Characterization of Two Japanese Ancient Swords through Neutron Imaging

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ABSTRACT
Japanese blades are culturally interesting objects both from the stylistic point of view and because of their fantastic performances. In this work, we present new results, using a non-invasive approach, concerning these peculiar artefacts. Two integer Japanese swords, pertaining to Koto (987-1596) and Shinto (1596-1781) periods have been analysed through neutron-imaging techniques. The experiments have been performed at the ICON beam line, operating at the spallation neutron source SINQ, Paul Scherrer Institut in Switzerland. The reconstruction of projection data into neutron tomographic slices or volumes, allowed us to identify some very peculiar characteristics, related to the forging methods and to the different thermal treatments applied to produce the cutting edge and its unique feature.

Keywords: ancient metallurgy, Japanese art, non-invasive method, neutron tomography

Introduction
The study of sword-forging techniques and their time-evolution represents one of the most interesting topics in the scientific investigation of the evolution of metallurgy. Weapons in general and swords in particular were produced using the most advanced techniques available according to the development level reached by a culture.

Until recently, this research activity was mainly based on standard analytical techniques like, for example, metallography [1–4]. However, this point-based surface-analysis technique, though characterized by a good accuracy and reliability, was soon recognized to be hardly applicable to precious museum specimens due to its inherent invasive character, which needs sampling or, at least, surface preparation.

In recent times, it has been recognized that this technique could be effectively complemented by an emerging non-invasive, experimental approach based on thermal neutron scattering, which allows to obtain an accurate quantitative characterization of the whole three-dimensional volume of metal artefacts [5-9]. Neutrons, thanks to their high penetration power in dense matter, represent an almost ideal tool to probe the microscopic properties of bulk dense materials [10, 11] and can be used to quantitatively characterize the microscopic structure of the artefacts at the atomic level. For metal samples, neutron scattering techniques are used to determine, qualitatively and quantitatively, the presence of different phases, as well as the presence and distribution of textures and residual strains at the atomic level. From this wealth of data it is possible to obtain useful information on the conservation status of the artefact, as well as to infer hints on the smelting and smithing procedures, through identification of some peculiar signatures related to these processes [12].

Moreover, neutrons can be used to obtain clean transmission images through thick metal samples (neutron radiography) as well as tomographic reconstructions of the samples internal volume, which give 3D detailed information on the micro-structural properties of the samples. In addition, neutron imaging techniques can be further extended to achieve material phase discrimination, by a proper selection of the neutron energy. In fact, monochromatic neutron beams give the possibility of modifying the image contrast, for the different phases, taking advantage of the abrupt
change of the attenuation coefficients in the proximity of the so-called Bragg cut-off [13].

The present investigation concerns a detailed study, through white beam neutron imaging, of two integer Japanese swords pertaining to Koto (987-1596) and Shinto (1596-1781) periods. We remind that the different styles of Japanese sword-making are historically divided into four periods [14, 15]:

1) Koto (old sword): A.D. 987–1596
2) Shinto (new sword): A.D. 1596–1781
3) Shinshinto (new new sword): A.D. 1781–1876
4) Gendaito (modern era sword): A.D. 1876–present

Furthermore, the Koto age is split into five traditions (Gokaden), which originated, locally, from the common evolution of replica of Chinese double-edge blades. They were modified in steps to obtain the definitive curved one-edge blades that are known all over the world. However, the fundamental techniques, like the smelting and smithing procedures, the forging, and the final treatments, were locally different and specific of the particular tradition and, possibly, of the schools inside each tradition. The provinces in which traditions started were either related to power centres or simply were in geographic areas rich in iron ore. Schools related to different traditions might co-exist in the same province.

The following period (Shinto) was characterized by the unification of the political power under the shogun and its control on the weapon production. As a consequence, the various differences among local traditions were greatly weakened, and only remaining as a sort of merely stylistic differentiation, with no real connection to the working process [15].

