Metallographic examination of a Japanese sword
Jerzy Piaskowski

Abstract

An early Japanese sword showed construction of the makuri-kitae or kofuse-kitae type. Its edge and outer zone were made of high carbon tool steel (0.6-0.8% C), while the core was of soft, low carbon steel (ca 0.2% C). The sword was quenched and showed an acicular (martensitic) structure near the edge.

Introduction

Early Japanese sword making started at about 700 AD. Some historians assume that iron technology was influenced from West Asian countries such as India, Iran and Turkey through the famous Silk Route. Later, the development of sword production was bound up with the history of Japan. Demand for swords was high in times of war, mostly in the period 1467-1603. Early Japanese swords and their technology are described in numerous Japanese publications.

Excellent research on Japanese swords was done by K Tawara at Tokyo Imperial University; he made great efforts to investigate the history of ancient Japanese ferrous metallurgy. His work has been continued by Tanimura (1939, 1980) who described the development of Japanese swords. The most detailed presentation of this topic in English is by Bain (1962). In 1936-38 research on the technology and structure of Japanese swords was carried out by Tanimura at KyÅšu Imperial University. In this research original iron and steel made in the Tatara furnace (ie directly smelted) were used, both high carbon, hypereutectoidal steel containing 1.2-1.7% C (tama-hagane) and low-carbon steel containing less than 0.05% C (hocho-tetsu) made by decarburizing pig iron from the Tatara furnace. This method of iron and steel smelting is described by Kubota (1970).

Tanimura (1980) examined two swords made in his laboratory; however no difference in the metal of the cross section was revealed. The first sword was made of eutectoidal steel containing ca 0.8% C while the second one was of middle carbon steel (ca 0.45% C).

Very few early Japanese swords have been examined metallurgically. C S Smith (1957) carried out the analysis of four such swords; his most important results are summarized in Table 1. Of these swords, one (No 3) was made of evenly carburised modern high carbon steel. The concentration of manganese, silicon and copper showed that the steel had been smelted using the modern indirect process.

The three other swords were made of directly smelted steel (ie it had been made using the bloomery process). Sword No 2, and probably both Nos 7 and 9, had constructions of the makuri-kitae or kofuse-kitae type

<table>
<thead>
<tr>
<th>Sword No</th>
<th>Dating (century)</th>
<th>Chemical composition (%)</th>
<th>Microhardness (kg/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C (edge)</td>
<td>C (body)</td>
</tr>
<tr>
<td>2</td>
<td>19th</td>
<td>0.62</td>
<td>0.10</td>
</tr>
<tr>
<td>3</td>
<td>c.1940</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>7</td>
<td>18th</td>
<td>0.69</td>
<td>0.43</td>
</tr>
<tr>
<td>9</td>
<td>16-17th</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 1: Data for four Japanese swords examined by Smith (1957).

Signed 'Omi no Kami Nabuyuki' * about 5mm from the cutting edge
Signed 'Sawata Kanemitsu' # about 4mm from the cutting edge
which was commonly used in Shinto-time period 6, i.e. in 1544-1800 AD (Tanimura 1980). The core in swords No 9 and No 7 was made of irregularly carburized steel, while the core in sword No 2 had the structure of very low carbon steel. The microhardness of the steel near the cutting edge was about 800 kg/mm², due to a martensitic structure obtained by quenching. Further from the edge, the microhardness of the blade is only 200-400 kg/mm².

Thanks to the help of Mr K Kubota the author had the opportunity to investigate a specimen of a Japanese sword made by an excellent blacksmith. The main goal of this examination was the better documentation of the metallographic structure of Japanese swords than had previously been published.

**Early sword technology in Japan**

The technology of making swords in Japan was very particular. The fragments of bloom, i.e. of crude iron (tama hagane), were forged into small plates, welded together (Fig 1), forged, bent again and welded many times (maybe 20-30). Then it was formed into a heavier piece, necessary for making the sword or other implement. These extremely laborious techniques which consumed much charcoal may be explained as follows:

In Japan the iron, smelted from low phosphorus ores in special bloomery furnaces (Tatara process), had a very varied and irregular carbon distribution. The bloom was composed of parts with very low carbon content (i.e. traces) but also parts containing more, up to 1.5% C. Some of the metal even melted and contained 3.0-4.0% C (pig iron) (Kubota 1970). Probably the latter was crushed and used for carburization of some of the plates.

