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An African Art Re-Discovered: New Revelations on Sword Manufacture in Dahomey

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Abstract: Antique swords from the pre-colonial West African kingdom of Dahomey are aesthetically unique, but they also have many design features inspired by swords from Europe, the Islamic world and elsewhere. As the kingdom was famous for importing luxury European objects, this study aimed to pinpoint evidence of Dahomean sword composition and manufacture to determine scientifically whether they were being made in Dahomey, or imported. An inter-disciplinary team made up of historical archaeologists and neutron scientists examined six 19th century Dahomean swords, using a non-invasive multi-methodological approach based on neutron tomography, powder diffraction full pattern analysis and diffraction residual stress measurements. The findings suggest that, despite their foreign design influences, not only were these striking heritage objects made in Africa, they may also have been likely made from locally smelted iron–something that contradicts the assumptions of the few existing historical reports. This has important implications for studies on the kingdom, and also helps to further the long-standing debate surrounding European iron imports—not just within Dahomey, but throughout the wider West African region.

Keywords: Dahomey; non-invasive analysis; neutron diffraction; neutron imaging; archaeometallurgy; African swords; African archaeology; African metallurgy; voyage iron

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1. Introduction

The Kingdom of Dahomey, now part of the Republic of Benin, was a unique centralized state on the Bight of Benin in West Africa, composed of people who identified ethnically as Fon, and occupying part of a coastal region that came to be called the Slave Coast (Figure 1). Spanning almost three centuries, from the early 17th to the late 19th centuries, Dahomey was among the most effective military powers in the region for most of that duration, and arguably the largest slave trading nation in West Africa. It was especially renowned for its unique female fighting force, coined the Dahomean 'Amazons' by contemporary Europeans—an exceptional corps of women soldiers and palace guards at the direct command of the king. Notably too, Dahomey's royal arts were unlike any other regional artistic tradition, incorporating the cultures of other conquered African peoples, as well as European and Islamic cultures, encountered through Dahomey's long-standing affiliation with foreign slave traders [1].

It is well known that many European weapons, including guns and cannons, were routinely imported into the kingdom, from its very early history in the 1600s right up until its fall to the French in the 1890s [2,3]. However, it is far more uncertain whether the unique swords of the kingdom were being made locally, or being custom-ordered through foreign cutlers. Both possibilities have intriguing implications for the history of the kingdom. Though distinctively Dahomean in their designs, these unique swords also have very obvious foreign influences, seen across the full range of antique Dahomean edged weapons that survive today, whether the military cutlasses used in slave raids, the wide variety of execution swords and daggers used in the kingdom's human sacrifices, the knives and choppers used in Vodun religious sacrifice, or the elaborate ceremonial swords that form part of the kingdom's royal regalia [4]. To help answer this question, this study aims to use neutron techniques to examine non-destructively the manufacture of a select group of Dahomean edged weapons, all dating from about the mid-to-late 19th century.

Figure 1. Dating from the early 17th to the late 19th century, the kingdom of Dahomey was situated on the coast of West Africa, on a stretch of coastline known as the Bight of Benin. Map provided by James Flexner of the University of Sydney.

2. Sample Materials

Based on a provenance preceding UNESCO's 1972 Convention concerning the Protection of World Natural and Cultural Heritage, six Dahomean swords were selected for this research (Figure 2, swords 1 to 6). These objects were collected privately from owners in France, Dahomey's colonial overseer from 1894 until its independence in 1960. Most of these swords had resided for decades in one old collection in Orleans. All had morphological characteristics that identified them as Dahomean, based on the few existing studies of Dahomean swords and related Dahomean objects [4–6]. Europe's cultural and material influence on Dahomey was particularly evident in the design of Dahomean edged weapons [4]. Typically, some of the six samples studied here show pronounced European influences, resembling the cutlasses used by the European sailors that Dahomeans encountered from the time of the kingdom's emergence as a major regional power. A *couteau de chasse*, a sword type used as both a maritime cutlass and a hunting sword in Europe, exemplified here by sword 7, has been included in the study for comparative purposes. This sword type inspired many of the features in swords 1, 2 and 3—from the style of guard, to the riveted hilt and even the clip-point blade [4,6].

Figure 2. Swords 1 to 6 have been identified as 19th century Dahomean swords and sword 7 is a European cutlass or *couteau de chasse* dated to the second half of the 18th century.

Others among them show other foreign influences, from places as unexpected as the Indian subcontinent. In particular, sword 5, a sword with provenance to Captain Tassard, a French officer serving in 19th century French West Africa, bears a strong resemblance to some variations of a sacrificial sword type from the Himalayas called a *râm d'ao*, documented by Lord Edgerton of Tatton in 1880 [7].

Research on private collections is unorthodox but, given the rarity of these swords, so far there has been little progress made in studying these weapons through the relatively sparse public collections found in France, even using conventional research tools. The ability to conduct research using neutron instruments not available in their country of origin provided a truly unique opportunity for significant research breakthroughs. As this paper will show, these data are now answering a number of important historical questions that have consistently eluded scholars till now. What's more, with the research complete, efforts are now underway to negotiate a repatriation to the Republic of Benin, where it is hoped these objects will be welcomed into local museums. Those efforts include direct discussions with the Deputy Director of the Institute of Crafts, Archaeology and Culture in Benin. These objects do not fall into the conventional category of a private collection, for their status as privately owned objects is only temporary and any added value or provenance created through this research is intended to benefit Benin and its people once ownership is transferred.

The Dahomean origin of these swords has been established through their features, listed more comprehensively in Table 1. In brief, swords 1, 2 and 3 share the same hilt configuration, identified as an abstract zoomorphic hilt common to many Dahomean swords in Anderson's typology [4]. All three also share distinctive Dahomean blade features—a stepped blade and imitation clip point [4,6]. All three have complex cup guard hilts identifiable as Dahomean [4]. All three have blade etchings typical of extant examples in the Musée du Quai Branly Jacques Chirac in Paris, as well as scepters in the same collection. Many of these have provenance to the Franco–Dahomean wars of 1890–1894 [4–6]. Likewise, sword 4 shares etchings identified on Dahomean scepters [5] and on other Dahomean edged weapons from the same period [4,6]. It also has the rounded pommel and cap identified with many Dahomean edged weapons, and the iron collar typical of most Dahomean swords [4].

Table 1. List of samples and characteristics, based on Anderson's typology [4].

	Type	*Estimated Age*	*Features*
1	Dahomean cutlass based on a European *couteau de chasse*	19th century	Double step, imitation clip point, abstract zoomorphic hilt, complex cup guard, hilt appliques, Dahomean blade etchings
2	Dahomean cutlass based on a European *couteau de chasse*	19th century	Double step, imitation clip point, abstract zoomorphic hilt, complex cup guard, hilt appliques, Dahomean blade etchings
3	Dahomean cutlass based on a European *couteau de chasse*	19th century	Contoured ricasso, additional yelman, filigree elements, abstract zoomorphic hilt, complex cup guard, Dahomean blade etching.
4	Chopper	19th century	Rounded pommel and pommel cap, iron collar, typical grip, Dahomean blade etching.
5	Sacrificial sword	19th century	Rounded pommel, billhook-shaped point, concave cutting edge, cross and zig zag decoration.
6	Figural sword	19th or early 20th century	Double vestigial stepped blade, figural blade, figural hilt, brass collar, brass cross guard.
7	European hunting sword or couteau de chasse	18th century (1750–1780)	Brass cup guard, deer horn hilt, hilt appliques, standard clip point, European blade decoration.

Sword 5 is identifiable as Dahomean as it has direct provenance to a Captain Tassard, who served in the French military in Dahomey, and died at the Battle of Timbuktu in 1894. This sword was brought to France in 1890 before his final return to Africa and purchased at his estate auction in 2007 [8]. Moreover, a virtually identical blade is illustrated on a 19th century journal detailing the French military invasion of Dahomey [9]. Sword 6 shares many attributes found in other late 19th century Dahomean swords, or early 20th century Fon swords, including a blade feature categorized as a 'double vestigial stepped blade' in Anderson's typology [4]. The figural shape at the blade extremity is a common artistic feature of ceremonial edged weapons from Dahomey, though figural blades such as this are very rarely found in swords anywhere else [4]. Sword 7, the European sword, has features and engravings identifiable with a European *couteau de chasse* dating from 1750–1780 [10].

3. Method

Nowadays, neutron tomography, powder diffraction full pattern analysis and residual stress measurement are well-established tools for scientific analysis, especially on heritage objects, where non-destructive approaches are essential. Neutron beams have a high penetration power that is ideal for surveying most cultural heritage specimens in a non-invasive way. The neutron, a heavy uncharged particle that interacts primarily with the atomic nuclei, has peculiar interaction mechanisms that enable it to probe most materials below the surface, sometimes to a depth of even tens of centimeters [11].

In particular, neutron imaging methods (radiography and tomography) provide a real-space representation of an object or phenomenon. The spatial distribution of matter inside an object can be reconstructed by recording the variation in intensity of the transmitted neutron beam that decreases exponentially along the path length through the sample, depending on the material elemental composition and density [12].

In neutron diffraction analyses, neutrons coherently and elastically scattered by the samples are detected in counters to measure their energy and angular distribution. Since neutron diffraction takes measurements from the bulk rather than from the surface, the data are statistically more representative compared with its X-ray equivalent technique. Neutron diffraction can provide qualitative and quantitative data about phase composition; crystal and magnetic structures of each constituent phase; (residual) micro strains and macro strains; and crystallographic texture [13].

In archaeometric studies, neutron imaging and diffraction methods are able to read the imprint left at different levels of the crystalline structure by distinctive manufacturing processes or by other actions that occurred during the life cycle of an item, i.e., mechanical and thermal impact, recycling and modern intervention [14–17].

When it comes to investigating antique edged weapons, neutron tomography is mostly used to characterize bulk structural and morphological features (i.e., the amount, distribution and shape of defects, porosity and non-metallic inclusions). Neutron powder diffraction full pattern analysis enables non-invasive quantification of the metal and non-metal phases that compose the samples as they relate to the smelting and smithing procedures. Finally, neutron diffraction stress measurement determines residual stress as an imprint of the manufacturing process.