For the analysis presented in this work, we have selected two ancient Japanese swords, which are depicted in Fig. 1. Blade S1 evidences traces of a signature which, however, it is not possible to be univocally interpreted. Nonetheless, several surface features are visible and the specimen can be univocally assigned to Mino tradition of the Shinto period. Blade S2 is unsigned. However, from its shape and size, it can be univocally attributed to the Koto Age.

**Fig. 1** Picture of the two Japanese sword blades objects of the present study.

**Experimental set-up**

The neutron imaging study has been performed using the ICON beamline [16]. This is a neutron imaging facility, which collects the neutron beam originating from the cold liquid D\textsubscript{2} moderator, at the spallation neutron source SINQ in the Paul Scherrer Institut in Switzerland.

As it is well known, tomographic techniques provide sliced images of an object from the transmission data, which are obtained by combining cross section measurements taken irradiating the sample from many different directions. The method can be readily applied to bulk metal samples using thermal and cold neutrons, which are detected using a proper scintillator plate. In order to reconstruct the three-dimensional volume map of the sample, single 2-D parallel projections are measured during the rotation of the object around its vertical axis over a range of (at least) 180°. After corrections of the raw images (neutron exposure, flatfield correction, bright spots filtering, rotation axis tilting), the tomographic slices are calculated using the standard inverse Radon transform (filtered back-projection) [17]. Finally, all slices are collected in an image stack representing the 3D volume data of the neutron attenuation properties of the sample. At the end of the process, the different parts of the object, with different neutron attenuation characteristics, can be visualized using a proper 3D rendering software [12, 18].
The sample preparation was extremely simple. Each blade was gently wrapped using aluminium foil and its lowest part was partially inserted into an aluminium cylindrical pipe both for safety and for dealing with an object with cylindrical symmetry sitting on the rotating stage. Moreover, the tip of each blade was separately investigated setting a configuration for acquiring projections at higher spatial resolution than the ones taken on the whole samples.

We remind that the very low microscopic cross section of aluminium makes this metal almost transparent to neutrons and avoids interference during the measurements. The collected data have been processed through the software package Octopus, developed at Ghent University [18].

The two Japanese blades were characterized using white beam tomography (WBT) whose instrumental set-up is reported in Tab. 1 (3rd column). We recall that conventional neutron radiography is performed with a polychromatic spectrum of thermal or cold neutrons (depending on the beamline) and that the interpretation of the image contrast is obtained by the integration of the attenuation coefficients over the whole energy range. As a consequence, the energy-dependent features are lost in the (energy-) averaging process.

| Imaging Method: | White beam tomography |
|-----------------|-----------------------|
| Measuring Position: | 3 |
| Aperture: | 20 [mm] |
| L/D: | 604 |
| Scintillator: | $^{6}$LiF/ZnS (1:2) 100 [µm] |
| Camera: | ANDOR TECHNOLOGY, DV434 - BV, SN: CCD-6964, (16 bit) |
| Lens: | Nikon, AF-S NIKKOR 50mm 1:1.4G, SN: 213200 (Lens 1) |
| CCD-Size: | 1024 x 1024 [pixel] |
| Field of View Length: | 232 x 232 [mm] |
| Object-Detector-Distance: | 17 [mm] |
| Spatial resolution: | 231 [µm] |
| Exposure Time: | 30 [s] |
| Rotating Angle: | 360 [º] |
| Number of Projections | 1024 [1] |
| Proton Current: | 1.5 [mA] |

**Results**

In the figures reported below, we show the reconstructions of the white beam neutron tomographies on the two blades. The present non-invasive analysis permitted to identify some peculiar characteristics related to the forging methods used by the different schools and traditions in Japan (i.e. temper extension along the edge, defects, slag inclusions, internal cracks). As previously mentioned, a higher spatial-resolution tomography was acquired for the tip of both samples, in order to completely investigate the feature of the quenching in this critical area of the sword. By analysing the results of the present measurements, we have been able to detect differences, between the two samples, originating from different forging styles.