Two kinds of metal were produced. These were 1) hard, tool steel (with high carbon content), used for making the sword edge and outer zone (takane) and 2) soft (low carbon) steel, used for making the core of the blade (shin-gane or hocho-tetsu). Probably during forging, the latter was exposed more often and for a longer time to the air at a high temperature and almost all its carbon was lost by decarburization. Using the two types of steel several weld constructions for sword blades were developed (Fig 2). Of these methods, makuri-kitae and kofuse-kitae were commonly used in Shinto-time period 6 (1544-1800).

After the forging to the desired form is completed, final shaping of the sword is by filing. On the back of the sword blade, where soft and tough properties are required, a thick clay coating is applied (Fig 3). The hardened zone, near the edge, is coated in a special way
with a very thin layer of selected clays to prevent oxidation. This differential coating is very important for making the characteristic pattern on the surface of the sword which was revealed by cleaning, grinding, polishing and etching. The area near the cutting edge, thanks to its martensitic structure is more resistant to the acid and remains bright whereas other metal layers, consisting of some products of austenite decomposition, become dark coloured.

Fig 3: Schematic cross section of blade prepared for quenching, after Smith (1957).

Methods of examination

The methods of examination of the specimen cut from a Japanese sword were the same as used by the author for metallographic researches on other early iron implements. The examinations were carried out in the laboratories of the Foundry Research Institute in Kraków, Poland.

Chemical analyses for main constituents and residuals were carried out, namely: carbon and sulphur — by Leco method, phosphorus, nickel and copper — by a photometric method, silicon and manganese by atomic absorption. The data obtained is a mean result for the whole blade. The carbon content was estimated based on the structure of the metal after the homogenisation of the specimen at 900°C for 10 minutes.

Metallographic observations were carried out using a Neophot 32 microscope, the grain size of the metal was determined compared with Polish standard PN-84/H-04507 (corresponding to American standard ASTM E 112-82), and microhardness measured using a Hanemann tester with 50g load for 15secs; every result is the arithmetic mean of 5 measurements. The Vickers hardness measurements were carried out using a 10kg load for 15 secs; every result is the arithmetic mean of 2-3 measurements. The structure of slag inclusions was estimated based on observations of the unetched specimens (at x500 magnification) and on the typology proposed by Piaskowski (1976).

The characteristics of slag inclusions in the metal were measured using a Quantimet 570 color. The measurements were carried out at x100 magnification. The number, area fraction and the statistical characteristics (, Me, Mo, S, A) of the size of the slag inclusions were determined. In all cases the distribution of the area of slag inclusions was far from a normal (Gaussian) one. Thus Pearson's asymmetry coefficient was calculated, based on the difference between arithmetic mean and the mode Mo:

\[ A_{s} = \frac{(\bar{x} - Mo)}{S} \]

It seems that the asymmetry coefficient, when the mode (Mo) is replaced by the median (Me), may be more precise:

\[ A'_{s} = 3(\bar{x} - Me)/S \]

Results

Chemical composition: The chemical analysis showed the following mean composition for the blade: 0.67% C, 0.052% P, 0.017% Cu, 0.018% Ni, 0.08% Si, 0.002% Mn, 0.0025% S.

Macrostructure: The macrostructure of the cross section of the sword showed that it consists of a core made of low carbon steel surrounded by high carbon steel (Fig 4).

Fig 4: Macrostructure of the cross section of the blade (a negative) showing hard steel outside a soft steel core. Nital etched ca x3. The areas shown in Figures 12-18 are indicated on the sketch.
The joining of low carbon steel and high carbon steel is more apparent under higher magnification (Fig 5). On the back of the sword a crack was observed (Fig 6).

