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On the protective effect of the stress distribution on a lamellar Edo period Samurai helmet: a neutron diffraction study

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Abstract

The paper focuses on a 17th century Japanese helmet (*kabuto*) from the Saotome School; previous investigations revealed that its lamellae, made of high quality low-carbon steel, were assembled following a novel structure that suggested higher resistance to firearms.

Neutron Diffraction represents the ideal technique for the characterisation of the micro-structural properties of metals. In this work, neutron diffraction on a highly collimated instrument, such as ENGIN-X (ISIS, UK), was used to quantify the distribution of residual strains along lamellae arranged in this newly discovered assembly method, and therefore infer on the mechanical properties of the Saotome *kabuto*.

Here we present novel results investigating residual stresses from diffraction measurements by using the instrument ENGIN-X. This study completes the previous cycle of neutron measurements on this sample and sheds light on the effectiveness of the assembly method of the plates.

Keywords Neutron diffraction · Residual stress mapping · Japanese helmets · kabuto · Archaeometallurgy

Introduction

Japanese armour originated in the 4th century CE and is based on prototypes from neighbouring China and Korea [1]. During the medieval period a distinct Japanese style of armour developed: Samurai warriors, who were fighting on horseback, had flexible armour made up of hundreds of small leather and/or iron scales, laced together in an overlapping pattern providing both strength and flexibility. Samurai used bow and arrows, and sword as weapons. For the lower ranking foot soldiers fighting with spears, the armour was lighter and less sophisticated and it was constructed with one continuous sheath-like torso. Japanese armour makers started using lacquer to render armour parts to protect them from rusting [1].

In the 15th century as fighting moved from cavalry to large armies of foot soldiers, armour styles changed and became lighter. Samurai headgear—the most important part of a suit of armour—also

developed, producing elaborately decorated helmets (*kabuto*) and masks to be visible on the battlefield, or designed with frightening appearance to scare opponents.

After the introduction of firearms in Japan in 1543 by the Portuguese, Samurai armour started evolving to adapt to the changing warfare style. Japanese armour makers developed new types of armour capable of sustaining the impact of musket fire [1]. These new types of armour were generally simpler (composed of few plates) and sturdier, and could be mass-produced to supply the high demand due to the internal conflicts that affected Japan until the early 17th century [1].

Around the 1600s and during the relatively peaceful Edo period (1603–1868), where samurai were in power and Japanese shogunate was enforcing an isolationist foreign policy, there is a surge in the production of artistic armours as samurai's role as warriors was in decline and traditional armours were no longer needed for battles. Such armours were mainly used for display or ceremony, representing the samurai wealth and military identity.

The seclusion policy ended in 1854, restarting foreign trade and interaction. In 1868 the Japanese empire was restored, and in 1876 the samurai status abolished, ending the privilege of bearing swords. Since the end of the shogunate, Japanese armours and swords immediately became objects of interest to world collectors. Many examples in excellent conservation status are considered National Treasure and have been housed in museums, temples, or held privately. For this reason traditional destructive analysis are not suitable for such artefacts.

This work carries on a non-invasive investigation on the microstructural properties of one of the oldest surviving *kabuto* from the Saotome School, dating back to beginning of the 17th Century [1]. The helmet was previously analysed by neutron diffraction and neutron imaging revealing that its lamellae are made of high quality low-carbon steel and riveted together following a novel structure, suggesting the search of a manufacturing technique that would provide higher resistance to firearms [2, 3]. Here we present further results from a neutron diffraction investigation using a highly collimated instrument, ENGIN-X (ISIS, UK) [4], that enables to quantify the distribution of macroscopic residual strains along the object. Depending on the length scale at which residual stress varies, stresses are divided in macro-stresses (*Type I*) and micro-stresses (*Type II* and *III*). Type I residual stresses are phase-independent deformations homogeneous over a very large number of crystal domains that are introduced during assembly by macroscopic plastic deformation. Type II residual stresses are intergranular strains that are homogenous within crystal domains; they can be a consequence of thermal and plastic deformations, or carburisation processes. Type III residual stresses are due to local defects like dislocations, vacancies, phase boundaries, or precipitates. The sampled gauge in neutron diffraction is usually too coarse to resolve Type II and III, so that they generally give rise to broadenings in the diffraction peaks.