The orthogonal virtual section of blade S1 evidenced the outline of a wide *hamon* and of a wide martensitic part on the edge of the blade. The *hamon* is the line between the martensitic edge and the rest of the body, typical of the Japanese blade. As it is visible in the enlarged picture of the tip (Fig. 2, right side), the *hamon* pattern appears well-defined also in the *kissaki*, the angled end part of the cutting edge, which forms the point of the blade. Moreover there are several interesting micro-structural features present behind the *hamon*. Looking at the attenuation power it seems possible that also that part is composed by martensite but no well defined border line between it and the standard steel is evident. We remind that Japanese sword-smiths had developed techniques permitting to hardening only selected parts of the blade as the cutting edge, leaving the body more flexible, and able to absorb the shock of a blow or the stress caused by a sudden twisting [19].

It should be noted that the *hamon* in the tip, the so called *boshi*, appears still well preserved with the
Martensite present also in the back. Because the tip is the likely most damaged part during sword fight, a possibly broken kissaki, should be often reshaped and polished, by changing the martensite distribution and reducing the curvature and size of the hamon at this position. In this case the peculiar phase distribution is well evident so that it is easy to conclude that the tip is the original one.

A particular feature emerges analyzing the neutron tomographic reconstruction of S1 (Fig. 2). A dark area, running along the profile of the hamon, can be recognized. Typically the hamon is characterized by a high content of martensite (a non-equilibrium metastable phase resulting from the transformation, without diffusion, of austenite) with the rest of the material transforming into ferrite. Indeed, martensite arises when austenitized iron–carbon alloys are rapidly cooled (or quenched) to a relatively low temperature (in the vicinity of the ambient) at such a high cooling rate that carbon atoms do not have time to diffuse out of the crystal structure in large enough quantities to generate cementite (Fe₃C). The face-centered cubic austenite transforms to a body-centered tetragonal form of ferrite, martensite, that is supersaturated with carbon [20]. The polymorphic transition from the highly packed structure of the fcc structure to the bct one is combined with a variation in volume of the metal induced by the variation in temperature. The dilatation of the steel, during the transformation of the ferrite to austenite, and its following contraction, during the formation of martensite, depend on the competition between the thermal volume variation and the transformation process [21]. If the thermal effect highly prevails, probably when starting temperature for the quenching process is much higher than the eutectoid transition temperature (≈727°C) and cooling rate is fast, it can cause the detachment of the interested area from the part of the blade that was kept thermally isolated during the process. The dark volume behind the hamon can be then interpreted as a part in which the average density of metal is lower than in solid metal and sub-micrometric creeps are diffused inside the volume itself. The effect on the external surface is a large dark shape of the hamon (very appreciated by many sword collectors) but the drawback is a weakening of the connection between the hard but brittle cutting edge with respect to the bulk of the sword. It is not easy to say if this effect is really detrimental of the sword performances since its extension and homogeneity could in some way reduce its negative effect.

A careful analysis of Fig. 2 (left picture) evidences the presence of small slag-inclusions, elongated and parallel to the back of the sword and to the hamon pattern. In addition, owing to the high resolution white beam tomography of the tip, we were able to resolve the trace of a single internal crack in the opposite area of the image with respect to the tip and extending along the backside (Fig. 2, right picture). Last, but not least, the kissaki (tip) presents a very complex structure as it is evident in the high resolution section (Fig. 2, right picture) showing several strips and elongated spots composed by different phases in the whole volume. As previously explained they are probably related to the martensite distribution obtained during the quenching and influenced by the microstructure produced by the hammering work performed to shape the tip that is usually bent backward from a diagonally cut bar [19]. Finally, the various cross sections, taken at different heights of blade S1 (Fig. 2, sequence of central images), evidence an inhomogeneous inner structure. The presence of a bright area, on each flat side of the sword, leads to two different explanations. The first hypothesis is related to a highly neutron attenuating material, i.e. goethite FeO(OH), diffusing from the surface to the inside of the blade. The second interpretation leads to the probable use of different types of steel characterized by different carbon contents. As the first hypothesis would imply the visible presence of rust traces onto the external surface (not detected in this case), we would be led to favour the second one. The variation of the gray tones in the core of the blade, visible in the cross sections images and in the orthogonal view, strongly suggest a preference for the second interpretation.
Fig. 2 On the left, the orthogonal section virtually cut at the centre of the blade. At its side, different slices, selected at different heights of the sample, show the progress of the *hamon* line along the blade and the inner structure of the whole object. On the right, the high spatial-resolution image of the tip, whose location is marked by a red frame in the orthogonal view, evidences the presence of slag inclusions (red rectangle) and a crack (red arrows) in sample S1.
Fig. 3 The orthogonal central view of sample S2 is reported on the left. The red lines indicate the height of the shown axial slices. A red frame points out the location of the high spatial-resolution image of the tip, reported on the right side. In the enlarged picture, the presence of a defect (red arrow) and the cloud of slag inclusions (red rectangle) are visible.
Fig. 4 Axial cross sections are acquired at the centre of each mekugi-ana. The red numbers identify the location of the holes in the S2 blade.