**Fig 5:** Macrostructure of the cross section of the middle part of the blade. Nital etched x10.

**Fig 6:** Macrostructure of the cross section of the back of the blade showing the crack. Nital etched x10.

**Slag inclusions:** The number of slag inclusions, especially in the core, was rather low. More inclusions were observed in the join (welding transition) between the core and the outer parts (Fig 7a). The slag inclusions were very small, probably they were dark coloured (type A in Piaskowski’s (1976) classification), but in some bigger slag inclusions the structure was more complicated, e.g. they contained some rounded light inclusions mixed with the gray and dark coloured constituents (type E — Fig 8).

**Fig 7:** The welding zone (at the bottom) between the outer part (to the left) and the core (to the right). a) the chain of slag inclusions x50, b) Nital etched x100.

**Fig 8:** The structure of bigger slag inclusions. Unetched x500.

No regular traces of welding between the primary plates (particles) were observed. In the outer zone bigger slag
inclusions were observed. It is rather difficult to explain their shape (Fig 9); maybe it was the slags (oxides?) on the boundaries of a plate.

![Fig 9](image-url)

**Fig 9**: A chain of slag inclusions found in the outer part of the sword. Unetched x50.

The characteristics of the measured slag inclusions in the sword are given in Table 2. The arithmetic mean (\( \bar{x} \)) and standard deviation (S) are given there in brackets because they cannot directly represent the size distribution. The number and the area fraction of slag inclusions were lower in the soft core than in the cutting edge and outer zone made of tool steel. The mode value of the size of slag inclusions (5 square microns) was lower than that observed in normal bloomery iron smelted in Europe. The distribution of frequency against area of slag inclusions (Fig 10) and the scatter plot of perimeter against area of these inclusions (Fig 11) were similar in all areas examined.

**Microstructure**: At the cutting edge an acicular (martensitic) structure was observed (Fig 12). Further from the edge the structure changed to bainite (Fig 13) and fine pearlite, with traces of ferrite on the grain boundaries (Fig 14). A similar structure was observed at the surface, midway between cutting edge and back of the sword (Fig 15).

![Graph](image-url)

**Fig 10**: Frequency histogram of the area of slag inclusions in a) the cutting edge, and b) in the core.

The structure of the core of the blade was extremely fine grained (class 10). At the join between the outer part and core no sudden change of structure was observed (Fig 7b). This was the result of carbon diffusion from the hard outer steel into the low carbon steel core during the heating and forging of the blade. The low phosphorus content of both kinds of steel makes this process easier. Etching the specimen with Oberhoffer’s reagent revealed homogenous phosphorus distribution in both low and high carbon steels; they contained low concentrations of this residual. The metallographic observations under higher magnification (x500) revealed the structure of the core, consisting fine grained ferrite and pearlite (Fig 16). Near the back of the sword fine distributed pearlite and ferrite were observed (Fig 17). Maybe this represents the original

<table>
<thead>
<tr>
<th>Location of measurement</th>
<th>Area fraction</th>
<th>No per mm²</th>
<th>Mean</th>
<th>Median</th>
<th>Mode</th>
<th>Standard deviation</th>
<th>Coefficient of anisotropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting edge</td>
<td>2.4</td>
<td>881</td>
<td>( \bar{x} )= (8.01)</td>
<td>6.644</td>
<td>5.0</td>
<td>(4.161)</td>
<td>0.483</td>
</tr>
<tr>
<td>Area of joining</td>
<td>4.2</td>
<td>201</td>
<td>( \bar{x} )= (13.23)</td>
<td>10.13</td>
<td>5.0</td>
<td>(8.937)</td>
<td>0.809</td>
</tr>
<tr>
<td>Soft steel core</td>
<td>1.9</td>
<td>199</td>
<td>( \bar{x} )= (10.33)</td>
<td>7.698</td>
<td>5.0</td>
<td>(6.610)</td>
<td>0.655</td>
</tr>
<tr>
<td>Hard steel layer near the surface</td>
<td>3.3</td>
<td>553</td>
<td>( \bar{x} )= (7.74)</td>
<td>6.595</td>
<td>5.0</td>
<td>(3.526)</td>
<td>0.493</td>
</tr>
</tbody>
</table>

**Table 2**: Data for slag inclusions in the sword.
structure of plates, not influenced by heat treatment of the blade. The surfaces of the crack in the back of the blade were corroded, maybe as result of oxidation in the blacksmith's fire (Fig 18). The structure in this area in the core of the blade consists of fine grained ferrite and
Fig 17: The structure of the core near the back of the blade. Nital etched x500.

