1. Introduction

The iron smelting by the Tatara process and the traditional Japanese sword making may be one of the most important aspects of the pre-modern Japanese iron and steel industry. Recently, a significant progress has been made in understanding the nature of the Tatara process and the sword making with the Tatara ingot as a starting material.1–4) The Tatara process is famous for the production of a heterogeneous bloom with a vertical C gradient from a cast iron at the bottom to an almost pure iron at the top. It is known that the Tatara furnace is specifically designed for smelting sand iron ore, which is abundantly available in Japan and well known for its high Ti content.2,5) If the Tatara bloom is to be used as a raw material for making swords it is necessary to develop a special method to handle effectively the inherent compositional and structural variations of the bloom. The undesirable aspects of both the heterogeneous Tatara ingot and the labor-intensive forge/fold operation are found complemented in their combination. It is shown that this combination provides an effective control over the compositional and microstructural variations inherent in the Tatara steel while it is shaped into a sword. The finished sword comes thereby to achieve fairly uniform structures, at least, macroscopically with the earlier variation still retained in the form of fine layered microstructures. The present study shows that the key role of forging in achieving the desired effects can be understood only if the dynamic evolution of microstructure from one stage to another is carefully examined because majority of the structural developments in the forging process have only a transient existence. Besides, they often hold crucial information relating the Japanese sword making to the general technical traditions of East Asia where cast iron has been playing an important role since the inception of iron-working. This article will detail the continuous microstructural development in the entire process of the traditional Japanese sword making, without which its technical and historical facets cannot be properly recognized.

KEY WORDS: progressive evolution of microstructure; Japanese sword making; Tatara ingot; forge/fold operation.
sword making, and prior to his departure from this world handed them over to Mr. Enami for future analysis. He had saved them until they were given to the present author for the comparison of ancient sword making technologies to be made between Japan and Korea. Mr. Enami heard from Mr. Shimizu that the raw material was smelted through the application of the traditional Japanese Tatara process using sand iron ore and charcoal.

A total of 11 pieces of iron and steel samples were received for examination, which had been classified by the provider in 3 groups as listed in Table 1 and shown in Figs. I(a), I(b), I(c) and I(d). They include 2 pieces of cast iron, 7 pieces of steel called ‘Tama-Hagane’ in Japanese meaning precious steel and 2 forged steel plates. The provider labeled the samples as in Table 1, in which they are listed in a different order according to the need in the present work. All the samples in both the cast iron and steel group were reportedly from one and the same Tatara ingot, but each from different parts. Many of them assume an irregular shape with many protrusions on the surface, indicating that they were torn away from the ingot at high temperatures. It is interesting to see in Table 1 that the samples in steel group are widely different in C content, comprising 1 piece of an almost pure iron, 2 pieces of low C steel and 4 pieces of high C steel. The cast iron sample #3-1, however, appears to have been frozen after it was taken. The weight of all the samples in the steel group and sample #3-2 is seen to range from 5.0 g to 12.5 g although sample #3-2 was initially heavier than 8.5 g because it was received with a part cut away. The provider reported that the small iron and steel samples are forged into thin sheets before they are combined by light hammering at a high temperature to make a steel plate such as sample #2-2. The steel plate then undergoes repeated cycles of forge/fold operation to fashion a strip resembling a sword blade from which sample #2-1 is taken. Of all the samples examined here sample #2-1 is closest to the final product, but to be finished it still needs additional treatments such as finish forging, heat-treatment, polishing and etching.

Small specimens were cut out from the 11 samples and mounted and treated following a standard metallographic procedure before being examined under the optical microscope and the scanning electron microscope (SEM) equipped with the energy dispersive spectrometer (EDS). The EDS analysis was only to check if any other elements