Concerning the sample S2, also in this case an inhomogeneous inner structure has been revealed by the analysis (see Fig. 3, left side and central images sequence).

The quenched region (hamon) along the cutting edge is thinner than in sample S1. Moreover, we could detect evidence of the diffuse presence of small slag-inclusions in the whole body of the sword. In particular, as visible from the orthogonal view of the high spatial resolution tomographic reconstruction (Fig. 3, right picture), a huge defect is recognizable near the tip and inclusions appear concentrated especially along the backside of the sample.

The tang, called nakago in Japanese, deserves to be mentioned. Three mekugi-ana are observed in the tang of the sample S2 (hardly visible in Fig. 1). The mekugi-ana are holes drilled in the tang for passing through a wooden peg in order to stick the hilt. Most blades have one mekugi-ana, whilst some have two or more, generally due to a reshaping of the tang, as it seems to be the case in the presently analyzed sample, where three peg-holes are counted. The evident observation of the hamon line, well extending into the tang, suggests that the original blade was shortened so that part of the blade is now transformed into the tang. This hypothesis is confirmed by the presence of a third mekugi-ana. Indeed, comparing the shape and geometry of the holes, we can distinguish a different direction in making the third hole, with respect to the others (Fig. 4). The fittings (koshirae) for long swords are different between the tachi and the katana sword types. The former is the first curved long sword type developed in Japan, much longer than the katana and used primarily from the back of a horse. Katana is developed later, it is down to 10 cm shorter than the tachi and was used also on foot. The way of wearing them inside the scabbard is totally different with the edge of the sword staying downward in the tachi and upward in the katana. Also the entrance side of the wooden peg is the opposite. This means that the sword S2 was forged as a tachi (hole n.3, the first impressed in the sword) and then shortened and reshaped twice as a katana (holes n.1 and n.2).

Finally, it is worthwhile to mention that sword S2 does not evidenced the presence of the black line facing the hamon on the inner side of the blade. The process of heating a sword until it is red hot, and then plunging it into water, is perhaps the most dramatic moment in the sword-smith’s practice [19]. So, the S2 blade was probably made following a more careful and less extreme thermal process than the Mino-Shinto sword (S1).

Conclusions

In the present work, we studied two Japanese swords, pertaining to different periods and forging traditions. White beam neutron tomographies have been used to investigate bulk metal samples in a non-invasive way that is mandatory for this kind of artefacts. White beam tomographies have allowed us to identify peculiar characteristics related to the forging methods as well as the thermal and mechanical treatments used by the schools who produced them:

- slag inclusions and cracks were mapped and localized;
- inner structure, resulting from the particular manufacturing process, were analysed all over the samples;
- the hamon line and related care in the quenching process has been evidenced;
marks of reshaping have been identified.
A similar investigation should be repeated on several
more swords with the aim to identify a set of
microstructural features peculiar of specific working
methods to be used as a reference standard for the
identification and authentication of the different
schools and traditions of ancient Japanese sword
forging.

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