Seminar on Japanese swords

Cambridge University Kendo Club

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Metallurgy and the Japanese sword

Nicholas Taylor

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1 Introduction

A good sword must fulfil two requirements. It must be hard enough to take a sharp edge, and tough enough that it will survive the rigours of battle. These two requirements, unfortunately, compete. A hard substance cannot yield to an applied force, and so tends to shatter. The traditional Japanese sword nonetheless manages to hold an exceptional edge, while remaining highly resilient. The smith employs a few techniques to achieve this. To understand them, though, one must first understand a little about steel.

2 The iron-carbon phase diagram

Figure 2, from [1], shows the iron-carbon equilibrium phase diagram near pure iron. Several of its features are relevant to sword-making.

Ferrite, also known as α-iron, is the form of iron stable at room temperature. As a consequence of its crystal structure, it cannot contain much carbon [2].

Austenite, also known as γ-iron, is the high-temperature form of iron. It is stable at temperatures which can be reached by a smith's forge. It has a different crystal structure and, as the phase diagram shows, can accommodate far more carbon than ferrite.

On cooling, and the consequent transformation from austenite to ferrite, the excess carbon usually separates out. Rather than forming elemental carbon, it forms a hard compound called cementite. Cementite (Fe_3C), while not thermodynamically stable, forms much more quickly than carbon. At room temperature, the necessary energy to transform from cementite to carbon is unavailable, so the cementite remains.

2.1 The eutectoid and pearlite

On cooling steel down line E (the *eutectoid composition*) in figure 2, neither cementite nor pearlite is favoured. At the transformation temperature between austenite and ferrite, the austenite turns into interleaved sheets of cementite and ferrite. This structure is called pearlite. Like the formation of cementite instead of carbon, this is an unstable state which can form relatively quickly. The large interface area between cementite and ferrite has a high energy, which would be reduced by the two phases forming spheres. However, the sheets ensure that the carbon need not diffuse far to leave the ferrite.

This competition between stability and speed of formation means the speed of cooling can change the coarseness of the pearlite structure. Slower cooling will allow more diffusion of carbon; the drive to reduce interfacial energy will ensure that this coarsens the structure.

The fine sheets, and the cementite content, make pearlite a fairly hard structure.

2.2 Varying the carbon composition

When cooling steel whose composition is not eutectoid (lines A and B on the phase diagram), one of the low-temperature structures will form first. A hypo-eutectoid composition will form ferrite first, and a hyper-eutectoid composition will favour cementite. Whichever phase forms first will form along the boundaries between austenite crystals, forming a complete network through the steel. The remaining austenite will then transform to pearlite.

the previous one. This process is repeated several times with progressively finer stones, each at its own angle. Each pass takes about half an hour for that short section of the sword. At each pass, the surface of the sword becomes smoother and the scratches of the later stones are so fine as to be almost invisible. Looking at the blade between the passes reveals progressively more of the patterns in the metal. The wavy curve of the hamon starts to come out quite clearly.

The polisher then moves to even finer abrasives: first, a particularly smooth grinding stone that has been sliced very thinly and glued with lacquer to a paper support. Then, a suspension of iron oxide in a special paste, filtered with a piece of cotton. By now he is rubbing the abrasives longitudinally against the blade with his thumb. At this late stage the hamon really stands out, compared to being just barely visible at the beginning of the polishing process. By holding the blade against a spotlight at the correct angle, and with the guidance of an expert teaching you what to look for, at this stage you may also see more subtle effects in the surface texture of the blade, such as a kind of wood-like grain formed by the thousands of folded layers of steel of which the hardened edge of the sword is made.

I had read about this process in Kapp et al. [2] before; but witnessing it in person, and being able to examine the naked katana blade in my own hands during rounds of polishing, made it really come alive. Although I feel I am still not yet worthy of owning a genuine Japanese sword, after this experience I am a bit closer to an understanding of what the sword can tell me once I am eventually ready for one.

Acknowledgements

I am extremely grateful to sword polisher Roberto Candido (also accomplished in kendo, iaido and Japanese archery on horseback) for admitting us into his workshop in Tsurumi and showing us his art and craft, and to Sergio Boffa for providing informed comments on what we were being shown. The visiting party, on that cold sunny morning of 30 December 2003, also included Hiroo Naganuma, Naoko Hamada and Yuko Yamaguchi.