<table>
<thead>
<tr>
<th>Group</th>
<th>Sample #</th>
<th>Weight [g]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>cast iron</td>
<td>3-1</td>
<td>29.5</td>
<td>white cast iron near eutectic</td>
</tr>
<tr>
<td></td>
<td>3-2</td>
<td>8.5</td>
<td>mostly peritectic dendrite with some interdendritic ledeburite</td>
</tr>
<tr>
<td>steel</td>
<td>1-1</td>
<td>12.5</td>
<td>low C steel, ferrite and pearlite</td>
</tr>
<tr>
<td></td>
<td>1-2</td>
<td>5.0</td>
<td>high C steel, proeutectoid cementite needles in pearlite matrix</td>
</tr>
<tr>
<td></td>
<td>1-3</td>
<td>18.0</td>
<td>high C steel, proeutectoid dendrite with a little interdendritic ledeburite</td>
</tr>
<tr>
<td></td>
<td>1-4</td>
<td>12.5</td>
<td>low C steel, ferrite and pearlite</td>
</tr>
<tr>
<td></td>
<td>1-5</td>
<td>7.5</td>
<td>steel near eutectoid, pearlite with a little intergranular cementite</td>
</tr>
<tr>
<td></td>
<td>1-6</td>
<td>5.5</td>
<td>high C steel, proeutectoid cementite needles in pearlite matrix</td>
</tr>
<tr>
<td></td>
<td>1-7</td>
<td>7.0</td>
<td>almost pure iron</td>
</tr>
<tr>
<td>forged plate</td>
<td>2-1</td>
<td>22.5</td>
<td>blade close to finish forging, layered microstructure</td>
</tr>
<tr>
<td></td>
<td>2-2</td>
<td>8.5</td>
<td>plate, microstructure consisting of layers of broken cementite particles in extremely fine pearlite or martensitic matrix</td>
</tr>
</tbody>
</table>

Fig. 1. General appearance of the samples provided. (a) Cast iron sample #3-1, (b) steel samples #1-1 through #1-7, (c) forged plate sample #2-2, (d) forged plate sample #2-1.
than Fe and C exist in such an amount as to affect the microstructure development. The specimens were etched around 5 sec using the solution of 3 volumetric % nitric acid in balance methanol.

3. Microstructure Examination

The results of microstructural examination will be presented first for the samples in cast iron and steel group of Table 1 in the order of C content from cast iron to almost pure iron. The results for the forged plate group will then be given, sample #2-2 first and then sample #2-1 since the former comes ahead of the latter in the sword making process.

3.1. Cast Iron

Figure 2(a) is an optical micrograph taken from sample #3-1, showing a white cast iron microstructure. It contains 4 large dark circular areas resulting from the gas bubbles entrapped during solidification. The structure is seen to consist of some dark proeutectic dendrites in the light matrix of eutectic ledeburite. The dendrite, initially austenitic upon solidification, is now of pearlite structure. The structure shown in Fig. 2(a) is typical of white cast iron whose C content is a little lower than eutectic, 4.3%. It is shown in Fig. 2(b), an EDS spectrum from Fig. 2(a), that no other elements than Fe and C are within the detection limit of the spectrometer, which is in contrast to the currently available commercial cast irons that usually contain Si from 1 to 2%. The low Si in cast iron promotes the formation of white cast iron, and is found to play an important role in the traditional Japanese sword making as is detailed later. Fig. 2(c), taken near the surface area, shows a dark layer at the bottom. This layer, corresponding to the outer surface, now takes on pearlite structure, which has been transformed from white cast iron by the removal of C atoms from the surface. This white cast iron sample, therefore, must have been treated at a high temperature for a substantial amount of time although it is not clear if it was done on purpose or by accident. If the same treatment had been given to a high Si cast iron, graphitization would have resulted throughout the sample in addition to decarburization at the surface. Judging from the surface features, round and smooth, and the C level of near eutectic, which gives the lowest melting temperature, this sample might be taken from a molten iron pool formed at the bottom of a Tatara ingot.

Figure 3 presents the microstructure of sample #3-2, showing many proeutectic secondary dendrite arms with the interdendritic ledeburite. The overall C content of this sample is estimated from comparing the area fraction of dendrites and ledeburite using an image analyzing technique to be around 2.5%. The secondary dendrite arms in Fig. 3, much larger than those in Fig. 2(a), indicate that the sample was treated in the two-phase region above the eutectic isotherm for a long time, causing the full development of proeutectic austenite. The interdendritic ledeburite that is relatively fine in Fig. 3, however, suggests that it cools down through the eutectic temperature at a relatively fast rate. This sample with its rough and irregular surface features and the full development of dendrites must have been taken in a half molten state from above the bottom where
sample #3-1 was taken.

3.2. Steel

All the 7 steel samples have similar outward appearances, and their rugged surfaces give the impression that they were not sawed but plucked at high temperatures. No difference was noticed when they were first received in a bag with a label ‘steel’, which explains why the sample was initially numbered at random. In retrospect, it seems likely that Mr. Shimizu who prepared the samples realized the differences although he may have failed to make the fact clear to Mr. Enami who saved them. As mentioned above, the 7 samples in steel group include 1 piece of almost pure iron #1-7, 2 pieces of low C steel #1-1, 1-4 and 4 pieces of high C steel. The C content and therefore the microstructure in a sample was not uniform owing primarily to decarburization taking place at the surface. The sample called low C steel, therefore, may have almost pure iron near the surface as much as the high C sample may be locally low in C.

