Microstructural Investigation on a Medieval Sword Produced in 12th Century A.D.

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The construction of sword during the medieval age reaches a good level of quality in the western world where the “Damascus” swords assumes a legendary fame. Even from the ancient times two types of “Damascus” swords have been known: the eastern type based on the application of the ipereuctoid steels and the Western Damascus or Welded Damascus, because obtained through the friction welding of thin strips featured by different carbon contents. In this study a sword found in 1948 on the Adige riverside, near Legnago, has been sectioned and examined by optical microscopy, SEM-EDS, SEM-EBSD and the micro-hardness Vickers testing in order to point out the main microstructural features of the welded system, to identify the chemical composition of the non-metallic inclusions and the crystallographic textures produced by the forging operation. The obtained results have permitted to formulate plausible hypothesis about the significant aspects of the production process: temperature of the ore reducing furnace and of the thermo-mechanical route followed by the ancient artisans.

KEY WORDS: Damascus sword; non-metallic inclusions; friction welding; textures; plastic deformation.

1. Introduction

Already in the ancient times and in the middle ages the mechanical features required for a sword can be identified in the high yield strength associated with a good toughness level. The high strength level of the alloy can grant the cutting efficiency of the blade and the absence of permanent plastic deformation while the toughness assures resistance against the development of a brittle fracture during the impulsive load application. In the metal alloys the coexistence of high yield strength and toughness can be a problem even nowadays. The techniques developed by the ancient artisans to reach this aim are an item of extreme interest. On the basis of the archeological research and the documentation we can recognize at least three processes for the production of the ancient steel sword1–3):

• Japanese technique designed for the production of the yakiba swords;
• “Eastern Damascus” technique diffused in the Indian-Persian regions;
• “Western Damascus” or “Welded Damascus” which has encountered a significant success in the regions around the Mediterranean Sea.

The Japanese swords (Suguha, Magariba) are produced starting from a bar of core steel featured by low carbon content which is wrapped by skin steel with high carbon. Then, the system of the two steels is forged to produce a high number of layers (approximately 1.000 to 30.000) by successive folding operations. The forged steel is coated by a layer of clay mixed with charcoal (yakibatsuchi). The clay coating is thinner near the blade, so that after the heating up to 820–850°C and the following plunging in the water, the blade can undergo a quenching process in order to produce the martensite. Only the blade zone undergoes the phase transformation which causes the precipitation of the martensite in the fast cooled regions and the related thermal expansion causes the particular bended shape (sori) typical of these swords.

The “Eastern Damascus” has been realized starting from an ipereuctoid steel produced in the Indian-Persian Region and called wootz steel. Some authors have advanced the hypothesis that this iron alloy can be the same material indicated as ferrum indicum by the Romans.4) The production of such a steel has been also recorded by the British colonial functionary during the 19th century and probably this is strongly analogous to the one implemented during the ancient times.5) Some fragments of sponge iron produced by direct reduction in the reduction furnace are closed in a clay shell with charcoal fragments and other organic material and then heated up to produce the combustion of the rich carbon substances. The produced carbon monoxide can adsorb on the steel surface producing the release of the carbon on the low-carbon steel fragments and then this implies a diffusion of carbon into the metal and a related decreasing of the melting point of the enriched zones. Thus, the steel enriched by carbon also over the eutectoid point is led (at least in part) to the liquid state and then cooled to the solid one. The produced little ingot is then heated for a carbide spheroidation treatment in order to increase the ductility and the related formability of the
alloy. The final microstructure rich in globular carbides embedded in the perlite gives a macroscopic striped aspect alternating the clear and dark zones in a particular mixing which turns out in that characteristic look defined as Damascus. The hardening is achieved through the plastic deformation working avoiding the quenching massive treatment which can cause an excessive brittleness of the swords.

In the Mediterranean regions this technique was not applied, because the only known method for increasing the carbon content of the low carbon steel produced by direct reduction was permanence of the reduced iron over the forge furnace where it underwent the diffusion of the carbon from the atmosphere strongly enriched by carbon monoxide. Only the thin steel strips can be efficiently carburised by this method and their thickness is not enough to constitute the body of the sword. So, the ancient artisans has ideated a construction procedure in which the sword is realized by assembling of different layers of strips featured by high and low carbon content. The final microstructure is realized by the combination of these different layers and at a macroscopic level results in an analogous striped aspect alternating the clear and dark zones similar to the look shown by the Eastern Damascus, but in this case this is the consequence of the combination between the low and high carbon strips. It is suggestive that an analogous process was followed centuries later in the Himalayan and Indochinese zones to produce the sword generally known as Kris and Pamor, respectively.