The investigations of the intensity and direction of these macrostrains is fundamental for the understanding of the mechanical properties of the metal. Because the helmet bowl is made of overlapping “S” shaped lamellae slotted in together [2], we expect that each component is in a permanent state of elastic tension (due to the macroscopic plastic deformation). To test this hypothesis, we mapped residual stress along a single lamella to infer on the tensile state, and therefore on the effectiveness, of this new structure. Residual stress is in fact one of the main factors affecting the mechanical properties of materials, since the stress vs strain response depends on the current state along the stress-strain curve, amongst them the need of a higher stress required to plastically deform the material. For example, compressive stress is a typical way of improving the behaviour under mechanical solicitation of modern industrial components. Time of Flight Neutron Diffraction (ToF-ND), as XRD, is a well-established method to characterize non-destructively local strain and stress,

1 using the lattice plane spacing as an internal strain gauge. While XRD—the most widely used stress
2 measurement method, would provide a limited measurement depth, neutrons represent the ideal probe
3 for investigating metals also providing millimetre scale cubic gauge volume analysis.

4 5 **Saotome kabuto**

6
7 Japanese armour makers used to sign some of the finer pieces, but characteristic features, shapes, and
8 construction styles make even unsigned pieces identifiable. The kabuto here investigated is a 64 plate
9 kabuto (see figure 1) signed by Saotome Ienari (see figure 2, left). The Saotome school was one of
10 the most prolific and most known family of kabuto making armourers of the 16th and 17th Century
11 [5], with Saotome Ienari being the third craftsman of the dynasty [1]. They were active in the Hitachi
12 province between the mid-16th Century and the end of the 18th Century [1]; the Hitachi Province was
13 an ancient province of Japan, corresponding to the area of Ibaraki Prefecture (see figure 2, right).



15 **Figure 1** *Suji-bachi* kabuto with 64 “ridged” lamellar plates, finished with a visor decorated with two facing gold dragons
16 This helmet was formerly part of the H. Russell Robinson Collection [4]. (Left) Side view; (Right) Top view;.

17
18 Saotome are known for producing very high quality *suji-bachi* kabuto, such as the one here presented,
19 “ridged” bowl-style helmet crafted with multiple plates. The Saotome kabuto plates are often narrow
20 because of their high number (from 62 to 72 or more plates), and “S” shaped with a wide area of
21 overlap between them, resulting in a quite thick and heavy helmet [1, 5]. This kabuto weighs 1.8 kg,
22 excluding the neck protection (*shikoro*) that is missing, compared to around 1.3 kg of similar ones of
23 non-Saotome craftsmanship [3]. The different plates are joined by rivets, filed to the surface, making
24 them invisible from the outside, as the surface is lacquered on the inside and patinated on the outside.

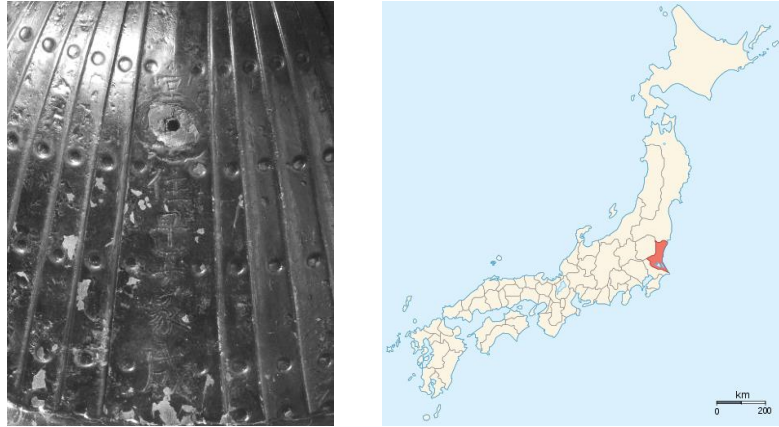


Figure 2 (Left) Signature detail on the inside of the helmet bowl “Hitachi no juu Saotome Ienari”, meaning “Saotome Ienari, resident of Hitachi province”; (Right) Hitachi province in ancient Japan.

The kabuto was already analysed through neutron techniques. Neutron diffraction highlighted the use of high quality wrought iron (around 0.1 wt% C) with no trace of silicates as slag, very high residual strains, tiny crystalline domains, and texture index from medium to high [3]. These characteristics suggested that the plates were probably cold worked for shaping the metal and increasing its hardness. Neutron tomography instead has been fundamental in understanding the assembly method of the individual plates, revealing the presence of a new structure [2] where diagonal rivets link the extreme end of a lower plate with the central part of the above one (see scheme in figure 3, left, compared to literature structures on the right). Despite the high weight (which counts as hindrance for the wearer) due to the large overlapping area between neighbouring plates, this structure leaves a pocket of air between the superimposed area that acts as a shock absorber [5], improving the overall protection compared to other structures reported in literature [1]. In addition, when the helmet is hit, the “S”-shaped plates involved in the blow transfer the impact to the next ones distributing the impact energy on a wider area. The diagonal rivets help maintaining the structure under an impact, counteracting their tendency to deform.