Microstructures observed in high C steel samples #1-3, #1-6, #1-2 and #1-5 are presented in Figs. 4, 5, 6 and 7, respectively. The structures shown in Fig. 4 consist of dark pearlite and light ledeburite, which means that this sample is almost cast iron. The dark regions were formed in solidification as proeuctectic austenite dendrites ahead of the light ones that were subsequently solidified in eutectic reaction. If the mother Tatara ingot was kept above the eutectic temperature during the sample taking, which is highly probable, the sample would be partly in a molten state and the eutectic reaction must have taken place after it was detached from the ingot. The structure in Fig. 5, however, does not have any eutectic structures, indicating that the sample was completely solidified before reaching the eutectic temperature due to its lower C content than that of Fig. 4. Figure 5 is seen to contain 3 grains each of which consists of many light needles embedded in the dark matrix. The grains represent the austenite phase formed as proeutectic dendrites in solidification while the needles represent the cementite phase precipitated out from the austenite matrix on cooling to the eutectoid isotherm, 727°C, due to the solubility of C in austenite reducing with the lowering temperature. The regularities observed in the arrangement of cementite needles within each grain result from the tendency of the cementite phase to precipitate along a specific crystallographic plane of austenite phase. Such an epitaxial relationship between austenite and cementite is understood as an effort of the alloy system to reduce the free energy required in creating the interface. The remaining austenite is then transformed to pearlite in the eutectoid reaction. The microstructure observed in Fig. 6 is similar to that of Fig. 5 in that it consists of proeutectoid cementite needles in the
matrix of pearlite. Their C content is likely to be about the same as well. Of the 4 samples classified as high C steel, sample #1-5 is found in Fig. 7 to contain the least amount of C. The structure is almost completely of pearlite and the C content must be close to eutectoid, 0.77%.

The microstructures of the two low C steel samples, #1-1 and #1-4, are presented in Figs. 8 and 9(a), respectively. They both consist of the light and dark regions corresponding respectively to ferrite and pearlite. The large dark areas in Fig. 9(a) are empty spaces. These samples are hypoeutectoid, i.e., with C less than 0.77%, and on cooling to the eutectoid isotherm proeutectoid ferrite was precipitated out from the austenite matrix with the remaining austenite subsequently turning into pearlite. It is noticed in both samples that the ferrite and pearlite phases tend to form band structures. The areas near the surface of these low C steel samples are found in some cases to be almost pure iron because of decarburization, as is shown in Fig. 9(b) taken near the surface of sample #1-4.

Figure 10 presents the microstructure of sample #1-7, the only sample that can be classified as almost pure iron, consisting mostly of the light ferrite grains with only a few small dark regions of pearlite and the grain boundaries dotted with the dark spots of nonmetallic inclusions. Such inclusions, whose presence is observed only in this sample, indicate the bloomery nature of the process producing the particular part from which this sample was taken. This concludes presentation of the microstructures observed in the cast iron and steel samples, both of which had no other treatment than what was applied in taking them from a mother Tatara ingot.

3.3. Forged Plate

As shown in Table 1 two samples in the forged plate group were provided for metallurgical examination. Sample #2-1 was received in the form of more like a sword blade only a few stages away from the final product, while sample #2-2 in the form of a small rectangular plate which is approximately 6.5 mm thick and must have been manufactured ahead of sample #2-1.

Figure 11(a), taken from the cross section of sample #2-2, shows white cementite particles in the dark matrix. It is seen in Fig. 11(b), a higher magnification picture taken from some other region of sample #2-2, that the large white area consists of ledeburite, a eutectic structure between cementite and austenite. The dark areas in both Figs. 11(a) and 11(b) are observed in Fig. 11(c), a secondary electron micrograph, to consist of extremely fine pearlite. Some of the matrix structures, primarily at the regions close to the surface, were martensite as shown in Fig. 11(d), a secondary electron micrograph where the plate type martensite appears dark against the lighter austenite that is retained. It is apparent that this sample has received a substantial amount of deformation at high temperatures. The distribution of cementite phase in Fig. 11(a) clearly delineates the forging planes. There is no doubt that the starting material...
contained sufficient C either to be hypoeutectic cast iron near the large white areas of ledeburite or hypereutectoid steel near the small white cementite fragments. It is not hard to imagine the original ledeburite structures and cementite needles such as shown in Figs. 4 and 5, respectively, going through deformation and fragmentation in the forging process to generate such structural arrangements as observed in Figs. 11(a) and 11(b). The brittle nature of cementite is here to promote its fragmentation, but the ductile matrix, austenite at the high forging temperatures, apparently restricts excessive crack propagation to arrest the fracture only within the neighborhood, and prevents the total fracture of the sample under deformation from occurring. The samples reviewed in the previous sections (#3-2 and #1-1 through #1-7) must have been individually forged before they were combined into a relatively thick plate such as the one like sample #2-2. The overall microstructures developed in such a plate will be determined by a specific combination of the small samples, each with its unique microstructure depending upon its C content. It is evident that the region of sample #2-2 where Fig. 11(a) was taken is mostly made of those whose C content is high enough to be cast iron or at least hypereutectoid steel.