2. Experimental Procedure

The object of the present analysis is a sword dated back to the 12th century and found in 1948 along the Adige riverside near Legnago in the northern Italy (Fig. 1).

The sword has been subjected to a great oxidation and damaging phenomena due also to the interaction of the environmental agents, but the shape can be inferred. The analysis of the microstructure has been performed on two cut sections (Fig. 2).

The observation of the microstructure has been realized after the grinding and polishing of the extracted coupons and after the immersion of the coupons in the Nital metallographic etching (0.5% HNO₃ for 100 mL of ethanol) for 25 s.

The chemical composition of the non-metallic inclusions has been measured through the SEM-EDS technique and within them all the different phases revealed by EBS (Electron-Back-Scattering) have been chemically analysed.

The SEM-EBSD (Electron-Back-Scattering-Diffraction) has been performed on an area of the sword sections perpendicular to the sword axis. The analysed area is featured by a 10 mm² extension and the area has been scanned by a pixel resolution of 2.5 μm², an accelerating voltage of 20 kV and the step size chosen for each maps is of Δϕ₂ = 10°.

Fig. 1. Location of the site at which the analysed sword was found in 1948.

Fig. 2. The examined sword. The arrows indicate the positions from which the analysed coupons have been sampled.
On each identified strip welded in the system constituting the sword, a micro-hardness Vickers test has been realized to point out the trend of the micro-hardness values along the sword section as a function of the depth from the lateral sword side.

3. Results

The macroscopic observation points out that the sword shows a double blade and it indicates also that the weapon is composed by regions featured by different microstructures (Fig. 3) probably characterized by a different carbon content and the optical microscope observations performed at the lowest magnitude (×25) permitted by the used system have clearly evidenced the layered structure accentuated by the fibrous look assumed by the dark-non metallic inclusions (Fig. 4).

The observations realized at higher magnification have

![Macroscopic observation on the section of the coupon cut near the handle of the sword.](image1)

![Optical micrographs performed at low magnitude pointing out the layered system which composes the sword.](image2)

![Optical micrograph pointing out two different ferritic layers and the welding zone characterized by a higher volume fraction of the non-metallic inclusions and by a finer grain size.](image3)
also revealed that the separation among the strips are featured by a larger amount of the non-metallic inclusions and that the ferrite grains interested by the presence of these elongated non-metallic phases are characterized by a finest size than the core regions of each strip (Figs. 5, 6, 7). Thus, the regions interested by the presence of the finest grain size and by the huge amount of the non-metallic inclusions can be recognized as the welding joining.

The ferritic structures are concentrated in the core of the sword, while an increasing carbon content has been pointed as the distance from the surface decreases and this determines the change of the structural components present within the sword (Fig. 8). A gradual but evident transition of the microstructures distinguishes the intermediate layers between the surface and the core (Fig. 9).

The outer layer are interested by a nearly complete perlitic structure indicating a carbon content in the 0.8–0.75% range. In particular regions the perlitic grains featuring the surface of the sword are surrounded by secondary-cementite structure indicating a carbon level which is locally even higher than the eutectoid carbon concentration (Fig. 10).

The SEM-EDS analysis has allowed to measure the chemical composition of the observed non-metallic phases. The performed investigations have pointed out that the largest amount of the non-metallic inclusions is composed by bi-phase structure (Figs. 11, 12), in which the dark phases is constituted by fayalite (\(2\text{FeO} \cdot \text{SiO}_2\)) and the clear one by iron oxide (\(\text{FeO}_n\)).

The measurements developed on a total number of 15 non-metallic inclusions show low variation around the average chemical composition (Table 1). It is worth noting that in the fayalite phase a significant increase of the phosphorus has been revealed.