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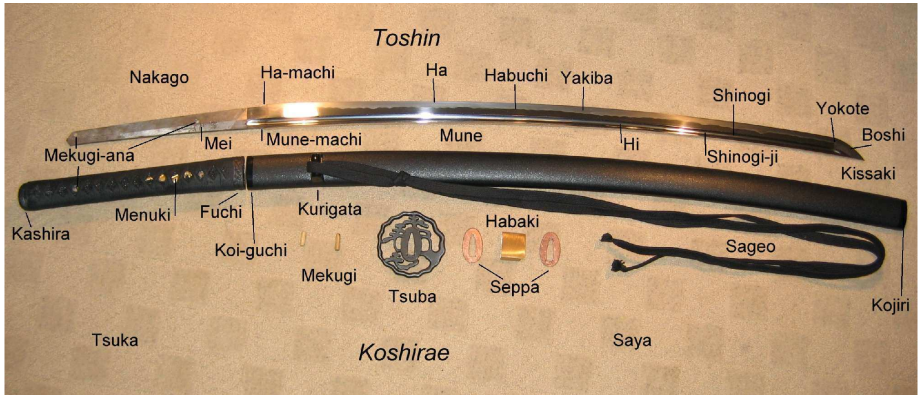
The Parts of the Japanese Sword.

The sword can be divided into two parts. We have the blade, or *toshin*, and we have the mountings, or *koshirae*.

Over the years different styles of mountings were devised, the one we are looking at here are referred to as *buke-zukuri*. These were worn thrust through a belt (*obi*) on the left hand side of the body. It was quite possible that a blade would have multiple sets of mountings over it's life; for example, today some antique swords are stored in *shirasaya*, and only placed in their formal mountings for display.

Here we have a diagram illustrating the major parts of the sword.



Koshirae	**Sword mountings.**
Tsuka	Hilt. Formed by two pieces of *honoki* (magnolia) wood joined top and bottom.
Kashira	End pommel.
Fuchi	Pommel near blade.
Ito	Binding of *tsuka* (usually fabric or leather).
Same	Rayskin under the *ito*. *Same* has grain which helps hold the *ito* in place.
Menuki	Hilt decorations. Can aid grip. Sometimes these are reversed.
Hishi-gami	Paper triangles that help support the *ito*.
Mekugi	Pin (usually bamboo) holding *tsuka* onto *nakago*.
Tsuba	Guard, to stop hands running onto blade.
Seppa	Washers placed between *fuchi*, *tsuba* and *habaki*.
Habaki	Blade collar; this forms an interference fit with the *koi-guchi*, retaining the sword in the *saya*
Saya	Scabbard, also made of *honoki*.
Koi-guchi	'Carp's Mouth'; the open end of the *saya*.
Kojiri	The closed end of the *saya*.
Kurigata	Knob on sword to attach *sageo*. Also helps stop sword sliding through obi. Ideally these three things are made of horn.
Sageo	Multi-purpose cord.
Kozuka	Small utility knife
Kogai	Skewer/ hair accessory.
Wari-bashi	Split chopsticks.
Shira-saya	Plain wooden storage mountings.

one's sword. Forging of the sword is almost a religious ceremony, and requires skill and long apprenticeship. Thus a swordsmith, as a creator of the powerful sword, is highly respected.

The blade itself is the actual weapon and thus requires reverence as such. However, the rule that one must not touch the blade with one's fingers is not only to prevent one from cutting oneself, but it also has a more practical reason: the salt and moisture on one's hands can cause rust marks on the blade and thus damage the valuable blade.

In Zen, the end point is the beginning, knowledge a full circle, and great understanding can only be expressed as nothingness. In kendo practise, the continuous training of thousands of cuts leads towards spontaneous knowledge of every situation, the sword becomes 'no sword', and eventually results in a realization of nothingness.

Manufacture of Japanese Swords

Richard Boothroyd

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The process of manufacturing swords in Japan was developed and refined over hundreds of years. There were usually several people involved (possibly up to six), each specializing in a specific part of the process.