In this study, the samples were characterized using three neutron beam instruments at ANSTO: the radiography and tomography instrument DINGO [18]; the high resolution powder diffractometer WOMBAT [19]; and the residual stress and texture diffractometer KOWARI [20]. As the beamtime on these instruments is in high demand, analysis was conducted on the sword blades alone, as this is where the most useful data could be extracted.

On DINGO, the high spatial resolution configuration was used, corresponding to a pixel size of ~40 μm (with the ratio of collimator–detector length L to inlet collimator diameter D equal to 1000). The tomographic scan consisted of 1800 angular projections, covering a range of 180°, and of 3 accumulations with an exposure time of 5 s acquired at each step angle. This was done to improve the image quality since the sum of short time radiographs produces higher signal-to-noise ratio (SNR), when added together, than the equivalent longer exposure. The portion of the beam transmitted through the sample was converted into visible light using a 100 μm thick ^{6}LiF/ZnS scintillator, which was then guided via a mirror to a Neo 5.5 sCMOS ANDOR camera—2560 × 2160 (5.5 Megapixel), 16-bit. The size of the field of view (about 80 × 80 mm^2) permitted only a portion of the sample to be studied at one time. By acquiring multiple frames, vertically displaced to the blade body, it was possible to investigate most of the sample volume. The projections were first treated by applying an outlier removal filter. Then, the accumulations were summed up for each step angle. Flat field normalization with dose correction and dark current subtraction was applied. The data were processed using the Octopus code for tomographic reconstruction [21], and the obtained slices were recomposed and evaluated using the Avizo 9.1 software.

To enhance the grayscale image quality, anisotropic diffusion (AD) and unsharp mask (UM) [22] filters were used. The AD filter merges regions of similar grayscale values and intra-region smoothing is promoted over edge smoothing. The blurring caused by the application of the AD filter was reduced by UM filter. The dataset was subsequently segmented by applying a watershed transform for sample masking. Separation of the strong pores was achieved by threshold segmentation while top-hat transform with a spherical probe of 5 px, and a threshold of 5500 was applied for weak pores.

The neutron diffraction–full pattern analysis was performed at 1.54 Å at the high-intensity diffractometer WOMBAT with a d-spacing range of 1.1–3.4 Å (or 26°–90° in the angular range) and peak resolution Δd/d~0.5% (or ~0.6° in angular scale) sufficient to resolve the phases of interest. An accumulation time of 1 h per pattern with 5 × 20 mm slit aperture was adequate to obtain high statistics on the overall bulk composition. During the measurement time, the blades were continuously spun to achieve better averaging and to eliminate experimentally some effects related to the specific sample geometry, texture and anisotropic absorption. The diffraction patterns were processed using the GSAS II code [23] in order to perform Rietveld refinement of the diffraction patterns.

Additionally, some effort was made to evaluate the spatial distribution of the secondary phases within the blades, across the width of the blades. For this purpose, the aperture was reduced to 1 × 20 mm size, and measurements were made at multiple locations across a blade in 2 mm steps with the blade static. A similar full pattern analysis was performed on the experimental datasets to extract the relative variation of the volume fraction of the secondary phase.

The neutron diffraction–residual stress analysis was conducted with a strategy already developed in similar forensic analyses on Samurai swords [24] and Cypriot knives [25]. In fact, investigating old blades presents two major challenges, technically and theoretically.

From a technical perspective, a high spatial resolution is required, ~0.3 mm, to detect material and treatment variations across a typical thickness of about 3 mm. This issue was overcome by conducting the measurement on the instrument KOWARI, ANSTO's neutron residual stress diffractometer, capable of sub-millimeter spatial resolution.

Although a full 2D mapping would be very desirable to spatially identified subtle variations in the blade cross-section, a compromise between resolution, number of measurement points and experimental time per point needs to be found. Therefore, only a limited number of one-dimensional scans were performed. However, the displacement and number of the measurement points (Figure 3) were selected in a way that would allow the distinction of relevant features in the blade.

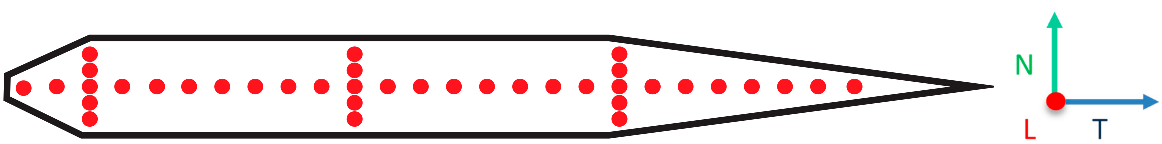

Figure 3. Example of two-dimensional mesh for the stress measurement experiment on KOWARI.

The strain measurement was carried out along three orthogonal directions (longitudinal, transverse and normal), with each acquisition point spaced by 0.3 mm in thickness and by 1.0 mm along the central line. A nominal gauge volume of 0.3 × 0.3 × 0.3 mm^3 was used for measurements of the longitudinal strain component. The extension of the gauge volume to 10 mm^3 along the longitudinal direction was allowed by the blade geometry in order to measure the normal and transverse components. Strain measurement was performed at a wavelength of 1.67 Å, which provides Fe(211) reflection at $2\theta = 90^\circ$. For the normal and transverse components, a typical accuracy of ± 30 µstrain was achieved after an acquisition time of 4 min. Instead, for the longitudinal strain component, a typical accuracy was ± 50 µstrain with a measurement time of 20 min. Overall, each blade was scanned in approximately 1.5 days of beamtime.

The additional challenge, from the theoretical point of view, resides in the fact that the experimentally measured peak shift is the combined effect of variations in (macro-stress free) d_0 and elastic macro-stress, both expected to be present in results relating to the manufacturing process. The de-convolution of these two contributions is essential for the aim of the experiment. While d_0 is determined a priori through destructive methods in traditional experiments, only non-invasive procedures can be applied when investigating cultural heritage artifacts. Therefore, some assumptions about the state of strain or stress within the body need to be enforced. In the current measurement, the zero-through-thickness-stress condition was applied. This strategy enabled the calculation of two stress components and one d_0-value out of the d-spacings for three measured directions. This plane-stress condition should be fulfilled with good accuracy (within our experimental errors) because of the sample planar geometry. The major uncertainty of this approach consists in the anisotropic behavior of d_0. However, if the above-mentioned assumption is accurate enough, and stress and d_0 are resolved correctly, then the transverse stress component should satisfy with boundary conditions on the top and bottom edges of the blades, and the longitudinal integral stress balance condition can be (at least approximately) evaluated.

4. Results: Neutron Tomography

In the attempt to pinpoint peculiarities indicative of different manufacturing processes, either European or Indigenous, the neutron-computed tomographic reconstructions enabled the investigation of the salient structural characteristics of the bulk of the blades (Figure 4).

There are measurable differences in porosity between the swords. Though subtle, ranging from 0.010 to 0.512 vol.%, these are suggestive of differences in construction. Porosity is an umbrella term covering micro- and meso-pore agglomerates and large macro-voids. The reasons for the formation of these pores can sometimes be deduced from their morphology. Casting voids, for example, are often the result of gas formation or solidification shrinkage while the metal is still in a liquid form. They can be eliminated or significantly reduced through hammering and annealing. The geometry, size, orientation, location and type of connectivity of the pores are related to the metal's manufacturing process. Based on a reconstructed three-dimensional model obtained through the tomographic analysis, porosities were extracted from the metal bulk virtually, their spatial distribution was visualized (Figure 5), and their amounts were quantified as a volume percentage for each blade (Table 2). Where appropriate, the shape of the pores was also evaluated in terms of (i) their three-dimensional volume; (ii) a Feret shape 3D, defined as D/d, where d is the minimum Feret diameter (a one-dimensional measurement that estimates how "wide" an object is in a given direction) and D is the maximum Feret diameter in the orthogonal direction; (iii) the length 3D, the maximum of the Feret diameters; and (iv) the width 3D, the minimum of the Feret diameters (Table 3) (Figure 6).