Saotome multi-plate structure:



Literature multi-plate structures:



Figure 3 Cross sections of possible assembly methods for multi-plate helmets: (Left) Riveting structure of this Saotome kabuto, with “S” shaped plates having large superimposition with the neighbouring ones and leaving a pocket of air in between for absorbing the blow; diagonal rivets filed to the surface (red) join adjacent plates [2]; (Right) Common (above) and “S” shaped plate (below) riveting method as reported in literature [1], having no or less efficient air pocket as shock absorber, resulting in a more rigid structure or in rivet deformations compromising the integrity of the assembly.

The aim of this study is investigating whether connecting plates are in permanent tensile state one against the other, and, if so, to what extent. We want to investigate how the tensile state changes along the plate following the curvature. This would give an idea of the reciprocal stability of the helmet components. Each “S”-shaped plate is in fact wedged in between two others, with its far ends touching the central parts of the neighbouring ones.

The measurements were carried out using the instrument ENGIN-X [4] at the ISIS pulsed neutron source (Rutherford Appleton Laboratory, Oxford, UK) [6].

Method and experimental set-up

ENGIN-X is a neutron powder diffractometer working with the time-of-flight ToF method dedicated to engineering science. It is optimized to investigate strain, its amount and direction in crystalline materials. Strain and stress are usually dependent on direction and position within the sample, therefore an accurate positioning system and a precise gauge volume definition is required.

The instrument uses typical gauge volumes of few cubic millimetres, achieved through a collimation system both on the incident beam and in front of the detectors, so that only neutrons scattered from the selected gauge volume reach the detectors. Scattered neutrons are recorded by two detector banks orthogonal to the incident beam, 1.5 m away from the sample position, called North and South. Here the ToF is recorded with respect to the burst time of the pulsed source and, depending on the scattering angle of the detector, the corresponding atomic lattice spacing is calculated using Bragg's law, similarly to XRD. For this experiment the ToF was acquired from 10,000 to 40,000 μs , corresponding to around 0.98–2.18 Å in d-spacing, covering the ferrite peaks (110), (200), (211), and (220).

The diffraction data were processed through EX-SBA, the Open Genie based calculation routine for ENGIN-X [4], and then fitted using the Rietveld method [7] using the GSAS code [8] through the EXPGUI interface [9]. For the peak profile fitting we used function 3, where peaks are defined as a convolution of the back-to back exponentials with a pseudo-Voigt.

Residual macrostrains are determined from the diffraction data by calculating the strain from the diffraction peak positions. Any stress, including applied or residual stresses, induces elongations and contractions within the crystal lattice producing a change in the interplanar spacing d of the lattice.

Given a specific set of $\{hkl\}$ lattice planes, the measured atomic lattice spacing d_{hkl} of a strained material functions as a deformation gauge: it provides a highly precise and spatially resolved means of evaluating residual strains. The magnitude of the movement of the peak is related to the amount of stress. If $d_{0,hkl}$ is the strain free (stress free) constant for the material investigated, then the strain ε_{hkl} is given by:

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}} \quad (1)$$

From the measurement of elastic strain, it is possible to calculate the relative mean stress, given that the elastic constants of the material are known. This is achieved through three independent measurements of the strains along the three orthogonal components chosen following the geometrically significant directions of the helmet (see figure 4, right), defined as:

- Axial strain ε_A : base of the helmet bowl to the top;
- Transversal strain ε_T : along the cross section of the plate (hoop direction of the helmet);
- Normal strain ε_N : across the thickness of the plate.

The strain ε_{hkl} is related to the stress σ_{hkl} through Hooke's law:

$$\varepsilon_{hkl} = \frac{1}{E} \sigma_{hkl} \quad (2)$$

where E is the Young's modulus of elasticity which represents the stiffness of the material. In cubic systems such as ferrite, the iron phase stable at room-temperature, stresses along the three directions can be calculated from strain using eq. 2; so that the axial stress σ_A is [10]:

$$\sigma_A = \frac{E}{(1-2\gamma)(1+\gamma)} \left[(1-\gamma)\varepsilon_A + \gamma(\varepsilon_T + \varepsilon_N) \right] \quad (3)$$

where γ is the Poisson's ratio. The same equation applies, with appropriate substitutions, to calculate σ_T and σ_N . Here we used the ferrite (110), (200), (211), and (220) reflections as these are the peaks having d-spacing falling in the 0.98–2.18 Å interval investigated. Since the Rietveld refinement provides a weighted average of the lattice determined from all peaks in the diffraction pattern, this can be considered representative for the macroscopic strain behaviour of the material and weakly affected by intergranular strains. To obtain the bulk properties of the material we used the Young's modulus $E = 209$ GPa and the Poisson's ratio $\gamma = 0.29$.