The method of manufacture was driven by the quality and availability of iron in Japan. There was much less iron available than in Europe, which is one of the main reasons behind the quality of Japanese blades. In Europe, many swords of low quality could be made cheaply (good quality swords were also made there, of course!). In Japan, a sword had to last a long time, so it had to be of much higher quality. Since the iron ore in Japan was of a poorer quality, it took longer to make each blade since all the imperfections had to be removed.

The first blades were constructed out of a single type of steel (non-laminated, or *maru*). Over time, several ways of combining different types of steel to form a laminated blade were created, which improved the properties of the final sword. The most common used three types of steel (*honsanmai*); one famous sword smith, Masamune, used a method that required seven types!

The sword smith would obtain some steel from scraps (e.g. nails, broken pots), but would mostly use a type of steel called *tamahagane*. This was produced from the generally poor quality iron ore available, being combined with carbon in a smelter.

The first stage of sword making involved splitting the wood charcoal that would be used in the furnace. This was called *sumiwari*. The best charcoal came from the pine tree, but the chestnut tree was also used. This was a very important step since different sizes of charcoal were needed to create the required temperature for each stage of the forging/quenching.

Production of burnt straw, *Aku*, came next. This was mostly used in the forging process, where the tamahagane would be forged to a base.

Next the pieces of tamahagane would be heated so they could be classified by their carbon content. This would then decide which part of the blade each piece would be used for. Soft steel, or *shigane*, would be used for the main bulk of the blade, to give the sword its flexibility. Hard steel, or *hagane*, would be used for the actual cutting edge. Medium steel, or *kawagane*, would be used for the sides or top of the blade.

The classified pieces of tamahagane would then have to be combined to form solid pieces of shigane, hagane and kawagane. A pile of tamahagane was made and then covered with paper to hold the pieces in place. Clay-water was poured on, the stack covered by Aku and then more clay-water. The pile was then heated, at which point the hammering began. Three people may be involved in this stage, the sword smith and two apprentices who use large hammers. They were led by the smaller hammer of the sword smith. Once the tamahagane were forged, the folding process began. The forged piece was folded transversely and longitudinally. At each fold, the tamahagane were heated and cooled by cold water. This oxidized the surface, and the removal of the oxidized layer increased the purity of the steel. The number of folds that occurred has become something of a legend, some people believing that literally dozens of folds are made, creating millions of layers. In reality, the number of folds that were made depended on the hardness of steel required. For shigane this usually meant 10 folds; for kawagane 12 to 16.

The pieces of steel were then arranged to form the layout of the final sword. These pieces were heated again, and the sword shape then hammered out (again with the assistance of 2 or 3 apprentices) This stage was called *hizukuri*. The tip (*kissaki*) and handle (*nakago*) were then formed, which fin-

drawn implied aggression or suspicion and the level of trust. By observing whether the sword was placed on the right side or left, cutting-edge pointing in or out, one could determine his attitude. When the swords are stored in a rack, similar indication could be observed. Normally, the wakizashi stored on the top rack and the katana on the bottom, both swords curving upwards. If the katana was stored on the top rack or the blades curving down it implied the owner's suspicion to the outsiders (or even guests).

There are many more aspects of reigi (etiquette) that involve just merely handling a sword from even before one enters the dojo and through and beyond the entire practice session. For example, one should never walk over a sword or kick a sword whether it is done knowingly or unknowingly. Shinai should be treated as if it was a real katana which would have injured one's foot. It is also an offence to the owner of the sword.

It is impolite to rest against a wall or to rest on one leg during a kendo training. Resting against a shinai is even more disrespectful than any of these. When a shinai is not in use during training at times like warm-up and rest period (if there is such), it should be left lying on the ground in a corner, or against a wall with the kensen pointing up. Moreover, the kensen should not touch the ground under any circumstances during training. Yet it is not rarely seen where some kendoka hit the ground with the shinai while performing suburi or geiko. Some even drop the shinai due to carelessness. Once the training commences and the shinai is drawn, the cutting-edge side of the shinai should not be touched unless it is for an avoidable reason. In a kendo shiai (competition) one would receive a hansoku (penalty) for doing so without referee's permission.