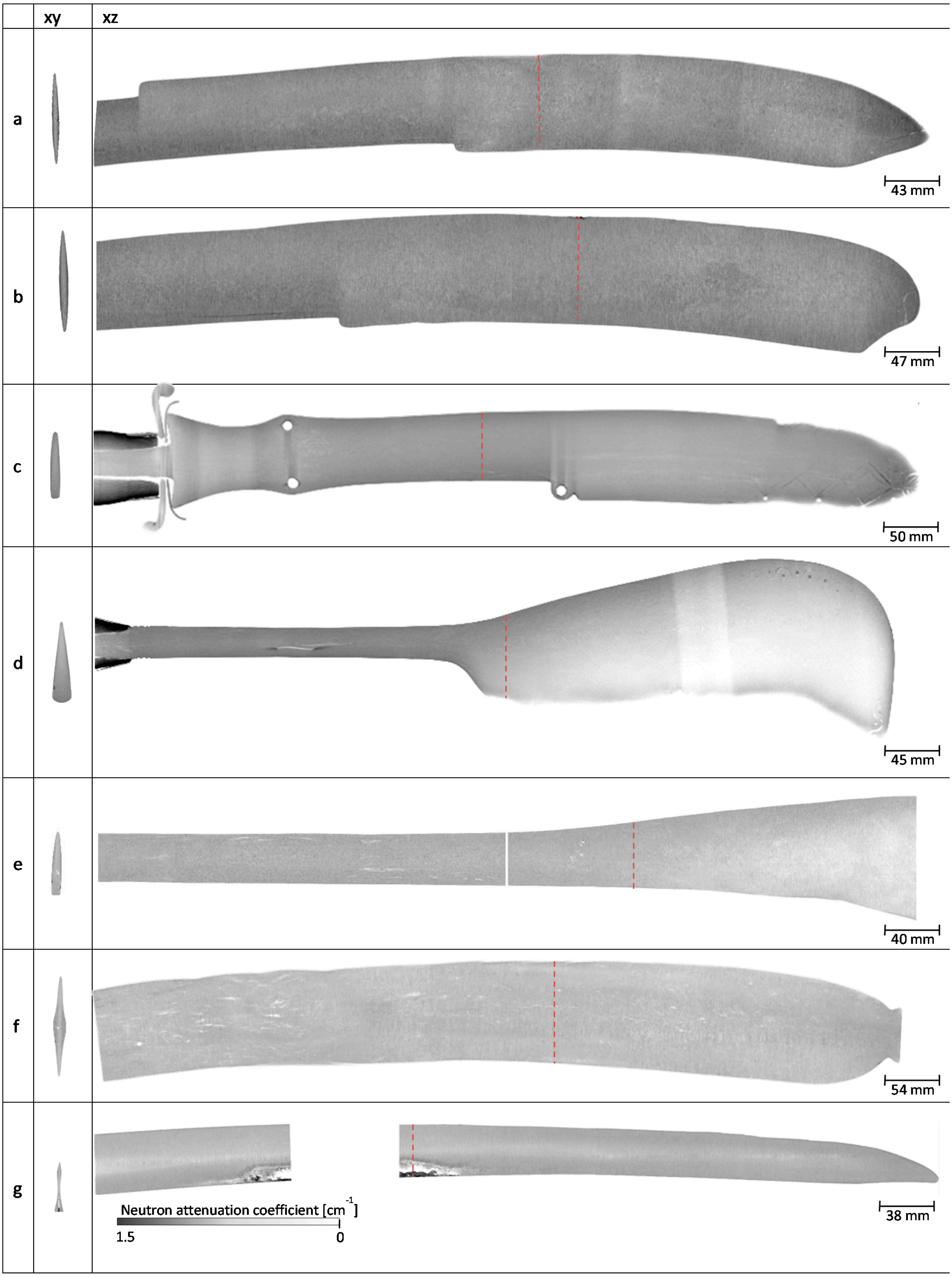

Figure 4. Normal (xy) and longitudinal (xz) tomographic reconstructed cross-sections of (**a**) sword 1, (**b**) sword 2, (**c**) sword 3, (**d**) sword 4, (**e**) sword 5, (**f**) sword 6, (**g**) sword 7. The dotted red line indicates the location of the xy section along the blade. A scale bar indicates the correspondence between gray tone and neutron attenuation coefficient.

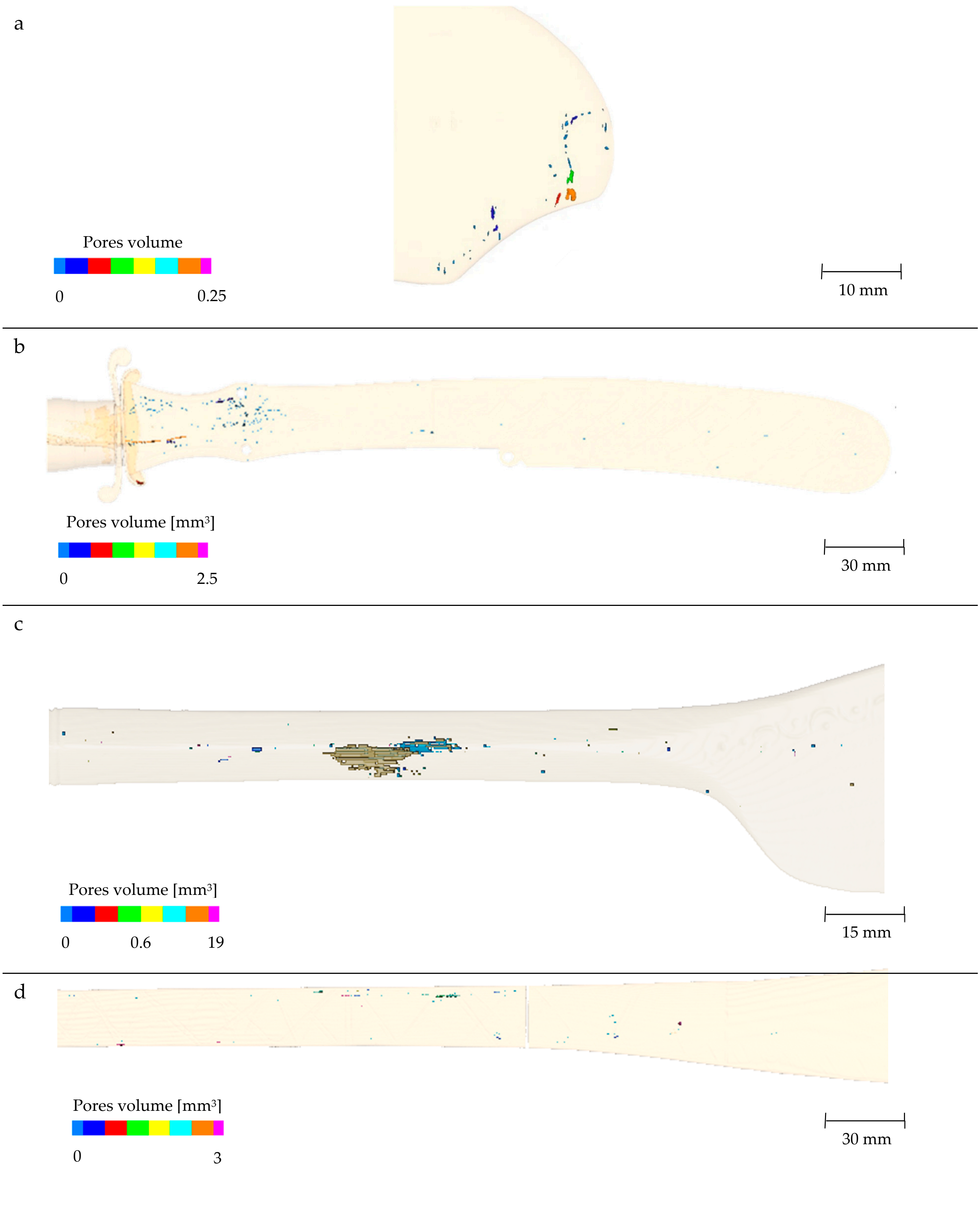

Figure 5. *Cont.*

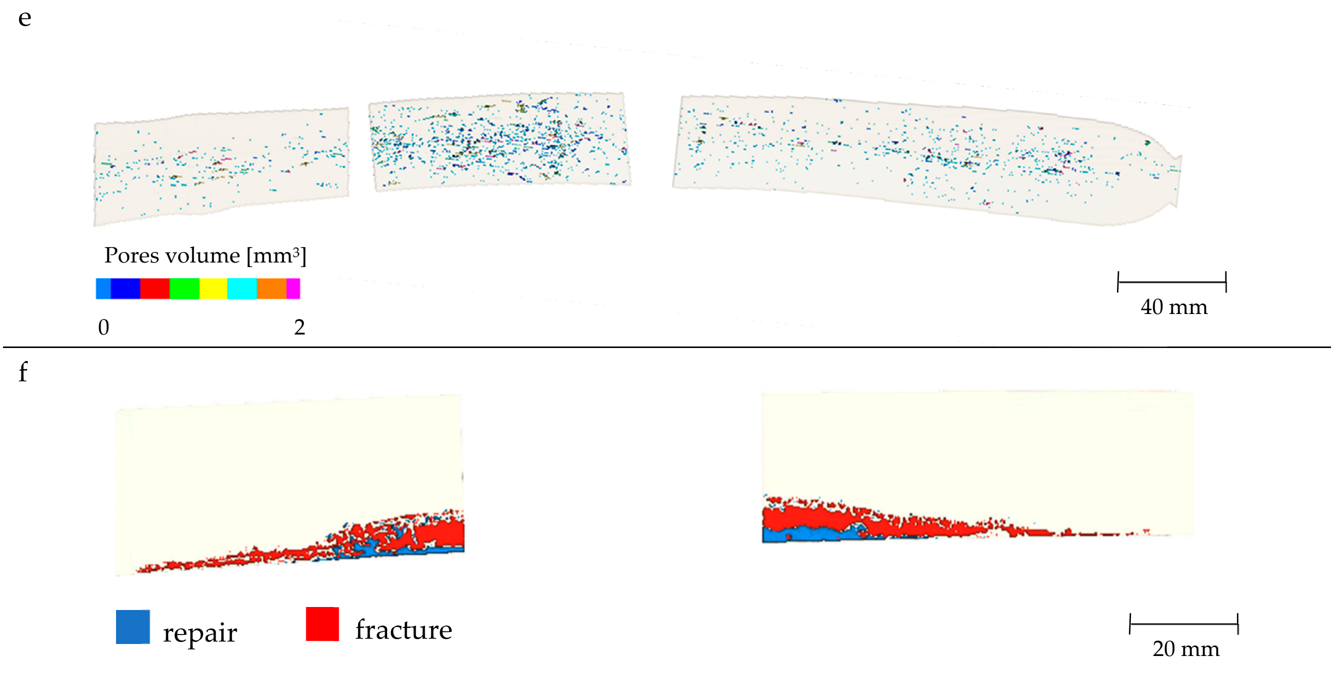

Figure 5. Three-dimensional map of the volume of porosities with the corresponding legend of colors are reported on the left side for (**a**) sword 2, (**b**) sword 3, (**c**) sword 4, (**d**) sword 5, (**e**) sword 6, (**f**) sword 7.