Figure 12 is an optical micrograph illustrating the microstructure observed in the whole cross section of sample #2-1. The pictures were taken at the original magnification of 50 times and tiled to provide the overall view of the forging patterns. The cross section is seen to narrow down in thickness approximately from 5 to 2 mm as one goes 25 mm from the right end to the left, giving the impression of a sword blade. The contrast in Fig. 12 results from the different microstructural distribution where the pearlite regions appear darker than the light ferrite regions. The presence of ferrite regions indicates that the average C content at this stage is substantially below eutectoid. The unique pattern consisting of multiple layers is self-explanatory of how this sample was fashioned from such a plate as sample #2-2. The latter must have gone through repeated forge/fold cycles each of which would double the number of layers with the accompanying reduction in their thickness. The contrast observed between layers as in Fig. 12 is apparently renewed in each cycle as the layer exposed on the surface and thereby decarburized is moved into the interior by folding. The layers once exposed are to appear light upon etching because of their low C content. Those that have never been exposed, however, are to maintain a relatively high C concentration and appear dark. The pattern in Fig. 12 shows the last folding having occurred at both the top and bottom halves in opposite direction, causing both edges to end approximately in the middle.

As mentioned previously, sample #2-1 is the one closest to the final product of all that were provided for the present study. It has to go through additional forging to be shaped into a complete sword as well as the final heat-treatment to obtain the microstructures guaranteeing the best performance required in service. Part of sample #2-1 was taken and heat-treated to get a rough estimation of the changes the subsequent thermal treatment may bring about. Figures 13(a) and 13(b) illustrate the microstructures of the two pieces taken from sample #2-1 that were kept at 900°C for 20 min followed, respectively, by quenching in water and by
cooling in air. They show the two faces that used to mate before being separated, and are arranged such that the structural variation along the thickness may be directly compared in the horizontal direction. The layered structures are still apparent, meaning that the gradient in C concentration remains even after the heat-treatment. It is noticed that the high C layers appear white in the quenched specimen, Fig. 13(a), while they appear dark in the air-cooled one, Fig. 13(b). The microstructures were all martensite in the former while they were mixtures of proeutectoid ferrite and pearlite in the latter. The hardness measurements show that the Vickers hardness values range 480–900 and 140–330 in the quenched and air-cooled specimen, respectively, with the higher values observed in the higher C areas in both.

4. Discussion

The traditional Japanese sword making estimated from examining the progressive microstructural development in the present study is in line with that which has been outlined, and may be summarized as follows. The first step is to break an ingot from the Tatara process into a number of small lumps each with a varying C content, apparently because of the C gradient inherent in the original Tatara ingot. They are then forged and combined to form a relatively large plate that may be effectively handled in the next operation. The plate then goes through the repeated cycles of forge/fold operation in which the overall C concentration and microstructures are adjusted while being shaped into a blade. This makes the average C content lowered well below eutectoid, and allows a number of layers to form in the terminal microstructure as shown in Fig. 12.

The present results show that the forging operation has a particular importance in the Japanese sword making processes in which almost every step is fraught with extensive forging. There is no doubt that its primary goal is to adjust the compositional and structural variations inherent in the Tatara ingot. The key role of forging in achieving the desired C concentration or structure like that in Fig. 12, however, cannot be properly addressed from merely examining the initial material or the finished sword. This is because the microstructural pattern holding crucial information on the exact role played by forging has only a passing existence, and is hardly observed without focusing on the
dynamic evolution of microstructures during the entire process. This point is best illustrated by referring to Figs. 11(a) and 11(b). The microstructure here represents an intermediate stage where the individual samples of varying C content are being assembled by forging. Without referring to this pattern it would be hard to explain how the variety of microstructures as seen in the initial samples are collectively transformed into the final form as that in Fig. 12. It is important to notice here in this transformation process that the iron carbide phase, cementite, plays a particularly important role in maximizing the desired effect of forging.