The non-metallic inclusions numbered from 1 to 7 belong to the welding zone, while the other ones belong to the bulk of the layers.
On the other hand, a little amount of the non-metallic inclusions shows only the prevalent presence of the SiO$_2$ featured by a more globular shape than the bi-phase inclusions (Fig. 13).

Also within the body of each welded layer the inclusions are featured by FeO$_2$ and by 2FeO·SiO$_2$.

The SEM-EBSD analysis has permitted to define the orientation map of each scanning area and the ODF representation is quite clear (Fig. 14) for the identification of the main texture components among which can be recognized:

- \{011\}(1\overline{1}0) Rotated Goss along the \(\alpha\)-fiber with a logarithmic intensity level of 8;
- \{111\}(1\overline{1}0) and \{111\}(1\overline{3}2) belonging to \(\gamma\)-fiber with a logarithmic intensity level of 8;
- \{123\}(211) S1-texture featured by a logarithmic intensity level of 7;
- \{001\}(100) Cube texture featured by logarithmic intensity level of 6.

### Table 1. Chemical composition of 15 non-metallic inclusions revealed in the analysed steel welded layers.

<table>
<thead>
<tr>
<th>Inclusions</th>
<th>%wt</th>
<th>MgO</th>
<th>Al$_2$O$_3$</th>
<th>SiO$_2$</th>
<th>P$_2$O$_5$</th>
<th>CaO</th>
<th>TiO$_2$</th>
<th>MnO</th>
<th>FeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>clear phase</td>
<td>-</td>
<td>0.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>dark phase</td>
<td>1.2</td>
<td>27.1</td>
<td>7.4</td>
<td>1.0</td>
<td>2.2</td>
<td>56.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 11. Example of a non-metallic inclusions featured by two phases.

Fig. 12. Example of a non-metallic inclusions featured by two phases.
The Vickers micro-hardness tests have been performed on the thickness centre of the different distinguished welded layers (Fig. 15) (Table 2). A very symmetric trend of the hardness profile has been pointed out from a surface layer to the opposite one and the decreasing trend from the surface to the core is very clear. The surface layers reach a micro-hardness value of 179–181HV while at the core this value decreases to 105HV.

![Figure 13](image)

**Fig. 13.** Example of a non-metallic inclusions prevalently composed by SiO₂ and Al₂O₃ observed near the biphasic inclusions on the welding zone between two strips.

### 4. Discussion

The layered structure can be easily recognized by the complete observation of the profile of the sword section (Fig. 8) on which the welded lines can be rapidly identified by the high concentration of the aligned non-metallic inclusions. The non-metallic inclusions separating the different layers are mainly constituted by fayalite which is featured by a low melting point (Fig. 16) of 1 481 K (1 208°C), but the observed saturation of FeO causes a further decrease to a lowest temperature of 1 448 K (1 175°C). This type of non-metallic inclusions features the welded lines and also the little non-metallic inclusions trapped in the body of the different layers originated by the trapped slag coming from the reduction furnace. The presence of those little non-metallic inclusions are due to the applied process in which the ore reduction certainly has taken place in the solid phase, actually in the Mediterranean and European area the production of liquid pig iron is not known. These observations suggest that the ancient metallurgical artisans have developed a particular formulation of the slags involved in the reduction operation and in the welding one which could improve the result of their own effort during the forging of the reduced bloom and of the strips to be welded.

![Figure 14](image)

**Fig. 14.** The ODF map revealed by the analysis of a zone of 10 mm² in the core of the analysed sword.

![Figure 15](image)

**Fig. 15.** The different analysed layer which have undergone the Vickers micro-hardness characterization.

![Figure 16](image)

**Fig. 16.** The FeO₇–SiO₂ phase diagram.
Actually, the formation of slags featured by a low-melting point during the iron ore reduction by the addition of SiO₂-based materials can improve the efficiency of the hammering operation performed in order to remove the trapped slags. Moreover, if the metallurgical artisans have found a good solution in the formation of the fayalite compounds, this indicates that the iron-ore reduction and the successive hammering of the bloom takes place at a temperature at least higher than 1 450 K and, provided the weakness of the applied fireclay refractory materials, they cannot take place over 1 523 K.\textsuperscript{12} Thus, it is possible to formulate the hypothesis that the iron-ore reduction has taken place between 1 450 K and 1 523 K while the immediate successive hammering have probably taken place at least over 1 450 K.