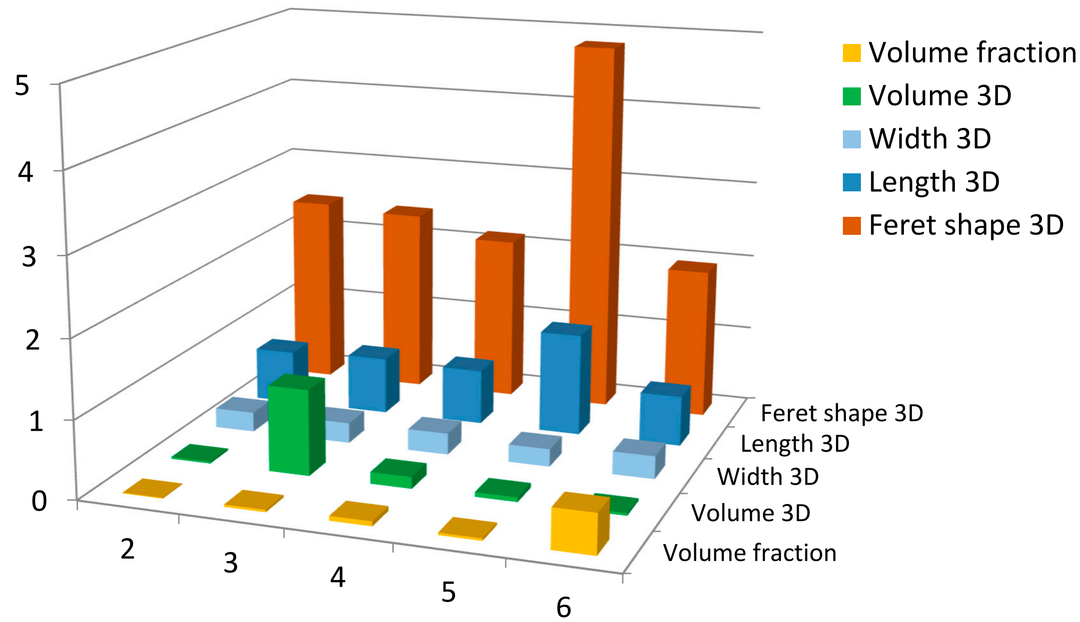

Figure 6. Volume fraction [vol.%], mean three-dimensional volume [mm^3], Feret shape 3D [a.u], 3D width [mm] and 3D length [mm] of porosities evaluated for samples 2–6.

Table 2. The volume fraction of different components quantified per each blade where porosities or other components where observed are reported as percent.

	1	*2*	*3*	*4*	*5*	*6*	*7*
Metal [%]	100	99.990	99.966	99.940	99.969	99.488	99.248
Porosities [%]	-	<0.010	0.034	0.060	0.031	0.512	0.482
Other [%]	-	-	-	-	-	-	0.269

Table 3. This table lists the different parameters for porosities in samples 2–6. The Feret shape 3D indicates the ratio D/d, where d is the minimum Feret diameter (a one-dimensional measurement that estimates how "wide" an object is in a given direction) and D is the maximum Feret diameter in the orthogonal direction; the length 3D refers to the maximum of the Feret diameters; and the width 3D to the minimum of the Feret diameters. The volume 3D represents the three-dimensional size of pores detected. Mean, standard deviation, minimum and maximum values are reported for each shape component.

	Feret Shape 3D				*Width 3D [mm]*				*Length 3D [mm]*				*Volume 3D [mm^3]*			
	Mean	**st.dev**	**Min**	**Max**	**Mean**	**st.dev**	**Min**	**Max**	**Mean**	**st.dev**	**Min**	**Max**	**Mean**	**st.dev**	**Min**	**Max**
2	2.452	0.844	1.200	4.144	0.254	0.128	0.087	0.742	0.692	0.471	**0.232**	1.971	0.024	0.042	0.001	0.225
3	2.390	1.841	1.081	**28.855**	0.262	0.127	0.098	1.075	**0.737**	1.443	0.194	**23.653**	**1.122**	0.149	**0.964**	1.367
4	2.136	1.046	0.999	9.407	0.276	0.382	**0.122**	**4.708**	0.712	1.599	0.193	17.289	0.150	1.456	0.001	**19.198**
5	**4.828**	2.912	**1.367**	19.330	0.311	0.224	0.143	1.818	0.227	0.189	0.072	1.312	1.323	2.236	0.232	22.505
6	1.952	1.143	0.964	23.717	**0.294**	0.202	0.051	3.502	0.649	0.807	0.185	19.134	0.031	0.120	0.002	3.832

Swords 1, 2 and 3, although similar in stylistic features, show some differences in internal structure. The tomographic images of sword 1 (Figure 4a) revealed the metal to be free of any detectable defect. Here, as well as in swords 3 and 4, since the tomographic cross-sections are near the surface, the visible gaps in the metal are due to decorative engravings. On the contrary, some small cracks can be observed at the very tip of sword 2 (Figure 4b), possibly caused by the tip of the blade being forged too finely, or perhaps because an already defected area had been exacerbated through use (Figure 5a).

Even though sword 3 (Figure 4c) shares the same basic form of swords 1 and 2, its tomographic images show higher porosities (0.060 vol.%), probably due to less rigorous hammering. The mean volume of the pores is also the highest recorded among the blades (Figure 6, Table 3). The pores appear mostly diffused in the portion of the blade closer to the hilt (Figure 5b). There are also two visible cracks, probably welding lines, running from the insertion of the tang down to the first fifth of the sword, which may have resulted from hammering the hilt insert into the blade body.

Although they are quite different morphologically, swords 4, 5 and 6 all have welding lines, or folds in their metal. Virtual cuts through the tomographic reconstruction of the samples reveal a layering of the metal, thus suggesting that the iron was folded many times in the forging process without completely removing the porosities embedded along the welding lines (Figure 4d–g).

There are also two wave-like cracks in the square cross-section that forms the rod of sword 4 (Figure 4d). These cracks probably also resulted from folding during forging (Figure 5c). From this it seems that the rod was worked less rigorously as the metal was bulkier. These folds might have been hammered out in the thin part of the chopper blade where a higher degree of hammering was required.

Similar features are observable in sword 5 (Figure 4e), but are even more pronounced. Here the layering in the material is concentrated in the first half of the blade, closer to the hilt. It is less apparent closer to the tip where the blade was probably subjected to more intensive hammering to achieve the thin, flat blade shape. Again, a direct correlation is evident between the intensity of the work and the porosity in the blade (Figure 5d).

Even to the naked eye, sword 6 (Figure 4f) has a rough surface texture that can be directly attributed to the sword's manufacture. In fact, the data from the neutron tomography demonstrate that the blade is highly porous along its entire length (0.512 vol.%) and show that these pores are aligned to the major axis (Figure 5e). In other words, they match the direction of the metal folds, roughly parallel to the edges, and to the median ridge.

This is quantified in terms of Feret shape 3D, the highest recorded among the investigated samples (Table 3, Figure 6).

Surprisingly, the most unexpected finding is in the images provided by neutron tomography related to sword 7 (Figure 4g), the European hunting sword that had been included principally for comparative analysis. The tomographic images revealed a significant amount of internal damage. While barely visible externally, there was a crack in the spine of the blade, damage that probably resulted from intense impact in use along an area that was already defected during production. A high neutron-attenuating material can be observed where the fracture surfaced, which may be the filling material used in a past repair or progressing mineralization (Figure 5f).

Although informative, tomographic data should be considered suggestive since they can highlight bulk features only at a macroscopic level, i.e., above 0.1 mm. A more robust insight into the actual manufacturing process can be provided by looking at a smaller scale: the crystalline structure of the metal. This can be achieved by neutron diffraction methods whose results will be presented in the next sections.

5. Neutron Residual Stress Analysis

The neutron diffraction–residual stress analysis was conducted on all the Dahomean blades with the exception of sword 4 (Figure 7). This item was excluded due to beamtime limitation and its peculiar shape. The distinctive form of sword 4 features a long rod culminating in a thin wide curved cutting end, making measurement of a selected cross-section barely representative for the actual treatment adopted in its making, and this is hardly relatable to the other samples.

In sword 1 the profiles of the longitudinal and transversal stress components show alternated zones in compressive and tensile states. To ascertain what this pattern is, independent from statistical fluctuations, a second cross-section was measured on the same sample. A similar trend was observed, suggesting either inhomogeneity in the material or the assemblage of different pieces of metal. However, these features were not visible in the neutron tomography or, if present, they might be below the detection limit of the measurement (~100 μm). The magnitude of the stress, ranging from 50 to 150 MPa, indicates that the blade was hot forged.

The most relevant feature of the stress profile in sword 2 is the presence of two compression zones at the edge of the blade. Here, the magnitude of the stress indicates forging by cold hammering, probably requiring the use of modern machinery. Nevertheless, the tomographic analysis showed very few internal defects in this blade.

As in sword 1, the absence of a long-scale pattern can be observed in sword 3. Here, hot forging or a final treatment with annealing is suggested by the magnitude of the stress detected at the cutting edge. In addition, in this case, oscillations in the stress profiles can be seen and are interpretable as non-uniform material or as the inclusion of different pieces of metal rather than one homogenous piece. This is also suggested by the tomographic reconstruction showing porosities preferentially distributed in layers, probably at the correspondence of welding lines, mostly concentrated close to the hilt.

The longitudinal stress component of sword 5 shows two compression zones at the edge separated by the center in a tensile state. Their magnitude suggests, once again, the application of hot forging or a final treatment with annealing. Here, the tomographic analysis reported very low porosities.