Even during modern kendo practices using shinai, these codes of conduct for katana should be respected. As the name kendo (劍道) suggests, it is the 'way of sword' not merely learning to fight with a sword. Many, if not all, of the mentioned etiquette become obvious or intuitive in the context of a katana but unfortunately, a surprising number of modern kendoka do not seem to see the appropriate connection between the katana and the shinai.

Katana was considered the soul of a samurai. For much of Japan's history, particularly in early Edo period, only samurai were allowed to carry swords and a peasant could face a death sentence if found carrying a sword. Although this practice and perception is rather obsolete in the modern sense, some of the spirit must be preserved as far as kendo is concerned so that the real meaning of kendo and its practice can prosper throughout time.

Functional differences between European medieval and Japanese swords

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The European swords discussed here are the 'knightly' swords, as described in [1]. They date from about 1050 to 1550 A.D., but their basic form had already been used by the Celts and Vikings. The Japanese swords are the Samurai swords, from about 800 to 1850 A.D. Obviously, form, length, weight etc. varied over the centuries, for European as well as Japanese swords, so we can only compare averages, or the extremes.

The most striking difference is the overall form: knightly swords are typically straight and double-edged, whereas Samurai swords are generally single-edged and very often curved. The curvature helps to draw and strike more quickly. In principle, the double edge should allow for more types of strikes.

Because of their double edge, knightly swords have a flattened diamond, hexagonal or octagonal cross-section, as opposed to the thick back of the Japanese swords. This means that for a fixed width, length, material and thickness at the thickest point, the knightly blade is going to weigh less than the Samurai blade, or alternatively, that the knightly blade can be longer with the same weight.

In addition, knightly swords typically have a *fuller*, a groove in the middle of the blade which also makes it lighter. The fuller can be quite short (half of the length of the blade) or run nearly the full length, and it can be broad or narrow. There can even be two or three fullers [1]. All of this influences the weight and balance of the sword.

European swords also typically have a *pommel*, a knob or disc at the end of the hilt, which Japanese swords lack. Its purpose is to counter-weigh the blade to balance the sword [2]. In close grappling fights, it can also be used to strike the opponent e.g. in the face. It can also be gripped firmly for extra torque.

The Japanese cross-guard, the *tsuba*, is round, oval or a rounded rectangle, flat and of a relatively small diameter, whereas the cross-guard of a knightly sword is normally wide and narrow, and can be straight or curve towards the point of the sword. Especially the upward curving cross-guards can be used to catch the opponent's blade and manoeuvre it away.

Due to the absence of a pommel and the relatively small tsuba, a Samurai sword has a more 'down to the basics' look, whereas the straight blade and guard of a knightly sword makes it look like a cross, a symbolism which might well have appealed to the knights.

Blade lengths of both types vary considerably: Japanese *wakizashi* have blades between 30 and 60 cm, while the blades of tachi and katana are more than 60 cm. Some *nodachi* can be as long as 120 cm [3, 4]. European swords can be one-handed, hand-and-a-half (also called *bastard swords*), or two-handed and vary in length and weight accordingly. The one-handed variants were mostly used together with a shield. The largest two-handed swords had blades of 120–150 cm and weighed several kilos, but the average weight of a knightly sword was only 1–1.5 kilos [1] and 80 cm is considered to be a medium length [1].

Samurai swords typically had a very distinct, 'pointy' point, so they could be used for thrusting. Due to the very sharp edge and the curvature, they were especially good for slicing cuts, and could be used in quite close combat [5]. European swords come in two groups [1]. In group one, which was used roughly from 1050–1350, the edges run mostly parallel and the point may be acute or rounded. These swords were mainly intended for shearing cuts against chain mail. In group two, used roughly from 1350–1550, the blade tapers over the full length, ending in a very acute point. These swords were much better for thrusting into the openings of full plate armor, something which would be much harder with a curved Japanese sword. Swords of both European groups could be used for long-reaching cuts, with long passing steps [5]. For very close combat, the 'half sword' techniques [6] can be employed in which one hand grips the blade of the sword. This is probably not advisable on a Japanese sword.