The presence of fayalite saturated with FeO\textsubscript{2} can permit to infer some information about the oxygen potential of the atmosphere interesting the ore reduction and the welding operations. The iron activity of the steel strips can be approximated near unity, while the activity of the iron oxide can be considered as 0.5 in 2FeO SiO\textsubscript{2} and 1 in the FeO\textsubscript{2} phase surrounding the fayalite.\textsuperscript{13} On the basis of the data of Gibbs free energy:\textsuperscript{13}:

\[ G_{\text{Fe}} = -83.25T + 42 425 \quad (J/mol \text{ Fe}) \quad \ldots(1) \]
\[ G_{\text{FeO}} = -148.79T - 209 463 \quad (J/mol \text{ FeO}) \quad \ldots(2) \]
\[ G_{O} = -145.28T - 76 028 \quad (J/mol \text{ O}) \quad \ldots(3) \]

the equilibrium constant for FeO\textsubscript{2} can be computed as:

\[ \Delta G_{\text{FeO}_2} = G_{\text{FeO}_2} - G_{\text{Fe}} - G_{O} \quad \ldots(4) \]
\[ K_{\text{FeO}_2} = \exp\left(\frac{-\Delta G_{\text{FeO}_2}}{RT}\right) \quad \ldots(5) \]

the oxygen activity in equilibrium with the observed phases can be set at the value:

\[ a_{O} = \frac{a_{\text{FeO}_2}}{K_{\text{FeO}_2} a_{\text{Fe}}} \quad \ldots(6) \]

and then the oxygen potential can be computed according to:

\[ \Delta \mu_{O} = RT \ln p_{O} \quad \ldots(7) \]

provided that:

\[ \frac{1}{2} \text{O}_2 \rightarrow \text{O} \quad \ldots(8) \]

is featured by a Gibbs standard free energy of:

\[ \Delta G_{O_2} = -3.37T - 116 300 \quad (J/mol \text{ O}) \quad \ldots(9) \]

Under the proposed hypothesis at 1 483 K (within the supposed thermal range) the computed oxygen potential of the atmosphere featuring nearly pure iron equilibrated with the fayalite is of \(-374\) kJ/mol O\textsubscript{2}. This oxygen potential is too high to permit a good carburation of the different coupled steel layers. This is a first clue that the carburizing process takes place in a different stage nor during the reduction process neither during the welding one. The carbon concentration in the outer layer reaches the iper-eutectoid values as proved by the presence of secondary cementite precipitated along the boundaries of the perlite grains (Fig. 10). This statement implies that the carburation process of the outer layers has been performed after the reduction process and before the welding one realized exploiting the heat and the atomic diffusion promoted by the friction phenomena induced among the different layers by the welding process. If this hypothesis is correct, the outer layers have been enriched by carbon before the welding process and during the welding process the carbon diffuses into the inner layers, producing the decreasing of the carbon concentration from the outer layers to the inner ones. The decreasing trend of the carbon content (Fig. 8) is sharper across the welded joining regions representing zones which slower the diffusion kinetics of carbon, because they are featured by a finest grain size and so by a larger extension of the grain boundaries per volume unit which has to be crossed by the carbon atoms. The smallest grain size found in correspondence with the welding lines and the more globular shape of these grains are phenomena consistent with the hypothesis of the realization of a friction welding in which the joining between the different adjacent layers implies also the recrystallization of the grains present in that zone, because this phenomenon is made possible by the heat developed near the welding line associated with the larger deformation produced by the compression force induced by hammering and by the related friction stresses and strains.

The huge amount of the bi-phase inclusions featured by fayalite on the welding lines separating the different joined strips is probably related to the intentional application of the low-melting slag on the surface of the forged strips to be welded. The presence of the SiO\textsubscript{2} non-metallic inclusions near the welding lines corroborate the hypothesis that the fayalite inclusions and slags are intentionally formed by addition of silica sand to the iron oxide slag. The coating of such a non-metallic fayalite compound saturated by iron oxide can perform a coating anti-oxidant function on the strip surface avoiding the oxidation of the metal which can compromise the realization and the successive stability of the welding joining. On the other hand, the temperature reached by the heat development due to the high friction produced by the hammering of the different strips can permit the evacuation of the anti-oxidant layer during the welding forging.