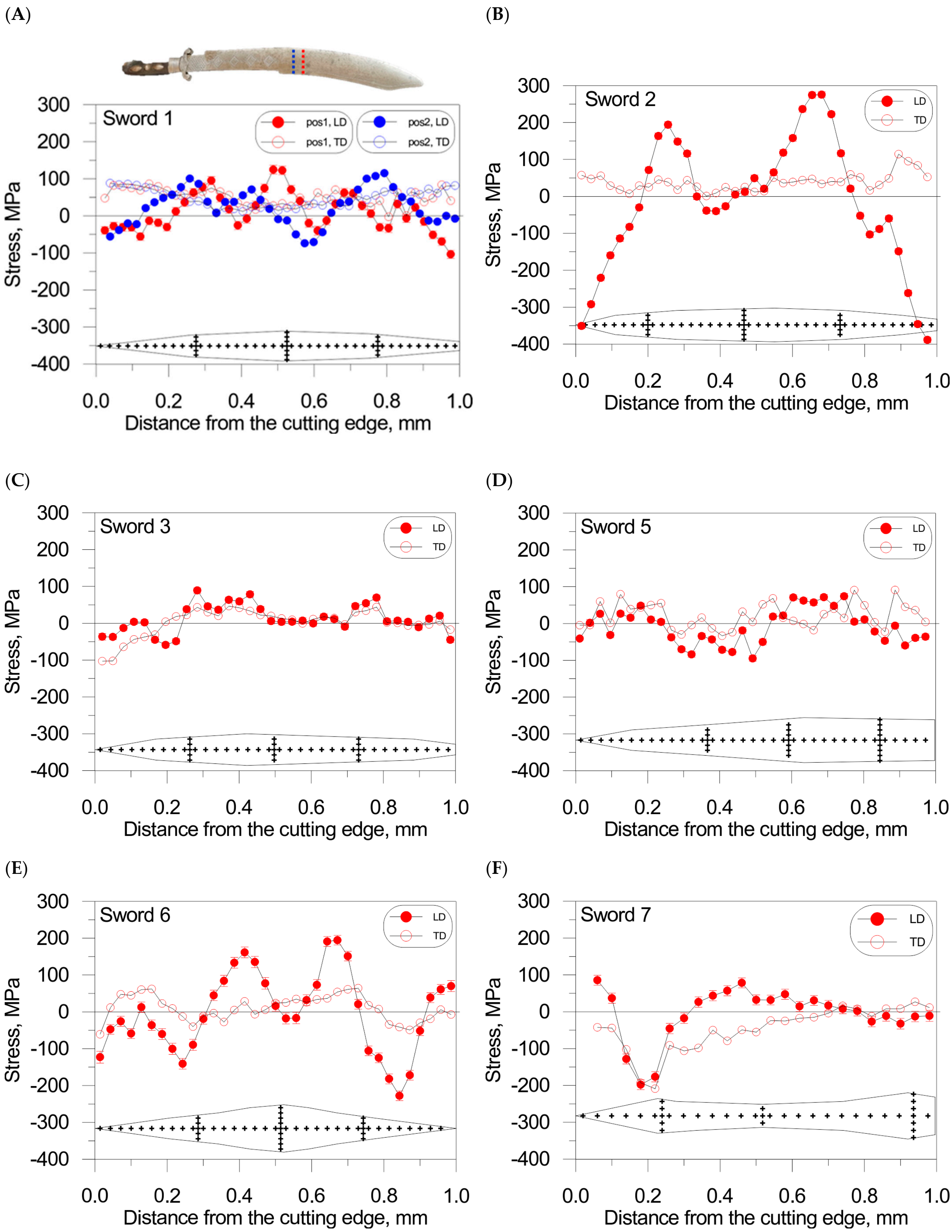

Figure 7. Central line profiles of the longitudinal and transversal stress components are reported for 6 blades (**A**–**F**). Since the samples differ in size, all curves are plotted in the scale normalized to 1 to make results geometrically comparable. The stresses were measured with an accuracy of <15 MPa. The samples also show variations of shape in cross-section; therefore, the two-dimensional mesh adopted for the stress measurement experiment complements each graph. The stress profiles for sample 1 (**A**) measured in two different positions of the blade length are reported together. The positions of the two cross-sections are mapped as red and blue dotted lines on the photographic image of the blade at the top.

Sword 6 shows two distinctive features. Firstly, the magnitude of the stress suggests that the metal was cold hammered, as also detected in Sword 2. In addition, there was some grinding, which created two tensile zones at both edges, also in cold conditions. This is complemented by the higher percentage of porosities evaluated through neutron tomography.

Overall, the results of the residual stress analysis show total inconsistency in the way the blades were manufactured. It appears that the blades were produced following different practices, manufacturing steps and treatments resulting in variation of the stress distributions.

6. Neutron Diffraction–Full Pattern Analysis

The neutron diffraction–full pattern analysis (Figure 8) demonstrated that, as expected, the major phase in all blades was α-iron. However, the primary scope of the measurement was to investigate the nature and amount of the secondary phases that could indicate the use of different metalworking processes (Table 4). Based on this analysis, sword 7 is the most outstanding sample, showing a presence of the only secondary phase, cementite, which was not observed in any other samples.

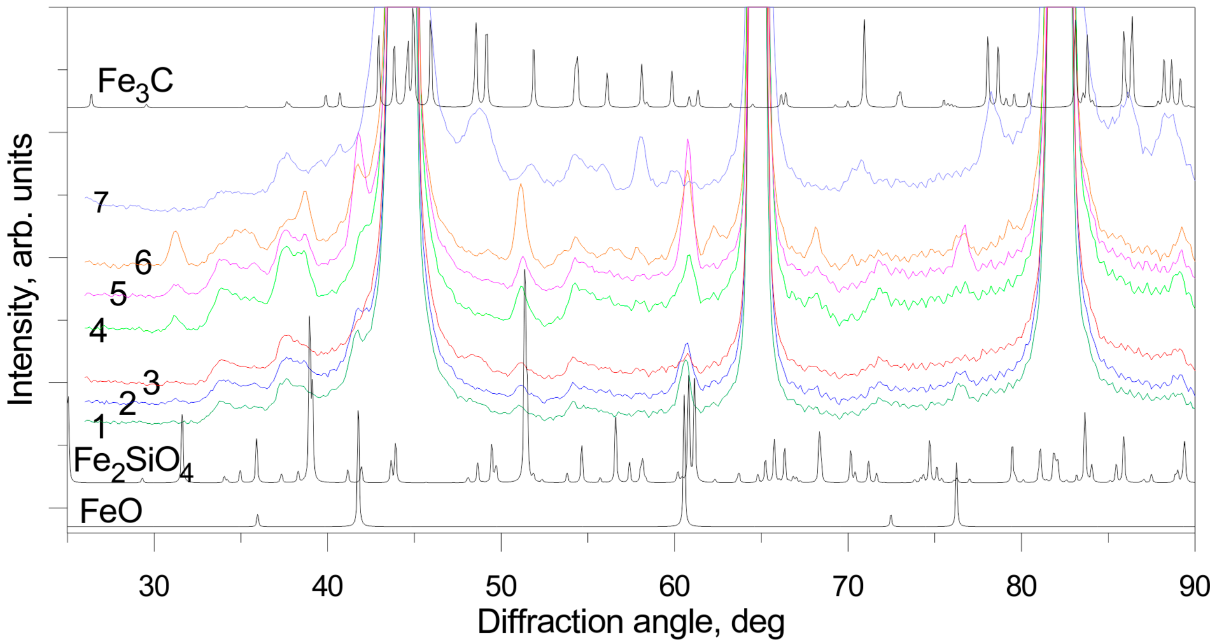

Figure 8. Experimental neutron full diffraction patterns for seven measured blades (1–7) as well as the calculated patterns for the identified secondary phases, FeO, Fe_2SiO_4 and Fe_3C. The calculated profiles intentionally have sharper peaks to better indicate their complex structure. The very large peaks at approximately 44°, 65 and 82° are from α-Fe. They are out of scale to illustrate better the secondary phases.

Table 4. The weight fraction of different phases quantified in the blades is reported alongside the associated error.

	α-Fe	Err	FeO	Err	Fe_2SiO_4	err	Fe_3O_4	err	Fe_3C	Err
1	0.9880	0.0000	0.0087	0.0006	0.0027	0.0020	0.0006	0.0008		
2	0.9853	0.0001	0.0091	0.0007	0.0040	0.0022	0.0016	0.0010		
3	0.9941	0.0000	0.0026	0.0006	0.0027	0.0006	0.0027	0.0021		
4	0.9757	0.0001	0.0075	0.0011	0.0122	0.0036	0.0045	0.0016		
5	0.9659	0.0002	0.0193	0.0010	0.0116	0.0029	0.0032	0.0012		
6	0.9526	0.0002	0.0095	0.0008	0.0320	0.0026	0.0059	0.0011		
7	0.9490	0.0003							0.0510	0.0037

Instead, all other samples, excepting sword 7, showed presence of wüstite (FeO, iron(II) oxide) in different amounts—as reported in Table 4 and graphically represented in Figure 9—and ranging within 1–2 wt%. An attempt was also made to fit the patterns using hematite (Fe_3O_4), but only sword 6 showed some trace amount of it, ~0.6 wt%. The presence of magnetite (Fe_2O_3) was not found. Moreover, for swords 4, 5 and 6 an additional phase, fayalite (Fe_2SiO_4), was found in an amount larger than 1 wt%. The original experimental diffraction data are shown in Figure 8 for easier comparison, together with the calculated individual phase patterns for easier peak identifications and judgement of relative intensities.

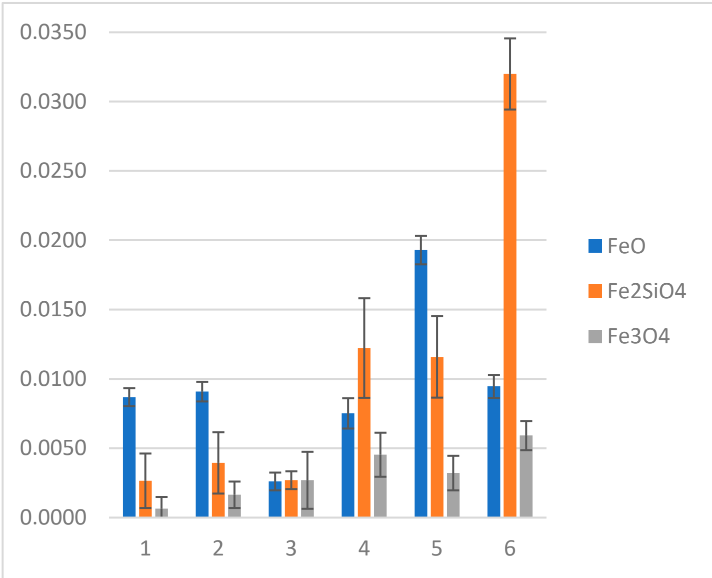

Figure 9. Weight fraction of secondary phases for swords 1–6.