Fig 18: The structure near the crack in the back of the blade. Unetched x500.

Fig 19: The structure near the crack in the back of the blade. Nital etched x500.

Conclusions

The Japanese sword examined showed blade construction of the makuri-kitae or kofuse-kitae type. Tanimura (1980) wrote that it was commonly used in the Shinto-time period 6 (1544-1800 AD) but Smith (1957) found the same structure in his sword No 2 deriving from the 19th century.

<table>
<thead>
<tr>
<th>Location examined</th>
<th>Structural constituents</th>
<th>Grain size</th>
<th>Microhardness kg/mm²</th>
<th>Vickers hardness (HV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>the core at the back of the blade</td>
<td>ferrite</td>
<td>12</td>
<td>195</td>
<td>193</td>
</tr>
<tr>
<td>the core nearer the cutting edge</td>
<td>pearlite</td>
<td>12</td>
<td>236</td>
<td>193</td>
</tr>
<tr>
<td>the core nearer the cutting edge</td>
<td>ferrite</td>
<td>*</td>
<td>260</td>
<td>191</td>
</tr>
<tr>
<td>near the back of the blade</td>
<td>pearlite</td>
<td>*</td>
<td>241</td>
<td>193</td>
</tr>
<tr>
<td>near the back of the blade</td>
<td>ferrite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>near the back of the blade</td>
<td>pearlite</td>
<td>*</td>
<td>283</td>
<td>221#</td>
</tr>
<tr>
<td>in the middle of the blade</td>
<td>sorbite</td>
<td>283</td>
<td>221#</td>
<td></td>
</tr>
<tr>
<td>in the middle of the blade</td>
<td>ferrite</td>
<td>283</td>
<td>221#</td>
<td></td>
</tr>
<tr>
<td>at the edge</td>
<td>bainite</td>
<td>283</td>
<td>221#</td>
<td></td>
</tr>
</tbody>
</table>

* at the grain boundaries
# further from the cutting edge than the microhardness measurements

Table 3: Metallographic data for the sword.
In these swords the technology was well mastered. The core was made of low carbon steel with even carburization, very suitable for this purpose. In two swords previously examined by Smith (1957), one from the 16-17th century (No 9) and one from the 18th century (No 2) the carburization of the core was considerably higher and irregular. Such blades were more rigid but not so shock resistant as the other swords examined by Smith (ibid) and by the present author.

It is interesting to note that there were considerably fewer slag inclusions in the core of the sword examined here than in the edge and outer zone of the blade; maybe multiple folding, bending, welding etc as described by Tanimura (1980) and Bain (1962) was used only for making the pieces of soft, low carbon steel (shin-gane or hocho-tetsu). Thus this very complicated and laborious technological process was applied not only for decarburization and homogenisation but also for partially removing the slag inclusions, which exist in all directly smelted iron.

Summarizing, this Japanese sword represents early technology (construction, welding and heat treatment) perfectly and appropriately mastered, although on the back of the sword a crack and the remains of a slaggy (?) substance have been observed.

References


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The author

Jerzy Piaskowski gained an MA from the Department of Metallurgy in the Academy of Mining and Metallurgy in 1948 and from the Department of Mathematics, Physics and Chemistry at Jagiellonian University in Kraków in 1952. In 1960 he obtained a DSc from the Silesian Polytechnic School. He has been an assistant professor since 1973 and from 1987 a full professor. Since 1947 he has been associated with the Foundry Institute in Kraków, working on physical metallurgy and malleable and nodular cast irons. From 1954 he undertook metallographic examination of early iron implements and is the author of numerous papers and books including On damascene steel (1974) and The technology of art castings (1981).

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