possibility conclusively. There is no evidence suggesting otherwise, and any bronze-bladed sword with iron in the hilt should be treated with extreme caution, as it is likely a pastiche. These discoveries would not have been possible without the application of neutron tomography which allowed, for the first time, to discover hydrogen-rich glue used in modern modifications of Iranian weaponry, without further compromising the integrity of the objects. The remnants of the original iron blades can now be investigated with other techniques, such as neutron diffraction, which can estimate the carbon content of the surviving tangs, intervening in wider debates about carburisation, steel, and the driving factors of iron innovation.

Declaration of competing interest

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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