Overall, the results of the neutron phase analysis show quantitatively a clear difference between the swords and three distinct groups of iron can be isolated based on the phase composition (considering only statistically significant values), also suggesting different practices of the metalworking:

- Swords 1, 2, 3: α-Fe + wüstite (fayalite < 0.5%)
- Swords 4, 5, 6: α-Fe + wüstite + fayalite (>1%)
- Sword 7: α-Fe + cementite

The two minor phases found in the studied blades 1–6, wüstite (FeO) and fayalite (Fe_2SiO_4), are related to the smelting process and present as slag inclusions in the metal. Wüstite is an intermediate phase generated during the reduction of the iron oxides composing the ore, hematite (Fe_2O_3) and magnetite (Fe_3O_4), into metallic iron under oxygen-depleted-atmosphere and high-temperature (around 1200 °C) conditions. Its quantity can be used as an index of the overall quality of the smelting process as it indicates the incomplete reduction of the ore due to a low temperature in the furnace [26]. Fayalite is one of the major constituents of slag inclusions, and forms through the reaction of the wüstite with the silica, present as a common contaminant in the iron ore, or other silicates (e.g., clays) added as flux [26] during smelting. It usually remains trapped inside the smelted iron and is later removed through hammer strokes. Its presence indicates the limited refinement of the metal during smithing, or a later addition as flux during forge welding.

Finally, the presence of cementite for sword 7 (third group) in an amount of 5 ± 0.4 wt%, which is equivalent to 0.33 ± 0.03 wt% carbon, classifies this alloy as a medium- or high-carbon steel with attribution to some "modern" era European steelproducing technology. On the other hand, the rest of the samples are made of wrought iron, with the quantity of carbon being too low for cementite to form.

The results of the spatially resolved measurements for the four selected blades are shown in Figure 10, in which the amount of the main secondary phase FeO is quantified as a function of its position within the blade (across its width). The phase amount, as extracted from the Rietveld analysis, is recalculated to the relative abundance referenced to the average value. The results demonstrate various types of distribution: with a sharp edge-like feature (sword 1), an almost linear gradient (sword 2), slow variation with tendency to parabolic dependence (sword 5) or no variation within the experimental error bars (sword 6). Since the average volume fraction in all these blades is low, below 2%, this small amount cannot change bulk stress equilibrium and therefore there is no correlation between these two characteristics. Additionally, there is no correlation with the results of the porosity analysis as the secondary phase particles do not necessarily follow the distribution of pores. However, these results (Figure 10) demonstrate the variable distribution and abundance of FeO, which is concurrent with the observed variability of the residual stress distribution or defect distribution.

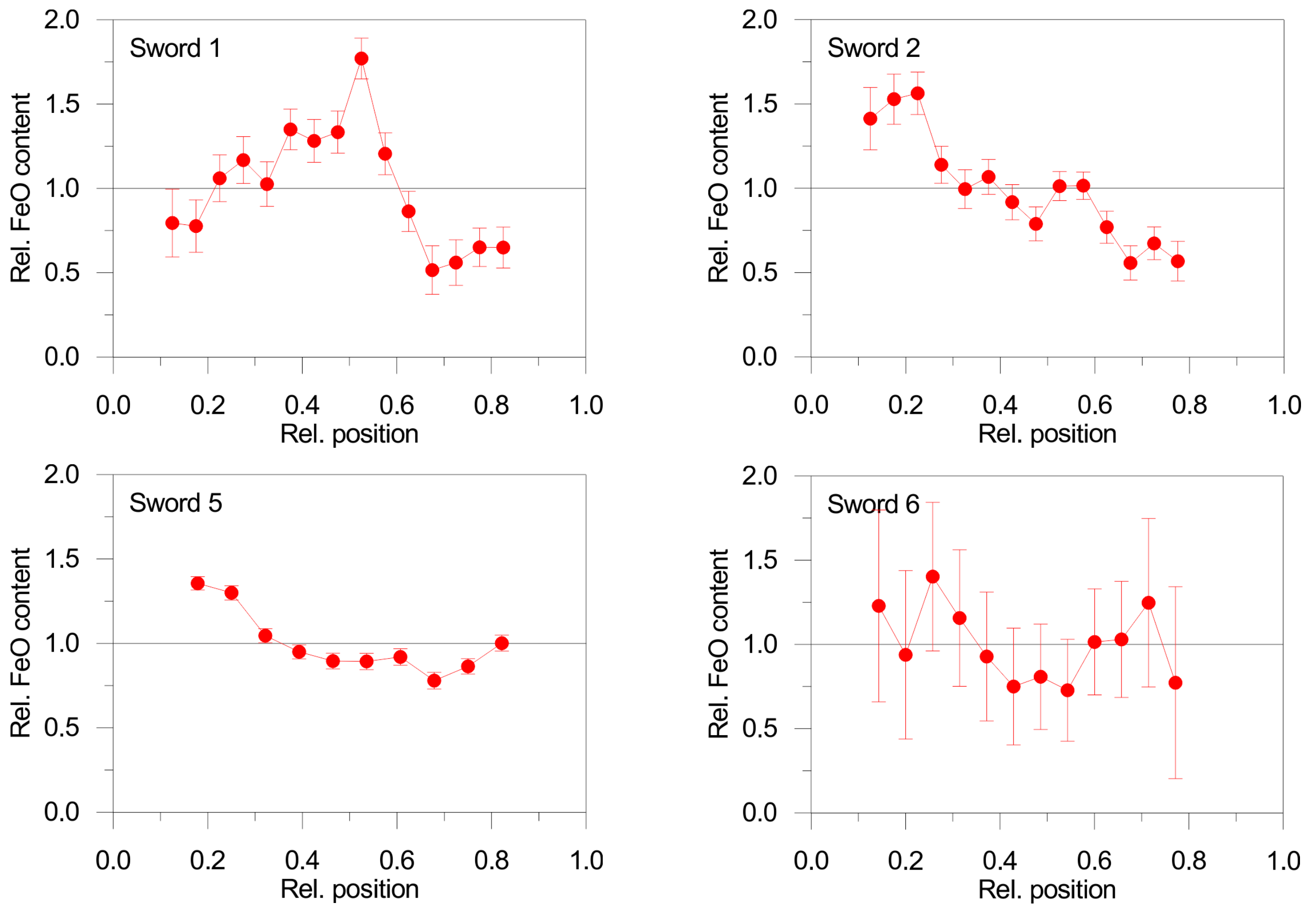

Figure 10. Distribution of the FeO secondary phase measured as a fraction from the average value across the width of the blades.

7. Discussion on Forging

The neutron tomography images provide a wealth of new insights into the manufacture of African swords. In particular, a distinctive forging technique has been identified, characterized by folds in the blade iron. These folds are not related to either 'Damascus' or pattern-welding, two other well-known blade-making techniques related to folding metal. Actually, true Damascus is only partially applied through forging, and is more dependent on casting Indian crucible steels—an art invented prior to the 7th century and largely lost by the 18th century. Pattern-welding, on the other hand, is applied entirely through forging, essentially by welding different irons with varying carbon compositions to create striking patterns visible on the surface of the blade. Therefore, the principal aim of both Damascus and pattern-welding is to beautify the blade by highlighting folded patterns on the blade surface and to obtain desired mechanical properties [27]. However, the folded iron patterns discovered here are not visible to the naked eye, but only evident through the tomographic images. They are not remotely related.

Significantly, the three swords with folding in the metal also happen to be those swords with the greatest porosity, namely swords 4, 5 and 6. There is also some evidence in the tomographic images of folds on the stem of sword 4, but not on the blade. This has interesting implications. Simply put, as the folding pattern is not visible on the flattened part of that blade in the tomographic images, there is a clear correlation between the evidence of a folded iron pattern and the intensity of the hammering on the metal. In other words, with enough smithing the folds can be eliminated completely.

In general, throughout Africa, bloomery iron was refined in two stages—after smelting, and during forging. Directly after smelting, the iron was refined by smelters while still hot, through hammering, which rendered it into a usable shape. It was then distributed to blacksmiths as a semi-refined product. The smiths then refined it further by working it on the forge [28,29]. Some folds in the iron may reflect the state of the material at the smelting stage, as the liquid slag and the various metallic globules and filaments flowed into a folded pattern. According to Fluzin, such folds are frequently observed in metal blooms, as well as in gromps and slag cakes, which are types of waste associated with different phases of iron refinement [28]. However, the neutron tomography here clearly shows that folds in the sword material were not merely owing to lack of refinement, but were actually part of the blade construction.

Even to the naked eye, sword 6 has fine fissures and cracks related to its manufacture. The data from the neutron tomography tests underline this strongly, confirming that the blade is highly porous along its full length and showing that these pores are aligned to the major axis. In other words, the pores match the direction of the metal folds, roughly parallel to the edges and the median ridge. In short, without question the folds were created while the metal was being shaped on the forge.

Sword 5, originally collected by Captain Tassard, is also notably porous, but here the folds in the material are concentrated in the first half of the blade, closer to the hilt. It is these folds that are most responsible for the high porosity reading. However, they are less apparent closer to the tip where the blade was subjected to more intensive hammering to achieve its thin, flat blade contour. Once again, here is direct proof that the blade's porosity is directly proportional to the quality and rigor of the smithing.

Tomographic images show sword 4 to be quite porous too. There are two wave-like folds in the square cross-section that forms the stem of the blade. In other words, the stem was clearly less worked than the rest of the blade, as the metal there was bulkier. Those folds might have been hammered out had the stem been subjected to the same degree of hammering as the thinner blade material near the blade's extremity.