For the correct selection and positioning of the measurement points, the Strain Scanning Simulation Software (SScanSS) [11,12] was used. SScanSS is the ENGIN-X virtual laboratory, it allows to scan the object with a laser arm and build a virtual model as input for the measurements (see figure 4). The SScanSS software was then used to specify the measurement points within the virtual model of the helmet and, after the alignment on the instrument using a reference touch-probe system, the exact coordinates of the measurement points were calculated.

Since the plate thickness of the kabuto was estimated from the neutron tomography to be slightly over 1.5 mm, we used the 0.5 mm collimation system, so that the strain measured represent the strain averaged over the gauge volume thus defined. To be sure to be centred on the metal, the centroids of the gauge volumes were positioned at about 0.7 mm below the surface of the object as obtained by the laser scan (see figure 4, right).

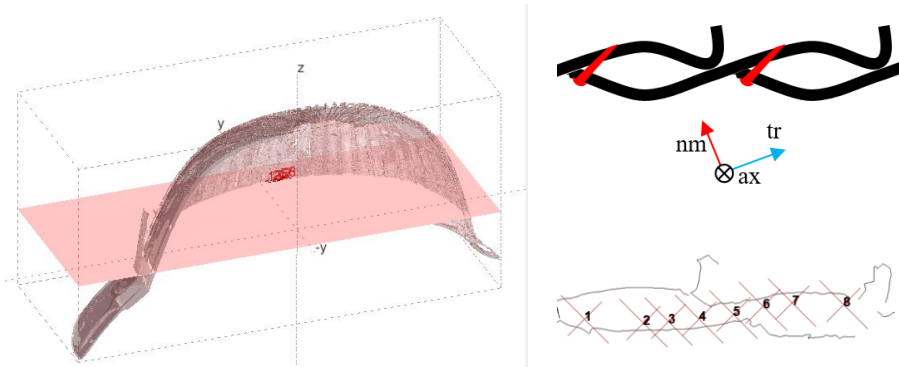


Figure 4 (Left) The ENGIN-X virtual laboratory, a three-dimensional model of the sample used for planning the experiment. The reconstruction of the sample was obtained with a laser scanner and input to the SScanSS virtual laboratory; the position of the investigation points is reported in red (Right). Correspondence between the schematics of an “S”-shaped plate with its principal directions (above) and the laser scan of the kabuto with the measuring points (below) in the ENGIN-X virtual laboratory system.

The sample was translated and rotated across the beam in order to scan the selected points across the plate, collecting diffraction patterns along the transversal direction with a step size of around 0.25 mm. However, because of the encumbrance of the 0.5 mm collimation system, only the collimators of the North diffraction bank of ENGIN-X were mounted to allow for sample positioning, resulting in three independent set of measurements acquired rotating the sample of 90 degrees. For normal and axial direction we investigated a gauge volume of $0.5 \times 0.5 \times 15$ mm³ (assuming the strain

to be homogenous in the axial direction), while for the transversal direction the selected gauge volume was $0.5 \times 0.5 \times 0.5 \text{ mm}^3$.

Results and discussion

Due to the ISIS beam instability, challenging positioning of the object, and inability to repeat the experiment, only the plate marked in figure 4 was investigated, out of the three planned in the original proposal.

The reference global stress-free lattice parameter d_0 was measured on a pure ferrite powder and local lattice variations in the samples were assumed independent from compositional changes (as diffusion of carbon in ferrite). This assumption is based on the fact that the artefact is made of carbon steel, where interstitial carbon can reach a maximum of 0.022 wt% in the ferritic phase, having almost no effect on the ferrite lattice spacing. Elements known to have a modifying effect on the iron lattice—like Ni, Mn, and Cr—are not expected to be present in historical iron.

The results are summarised in figure 5, alongside the relative positions of the probed points. Measurement point #8 was removed from the plot as the gauge volume investigated was not properly filled by the metal, probably due to a thicker layer of patina on the surface.