The high inclusional amount encountered on the welding lines and the smallest grain size here observed (associated to a largest boundary surface) have certainly played an important role on controlling the carbon diffusion. Actually, the sharpest variation of carbon content interests the transition zone between a strip and the adjacent one. Probably the ancient smiths have started from outer strips rich in carbon which reach a values even higher than the eutectoid composition, and the core strip of low carbon steels which are enriched by carbon during the forging at high temperature. The observed sections cannot cast light about the possibility that the ancient artisans have produced the analysed sword by the progressive bending of only two layers, a first one hugely enriched by carbon and a second one poor in this element, because the iper-eutectoid layers have not been recognized in the core of the sword. On the other hand, it is also possible that those artisans have progres-
sively bended the different strips and have enriched the outer layers by carbon only after the realization of the friction welding.

The strong presence of α-fiber and of γ-fiber indicates that the final plastic deformation of the sword has been prevalently performed in the ferritic phase and in the austenitic one without the recrystallization of this last phase which would have promoted the formation of large rotated cube textures {100}/(110) that have not been observed. So it is plausible to think that the final performed forging has been realized around 1 023–1 073 K.14) This temperature range can be suggested also by the fact that the ferritic grains recrystallized on the welded joining during the friction welding operation do not grow while the ones belonging to the core of each single strip do not recrystallize and maintain the elongated forms.

The absence of recrystallization influences also the revealed hardness profile, which shows a strong increase near the surface in which the enrichment by carbon has promoted the strengthening mechanism which has not been relaxed by the recrystallization phenomena. The softest behaviour of the core is related to the lower carbon content and to the less intensive deformation undergone by this inner strip.

On the basis of this observation it can be concluded that the ancient metallurgical artisans have designed and structured an efficient system for the production of the Western Welded Damascus which could grant a high strength of the blade and good toughness of the core.

5. Conclusions

- The analysed sword dated at 12th century represents a significant example of the “Western Damascus” or of “Welded Damascus”, so called because the sword is built through the friction welding of steel strips featured by a different carbon content;
- eight steel strips have been clearly identified by the optical microscope observation;
- the carburation process has been probably performed after the ore reduction and before the welding process, because the oxygen potential featuring the revealed non-metallic inclusions equilibrated with the steel is not certainly compatible with the iper-eutectoid carbon content revealed in the outer layers;
- the zones of the joining welded by friction are featured by ferrite grains which are more globular and finer than the ones present in the body of the layers and the larger extension of the boundaries associated with the finer grain size represent a slowing factor of the carbon diffusion from the carbon enriched outer layers to the inner ones;
- between the adjacent different strips a significant increase of the density of the non-metallic inclusions is revealed. The non-metallic inclusions are mainly constituted by fayalite (2FeO·SiO₂) which represents the eutectic of the FeO–SiO₂ system and has been probably added on the surface of the different steel layers to protect it from oxidation before the realization of the welding due to the high temperature developed during friction;
- the same type of the non metallic inclusions of featured by a finer size is revealed also in the body of the different layers;
- the traces of some SiO₂-based non-metallic inclusions seem to suggest this compound has been added under the form of sand in order to intentionally form the fayalite non-metallic inclusions saturated by FeO grooved by the lowest melting point in the FeO–SiO₂ system at 1 448 K;
- this last statement and the maximum temperature allowed by the refractories used in this age seems to suggest that the ore reduction and the welding process probably have taken place between 1 448 K and 1 553 K;
- the micro-hardness indicates that the hardening profile has shown a decreasing trend from the outer layer to the inner ones and the evaluation of the microstructure has proved that the hardening has been induced only by the hammering and not by the application of particular thermal treatment;
- the textures featured by the strong presence of α-fiber and of γ-fiber indicate that the final plastic deformation of the sword has been prevalently performed in the ferritic phase and in the austenitic one without the recrystallisation of this last phase which would have promoted the formation of large rotated cube textures {100}/(110) that have not been observed. It is plausible to think that the last performed forging has been realized around 1 023–1 073 K a temperature range allowing the formation of the observed texture components and the absence of the recrystallization of the austenitic phase.

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