While revealing no folds, the tomographic images of sword 3 do show small diffuse porosities in the first part of the blade, close to the hilt. They also show two cracks running from the insertion of the tang down to the first fifth of the blade, ostensibly related to the way the core of the tang was attached to the body of the blade in the smithing process. In sharp contrast, the tomographic images reveal that swords 1 and 2 were highly homogenous and had an even structure, with few defects, and no inclusions to the base material. Thus, there was practically no porosity in either of these blades. While the tomographic images of sword 2 reveal some small cracks at the very tip, where the smithing resulted in metal so fine it fractured under force, at just 0.01% porosity the impact of this damage is negligible on the sword's porosity reading. Overall then, the porosity measurements reveal a sharp distinction between swords 1 and 2, which have 0% porosity or close to it, and the rest, which have a noticeably higher porosity.

The higher quality workmanship of both of these samples is matched by their other quality components. Put simply, swords 1 and 2 have more ornate hilt appliques and guards. Likewise, both swords have blade etching of a visibly higher grade and finish. This suggests that more effort was expended on these two blades, which may have been intended for people of a higher social rank. Both are clearly decorative or ceremonial, for neither have much practical utility. They are too light for decapitation, and their blunted points also make them ineffective at thrusting or stabbing. In fact, the edge of sword 1 has never been sharpened, making it unsuitable for cutting of any kind.

Sword 3, though the same sword type, is clearly not quite of the same manufacturing quality. This is apparent even in the tomographic data, which show a higher porosity than swords 1 and 2, despite no evidence of folding. In part, this may be due to very small porosities left in the metal during smelting. However, it is primarily because of small fissures at the base where the tang was inserted into the main body of the blade; in other words, because of minor damage incurred during construction.

All these data show how the six sample swords fall neatly into two main groups. Swords 1, 2 and 3 evince no folded forging to the blades, and have more decorative furniture, including more ornate guards, hilt appliques and engravings. More to the point, swords 1, 2 and 3 are the same sword pattern, with the same hilt and blade characteristics. On the other hand, even though swords 4, 5 and 6 are different from one another in many notable ways, their blades were all forged with the same folded iron technique.

That the data resolve into two clearly distinct groups in this way is significant. Nonetheless, there are some data relating to the forging of these swords that do not fit quite as neatly. Only sword 6 shows evidence of edge filing or grinding. Moreover, the diffraction stress analysis data suggest that sword 3 was constructed with iron from numerous sources. Smaller iron pieces with different properties—notably hard vs. soft irons—had been mixed in the smithing process. This recalls some metallographic analyses on archaeological finds that show that African blacksmiths routinely assembled metal fragments of different origins when forging something new—a form of recycling [30]. Kriger outlines this too in her analysis of smithing processes in Central and West Central Africa [29].

While swords 1, 4 and 5 show signs of hot forging, where the blades were hammered while still red-hot, or alternatively of annealing, sword 2 and sword 6 appear to have undergone cold forging. Here the data show compression zones of greater magnitude at their blade edges, revealing these were forged once the metal had cooled. Ultimately, unlike the folded forging technique, these differences do not seem especially significant, or suggest anything more than that different smiths had different working methods.

8. Discussion on Smelting

According to the diffraction data, all six swords are composed of ferrite (α-iron), and there are no signs of any other mineral microstructures, such as cementite or pearlite, which are associated with high-carbon iron. Indeed, the data show that all six swords can be defined as wrought iron. As already discussed, the presence of wüstite can be indicative of incomplete reduction during the smelting process, and it frequently forms when iron is smelted at a low temperature [26].

Occam's razor, the law that posits that the simplest solution is usually the best, might favor the conclusion that this is African iron. The fact is that the data suggest that the iron in all six African swords has the characteristics of iron smelted in the bloomery furnaces that were used in iron production all over pre-colonial Africa [31]. Bloomery furnaces employ what is called the 'direct method', where the temperature of the furnace is lower than the melting point of the iron, which might explain the presence of wüstite [28]. By contrast, the iron in the European sword included for comparative purposes (sword 7) could not have been formed by the same process. Rather than wüstite, it has cementite—an iron carbide that illustrates that this material was created in a very effective reducing atmosphere, where oxidation was arrested. This indicates very high temperatures, such as those attained in a blast furnace.

Furthermore, the diffraction tests also reveal a significant amount of slag in all six Dahomean samples. Slag inclusions are a notable feature of bloomery iron, and much less so of more modern refining processes [32]. Nonetheless, despite all this preliminary evidence, the findings on smelting are less cut and dried than the findings on forging.

The smelting process in Northern Europe, where sword 7 was made, employed what are called blast furnaces, first developed in Sweden as early as the 12th century. Here, bloomery iron production had long been replaced. Initially using water wheels or water-driven trompes, blast furnaces were capable of creating far higher furnace temperatures than the air-driven draft furnaces of traditional bloomery iron production [33–35]. Water power methods were later replaced by steam power, and then electric power, but the principle remained the same—the furnace achieved temperatures that far exceeded the melting point of the ore. From this process, two separate cast iron materials were produced—gray iron, characterized by graphite flakes, and another cast iron component without graphite flakes and a higher concentration of cementite, often described as 'white iron'. As cementite can act as a hardening agent, strengthening the steel, the white iron could be refined further into steel after decarburization. The steel in the European sample (sword 7) was transformed from white molten cast iron in this way, which is why this was called the 'indirect' method, since there was an additional step [33,34].

The pig iron could also be refined into wrought iron through a process called puddling, first by oxidizing the high silicon content to form white cast iron, and then by reducing the carbon by stirring the metal in a coal-burning furnace. Developed in England in 1784, puddling was soon adopted by other major iron and steel exporters, including Sweden, and only supplanted by other technologies towards the end of the 19th century [26].

Both bloomery iron and puddled iron are defined as wrought iron because of their low carbon content. Both have wüstite, though it may not have occurred for the same reason. In bloomery iron, it may be a result of incomplete reduction. However, in puddled iron it may result through oxidation. Both irons also have significant slag inclusions. Though there may be less slag in puddling iron, for slag is scraped off the surface in the process, it is difficult to establish this as a universal characteristic. Therefore, it can be difficult to distinguish between bloomery iron and wrought iron—in essence, they are the same material, even though they are produced by different methods.

Some research breakthroughs have been made in distinguishing wrought iron produced through the direct method from wrought iron produced through the indirect method; in other words, bloomery iron from puddled iron [36]. This has involved examining slag inclusions to determine what fuel was used during smelting. However, importantly, such research is dependent on destructive techniques, and so is beyond the scope of this study, which has sought to preserve these swords.

The only other mineral present in the six Dahomean swords is fayalite, which shows that sand or silica was likely used as a flux at some point in the manufacture. Of course, silica is a common contaminant in iron. Around the world, blacksmiths use flux to improve welding, partly by removing contaminants at the join, but also by lowering the temperature needed for welds to occur on the surface of the metal. In Africa, such fluxes were also used during smelting bloomery iron to lower the melting point of iron ore [28].

Fayalite was found in all swords, but at significantly lower levels in swords 1, 2 and 3; below 0.5% compared with over 1% in swords 4, 5 and 6. Therefore, the mineral composition here confirms the impression that there are two groups—swords 1, 2 and 3 in one group, and swords 4, 5 and 6 in another. As significantly higher amounts of fayalite are present in those swords with a folded iron construction, there is a clear pattern between the forging technique employed and the presence of fayalite. Flux seems to have been used to strengthen welds between the folded strips of iron while forging. The relative lack of fayalite in swords 1, 2 and 3 suggests that less flux was needed because no folding technique was used. Nonetheless, the presence of low levels of fayalite in swords 1, 2 and 3 suggests that sand may still have been used as a flux during the smelting phase.

9. Conclusions and Historical Implications

The combination of findings suggests that all six Dahomean sword blades were made by African smiths. In particular, swords 4, 5 and 6 were made with a folded forging technique that has not been observed in swords elsewhere. However, as this study is the only one of its kind, more tomographic imaging needs to be done on African swords to form a better idea of how typical this is of African blades.

There are compelling indicators that also point to African forging in swords 1, 2 and 3. The most obvious is not based on scientific data, but on the decorative etchings on the surface of all three blades—etchings identified in other regalia swords from Dahomey [4].

In Solingen Germany, some swords were exported with custom etchings specifically intended for foreign markets; places such as South America, for instance. However, those examples are well known. Sometimes they even appear in German product catalogs and they almost always bear their German maker's mark [37]. However, there is no indication that anything such as that happened here. These swords do not appear in any such literature, and their etchings are not identifiable through work done in Solingen or Sheffield or any other well-known international blade-producing centers.

Furthermore, while swords 1, 2 and 3 were not made with a folding technique, sword 3 does include composite irons observed in African iron recycling practices. This might have been done on the forge, while creating the blade, but not necessarily. It is quite possible that a billet or iron bar could have been made out of recycled iron from different sources before arriving at any blacksmith's forge. In fact, it is worth pondering whether the blades of all three of these swords were shaped out of pre-fabricated billets or bars, negating the need to fold the iron on the forge while shaping the blade. All three blades are relatively short, at about 39 cm, 35 cm and 29 cm, respectively, so could have been hammered from an iron bar unit into their existing blade forms.

While there are indications of African forging for all six swords, the provenance of the metal is less definite. Currently, there is no definitive evidence that Dahomey smelted any of its own iron. In fact, some archaeologists maintain that a major iron industry in the Dahomey Gap region had collapsed by the early 17th century, owing principally to climactic catastrophe and the disappearance of the local industry's hardwood fuel supply [38]. According to oral history, iron was re-introduced during the reign of King Ghezo (1818–1859) [39]. However, if Ghezo did bring back iron smelting to Dahomey, then compelling archaeological evidence of it has yet to emerge.

A possible source of iron for Dahomey was Bassar, today in Togo—a pre-colonial iron-producing center of industrial scale [34,38,40]. Some historical research suggests that Bassar's iron production, though hugely significant in terms of African iron production, was far smaller than the iron tonnage being imported from Europe into West Africa, at least in the 18th century—well over a thousand tons per year from Europe versus an annual maximum production of just 80 tons a year in Bassar [34,40]. However, while that may hold for the 18th century, iron imports were strongly correlated to the slave trade, and following the international abolition of slavery after 1807, that would likely have changed significantly.