As a general consideration, tensile stress conditions can negatively affect material performance or component life, while compressive stress conditions can improve material fatigue strength. Given the strain principal directions as defined above, it is clear that the most important direction for the effectiveness of the structure is the normal one, along which the blows would be struck onto the helmet. Instead, minor strength components from the blow are expected to affect the axial and transversal direction.

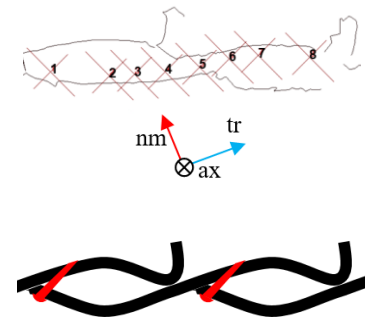
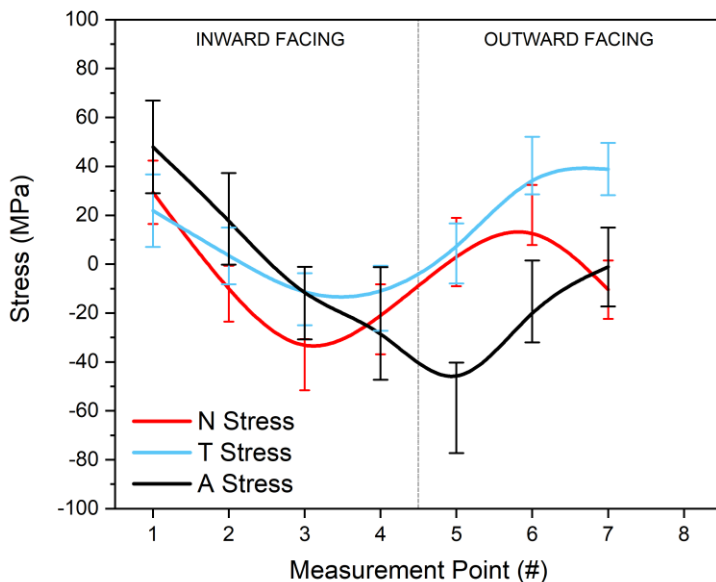


Figure 5 (Left) Stress distribution and orientation along plate cross section. Measurement points 1–4 face the inside of the helmet, while points 5–8 are relative to the exposed surface of the plate. The gauge volume for measurement point #8 was not properly centred in the plate. (Right). Position of the measuring points along the plate cross-section and principal directions.

It is clear from Figure 5 that the part of the “S”-shaped plate underneath the neighbouring one (measurement points 1–4, the inward facing *concave area*) is in a compressive state along the normal and transversal directions. This suggests a higher resistance to deformation for stresses applied along the normal and transversal directions in the inward facing part compared to the part bulging out and superimposing the neighbouring plate (measurement points 5–7, the outward facing *convex area*). When hit, the outward convex area is in fact more prone to deformation compared to the inward facing one. The outer area, by deforming, acts as sacrificial element, attenuating the blow and redistributing the residual fraction of it to the neighbour plates. When a residual fraction of the blow affects the concave part of the structure, it finds a stronger and more resistant material less prone to deformation. Being this area closer to the wearer’s head, it is important that its integrity is protected. This is a common practice even in modern engineering components, when the most important area is designed to be safeguarded at the expenses of a sacrificial part which deforms protecting the rest of the structure as, for example, rupture disks in high pressure circuits.

Conclusions

This early 17th Century Samurai *kabuto* constitutes an example of the technological developments that followed the introduction of firearms in Japan in the 16th Century, when armourers experimented with new manufacturing and assembly methods to produce pieces providing higher protection to the wearer [13]. Given that a harquebus offers attack power of around 1300 J [14], against 80 J and 60–130 J for arrow and sword/axe respectively, we can observe that the induced stress is of the same order of magnitude of the residual strain measured and the yield strength of the material.

The experiment entailed many difficulties related to positioning, measurement point selection, and beam instability, hence we investigated residual stresses along a single plate of the Saotome *kabuto*. Although the area investigated is limited, we highlighted the presence of what seems to be a very efficient solution to increase the protection given by the helmet. These are tentative conclusions based on limited data, but interpreted considering the historical background when the object was manufactured.

Despite the challenging experiment, neutron diffraction techniques represent the ideal tool to investigate, non-destructively, stresses in metallic objects, not only in the case of modern engineering components, but also in more complex and less understood objects such as ancient armour components or metallic artefacts more generally.

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