Figures 11(a) and 11(b) visualize the mass of cementite phases being fragmented or deformed upon forging. It is seen that the extreme brittleness of cementite is most effectively exploited to the easy formation of tiny cementite fragments while the ductile matrix keeps them from falling apart. As is apparent in Figs. 2(a) and 10 and Table 1, samples from the parent ingot have a wide range of C content from around 4.3% to almost nothing with majority of them positioned significantly above the eutectoid. This means that in their combination the overall C content has to be lowered significantly while the structure pattern emerges as desired. Forging evidently promotes decarburization by enlarging the surface area. But it would not be met with such a great success without the cementite phase in the form of tiny fragments, which is to accelerate their dissolution in the iron matrix and thereby the subsequent decarbonization. By the time the forge/fold operation approaches the final stage the average C concentration is seen in Fig. 12 to fall below eutectoid with the layered microstructures fully developed. The structure at this stage may be considered quite uniform over the whole cross section in the sense that every part consists of a nearly identical set of multiple thin layers.

The above process is reminiscent of the ancient steel making from white cast iron which, according to the Chinese texts quoted by Needham,6) is subjected to repeated forging while it is open to an air blast. The exact nature of this steel making process, especially the role of forging, has not been fully understood thus far. The present study, however, shows that the key role of forging in the steel making process has to be addressed in association with the brittle nature of white structure that is maintained even at the high forging temperatures. In this process, therefore, the conversion of carbide crystals to graphite is to be strictly suppressed by limiting the Si content in cast iron. This does not seem to cause a serious problem in the present Tatara samples because their Si content is found in Fig. 2(b) to be below the detection limit of EDS.

The next step to be taken on sample #2-1 before being a finished sword will be the thermal treatment to adjust the mechanical properties for the best performance. The science involved in this process is detailed in Inoue’s paper, but without paying sufficient attention to the probable layered microstructures formed in the sword under treatment.15 But the layers, each with different C content and structure, will show a completely different response to the treatment even under the identical thermal conditions. This point is illustrated in Figs. 13(a) and 13(b) where the Vickers hardness value ranges 480–990 and 140–330 in the quenched and air-cooled specimen, respectively. The actual thermal treatment will be given in such a way as to guarantee the dual requirement, strength and toughness, in preparation for the extreme impact situation while making the most of the layered structures. One possibility is to distinguish the cutting edge from the remaining part by subjecting the former to a rapid quenching but the latter to a relatively slow cooling. This technique, which is commonly observed in ancient sword making in the Korean peninsula,12) would make the sword strong and hard at the cutting edge while the rest of the blade is tough enough to hold crack formation at the edge. In addition, the finelayered structures, which will result in the alternating arrangement of the hard and the relatively soft regions even at the cutting edge, will help attain the best combination of strength and toughness. Besides, the beautiful patterns that may emerge on the surface due to the layered structures will make the Japanese sword even more attractive to samurais as well as lay people.

5. Conclusion

The present study has established that the uniqueness of the traditional Japanese sword making lies in the excellent combination of the parent material and the manufacturing techniques in such a way as to overcome their seemingly less desirable features. The Tatara ingot with its compositional and structural variation would not be a suitable material for making a quality sword without the repeated forge/fold operation. The forge/fold operation, in turn, with its labor-intensive features, would not be an efficient manufacturing technique if the starting material were homogeneous in composition and structure unlike the Tatara ingot. The results show that the brittle cementite phase present in the majority of Tatara samples is the key element that allows the forging operation to be extremely effective. The easy fragmentation of cementite in the relatively ductile matrix whose surface area is being enlarged upon forging is found to accelerate both the decarburization at the surface and the formation of a desired internal structure pattern.

It is important to notice that the origin of the above process is traced from the ancient steel making from white cast iron where extensive forging in association with the brittle cementite phase has an equal importance. In this respect, the traditional Japanese sword making may be considered a unique steel making process where the repeated forging greatly facilitates the control of C content through the mechanical mixing of the high and low C samples. The difference is that the steel making is accomplished together with the shaping of a sword blade, just like the Tatara process where such multiple ingredients as cast iron, steel of varying C content and almost pure iron are smelted in one and the same operation. It may be said that the Japanese sword is the natural product of the ancient technical framework of East Asia where the tradition of cast iron use has long been established since the very beginning of its iron production.

Acknowledgements

Dr. Kazuyuki Enami is gratefully acknowledged for allowing the samples to be examined. The suggestions from the reviewers were invaluable in the revision. This work was supported by 2003 Hongik University Research Fund.
REFERENCES