Relatively recent research indicates that almost all imported iron in West Africa, called 'voyage iron' by historical scholars, came from either Sweden or the Ruhr Valley region on the European mainland. Shipping records from some of the most active trading companies, notably Britain's Royal African Company (RAC) and Denmark's Vestindisk-Guineisk Kompagni, reveal that West African iron consumers insisted on very strict specifications for their European iron as it was also used as specie, or currency, in the slave trade. The iron specs demanded by West African traders changed frequently, sometimes with very little notice. Only Sweden's iron industry, and some iron producers in the Ruhr Valley, could adapt to new export specs quickly enough. Thus, known European iron exports to West Africa comprised low-carbon iron smelted by the indirect method. Almost certainly, what historians have been calling 'voyage iron' was actually 'puddled iron', processed from pig iron into wrought iron and exported in bar form, at least after the invention of the puddling process in 1784. This was produced in Sweden and select regions on the European mainland and then transported to Liverpool where it was re-exported to West Africa [34].

Historians have conjectured that voyage iron was softer than African bloomery iron, and there is anecdotal evidence that Africans and Europeans alike considered West African iron to be better than the imported variety [34]. In the 18th century, one agent of Denmark's Vestindisk-Guineisk Kompagni, on seeing spears from the Gold Coast, conceded that African iron was far harder [34,41]. However, that was in 1760, some 24 years before the invention of the puddling method.

According to Evans and Rydén, voyage iron was "a malleable material almost completely free of carbon", and less suitable than local iron for tools or weapons that required a cutting edge. Consequently, they have speculated whether it may have been used to supplement local African iron reserves, which they posit to have been more suitable for African tools and weapons [34]. Does sword 3 represent the very first evidence of a mixing of local and imported irons? After all, the diffraction data do show evidence of composite irons in the sword's make-up, some hard and some soft. That is a fascinating possibility. However, sword 3 is undoubtedly a 19th century sword and it is unlikely that there were reserves of the earlier pig iron still around. Moreover, carbon levels do differ from one iron ore to another, before any smelting has ever taken place [35]. Thus, the evidence of combined irons in sword 3 may simply confirm that African smelted iron was not uniform.

The fact is that historical reports that voyage iron was softer than African bloomery iron need to be interrogated after 1784, for the product almost certainly changed. Both bloomery iron and puddled iron are similarly low in carbon. Typically, neither bloomery iron nor puddled iron can be tempered or hardened through heat treatment. Both require hammering or 'work hardening', and the evidence of extensive hammering in these swords, with their impressively low porosity, makes sense for both kinds of iron.

Furthermore, puddled iron is known to have had more carbon content than later irons refined through the newer processes that supplanted the puddling method—notably the Aston process, which evolved from the Bessemer process that replaced puddling methods in the later 19th century [42]. Given that fact, could puddled iron really have been so much softer than bloomery iron? The only way to truly determine that is to measure the carbon in both puddled iron and African bloomery iron, something that would require invasive methods not suitable to this project. In all likelihood, by definition, 'voyage iron' post-1784 was in fact much the same material as African bloomery iron.

To add to the confusion, much of Southern Europe, including Portugal, continued to produce iron in bloomery furnaces even in the 19th century [34]. Portugal was of course one of the most important traders in the Bight of Benin. Furthermore, this study cannot exclude the possibility that some of this iron may have come from the Portuguese colony of Brazil, also historically linked to the Bight of Benin slave trade. In truth, Brazil only began its transition to blast furnace iron production well into the 1800s [33].

Historical reports are not illuminating on the provenance of iron in Dahomey either. Up until now it has been assumed that the iron used in Dahomey was imported from Europe, even during the 19th century, when trade relations had changed after the 1807 Slave Trade Act abolishing human trafficking internationally. British visitors to Dahomey—the British Consul Richard Burton, in the 1860s, and J. A. Skertchly in the early 1870s—both attested to the fact that Dahomey did not produce its own iron [43,44]. Both were aware of huge iron smelting centers in the interior but stated that most iron in Abomey came from European imports on the coast. Skertchly specifically said that the iron came from England, which would suggest it was 'voyage iron', exported from Liverpool. However, he provides no actual evidence. It is also clear that Skertchly based many of his observations on what Burton had said concerning his visit a decade before, and there is no evidence that Burton's statement on this was anything more than an assumption.

According to Skertchly: "Very little (iron) is bought from the tribes to the north, and this is exclusively used for fetiche purposes" [44]. Fetiche was a derogatory word used to describe anything related to the Vodun religion and derives from a Portuguese word that means 'witchcraft'. It is well documented that West Africans believed European iron to be ritually inadequate—the term 'deaf' has been used to connote its insensate quality in all things metaphysical or spiritual [45]. Therefore, it is highly unlikely it would ever have been used in religious rituals if local iron was available.

This is relevant because all the swords examined here were ritual objects. Swords 1, 2 and 3 were objects of royal regalia in a kingdom where there were no neat divisions between religion and the state. The symbols on these swords not only reference Dahomean royalty, but also the iron god Gu [4,6]. Furthermore, swords 4 and 5 were undoubtedly used in Vodun ritual in one form or another, for they are both sacrificial swords. Both swords have a small cutting edge on the bottom edge of the blade and are simply not functional for fighting, only decapitation—either of small animals, in the case of sword 4, or larger animals or humans, in the case of the longer and heavier sword 5 [4]. Furthermore, sword 6 has no practical utility at all, for it has no sharp cutting edge and with the figural hand at the blade extremity it could not be used for stabbing or thrusting. Its only conceivable function is as a cult or ritual object.

Magico-religious rites and observances relating to both the smelting and forging of iron were taken extremely seriously all over pre-colonial Africa, even when it came to iron for ordinary domestic or agrarian use [46]. This was also the case in pre-colonial Dahomey where propitiation of the iron god Gu was universal. However, the magical qualities of iron were even more important when it came to objects connected to religious practice. The importance of this is far too well documented to be ignored. While prior to the puddling method imported iron was no doubt genuinely inferior, even pejoratively called 'rotten iron' in certain places in Central West Africa [47], after 1784 that was likely not the case. However, local iron was still preferred, not necessarily because it was a better or harder material, but simply because it had the right spiritual credentials [45].

There were other uses that seem to have been deemed more appropriate for European iron, including making bullets for the muskets and Dane guns still widely in use, which utilized iron ball pellets. The practice of making bullets from bars of imported iron was well recorded among the neighboring Yoruba by British observers in the Yoruba wars of that time [48]. It was also observed by the Scottish adventurer John Duncan in 1849 when in Abomey, Dahomey's capital [49]. It is likely that European iron was used for making agrarian tools. Indeed, Evans and Rydén have made a direct correlation between increased iron imports and periods of agricultural growth [34]. However, given the data on Vodun ritual and local veneration of iron as an aspect of the god Gu, it seems unlikely that European iron would have been considered appropriate for these swords.

On the surface, the thing that seems to have convinced Skertchly, and perhaps Burton too, that Dahomean iron was imported was the mere fact that it came in the form of bars and rods. Skertchly certainly witnessed this [44]. However, it is now known that iron bars were also manufactured in Africa. Kriger demonstrates how African bloomery iron was sometimes produced in bar iron units in Central West Africa in the 19th century, where they functioned as currency—one of many iron currency forms. These bars were not always fashioned at the smelting stage—sometimes smiths hammered them into bars from rougher iron bloom material [29]. In fact, far closer to Dahomey, David has drawn on early colonial accounts to show that the Sukur smiths in the Mandara Mountains, on the boundaries of Nigeria and Cameroon, fashioned bloomery iron into a semi-finished bar iron product, which was exported in large quantities to the Lake Chad region. Importantly, this was happening before colonial markets had even opened up in that region [50,51]. While it is unlikely that either of these were a direct source of iron for Dahomey, both offer a precedent for African bar iron in pre-colonial times, independent of European iron imports from the sea.

As for rods, African iron was fashioned into rods in the form of 'Kissi pennies'—bloomery iron from the Sierra Leone and Liberia region [52]. African iron currencies existed in a bewildering variety of forms and it is certainly not impossible that there were other iron rods in circulation as currency in Africa. On the other hand, it is not known whether rods were ever imported from England. Indeed, the prevailing studies suggest that voyage iron was provided in bar form only, to strict specifications with very clear stamps. After all, iron bars also functioned as a form of specie [34]. However, current historical studies are far too wide ranging, and more studies are needed to differentiate voyage iron in the 18th century from imported iron in the 19th century, after the passing of the Slave Trade Act of 1807, as well as the Equipment Act of 1839. The abolition of slave trading would surely have changed the entire trading dynamic, but so far studies on voyage iron have not examined this. It is also not clear whether the introduction of a puddling process would have changed the pattern of export; after all, puddling is an English invention, even though it was also adopted in Sweden.

In conclusion, the scientific data do not currently offer indisputable evidence of the provenance of the iron. However, at the very least, the neutron data here show that the iron used in these swords was just as likely to be African iron as imported iron from Europe or Brazil. That represents a significant step from current assumptions that most iron in 19th century Dahomey was imported from Europe. In fact, those assumptions do not really stand up well to scrutiny, especially as more and more studies bring the sophistication of Africa's pre-colonial iron industries into focus. However, they also cannot be completely dismissed yet. Future isotype analyses could help to make new breakthroughs, with the help of destructive methods, including those initiated by Dillman and L'Heritier [36]. However, more data on African iron would be needed.

Regarding the manufacture of these swords, the evidence suggests that all were masterfully created by local smiths, half of them using a distinctive forging technique that appears to be autochthonous. It is a conclusion that could not have been drawn without a truly inter-disciplinary effort—an assessment of the historical context, an examination of foreign influences on Dahomean sword morphology, insights from African archaeometallurgy and data extracted through neutron particle research.

Given that the swords in this research were selected for their provenance, and as such represent a relatively random sample, there is no reason to think that a larger research sample might have made a meaningful difference to the findings. Consequently, not only does this project have important implications for the history of Dahomey, it also enables new insights into patterns of iron production and trade in pre-colonial West Africa, certainly in the second half of the 19th century.

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