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Katana and Kendo: Background and Reigi

Hyo Won Kim

Katana

Katana (刀) refers to the traditional Japanese samurai swords. Although the pronunciation *ka-ta-na* comes from the kunyomi[*] of the kanji 刀 which means 'sword' in a generic sense, the katana refers to samurai swords which have a characteristic curve and shape as shown in Figure 1. It has a single cutting edge on the far-side from the centre of curvature (bottom side as seen in Figure 1). These particular swords are sometimes called daitō (大刀) which means 'long sword'.

Figure 1: Katana

A samurai would wear a katana as a primary weapon together with a similar but shorter sword known as wakizashi. The wakizashi was used when the katana was unavailable so it was carried at all times even when entering a building. They are collectively known as daisho (大小) which means 'large and small' referring to the katana and wakizashi respectively. In the context of modern kendo using shinai, the attention of this article is drawn only to the katana.

Katana in Kendo

In modern kendo, a shinai is used in place of a katana. A shinai comprises of four split bamboo slats held together by leather covers called saki-gawa at the tip, tsuka-gawa at the handle, leather strip called nakayui at one third length from the tip, and a string called tsuru as shown in Figure 2[†]. Some resemblance of its features to that of katana (Figure 1) is noticeable. The nakayui indicates the striking area, monouich, and the tsuru represents the blunt edge on the back of the blade.

[*] Japanese reading of the Chinese character
[†] Few components (saki-gomu and chigiri) within the shinai are ommitted

The katana can be held either with one hand or with both hands. The latter is most common and it is also almost always the case in kendo with shinai. The katana is primarily used for cutting. The kensen (tip of the sword) embodies a chisel-like shape which allows for thrusting. The cutting action is equivalent to the men-, kote-, and do-uchi and the thrust to tsuki.

Figure 2: Shinai

Reigi in Handling Swords

Everything that is done in kendo should be done in the light of the samurai spirit as one would with a katana. The katana is worn on the left-hand side with the cutting-edge up so that when it is drawn, the curvature of the blade will naturally place your right hand directly in front in the centre line. A shinai too is worn on the left with cutting-edge up with the same implications in mind despite the lack of curvature.

During a kendo practice in a dojo, the position and the orientation of the kendoka is determined by the layout of the dojo or more specifically, by the location of shomen and the entrance relative to the sensei's sword. The sensei's sword, when placed on his left, should not be between the sensei and the entrance. It is so that an intruder would have no chance of reaching for his sword as well as that the sensei could draw the sword and strike in one motion if needed.

When a kendoka kneels down, for example at the beginning and the end of a training session, the shinai is left on the left-hand side with the cutting-edge pointing inwards (i.e. with tsuru facing outwards). One's readiness is implied by placing the shinai on the left side without causing offence to anyone else in the dojo by pointing the cutting edge inwards. As for a samurai, positioning of the sword in its scabbard in a manner that could easily be

ished the forging stage.

The blade was then prepared for quenching, which was when the blade obtained the characteristic curve shape. Differing thicknesses of clay mixture (*yakiba-tsuchi*) were applied to the cutting edge and top of the blade. Each sword smith had their own special recipe for this mixture. When the blade was heated and quenched, the different sections cooled at different rates, and so the steel took on the required properties (hard but brittle, or soft and flexible). This was where the distinctive properties of the blade, such as the *hamon*, would appear. The quenching step was a highly critical stage, since the blade had to be uniformly heated to a very precise temperature (720–780°C) before being plunged into cold water (the temperature of which was also critical)

The sword smith would then inscribe his name on the nakago and possibly make an inscription on the base of the blade. The sword could then be passed to the sword polisher.

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Zen and the Way of the Sword

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The earliest swords in Japan were Chinese swords in the second century BC, referred to as *ken* or *tsurugi*. The first curved swords appeared during the sixth and seventh centuries, and were called *kanto tachi*. In the eighth century, during the Nara period, the first Japanese swords, of the curved type, appeared.

In ancient times there were no schools of swordsmanship, but the lords and warriors maintained their own sword fighting schools. During the Kamakura and Muromachi periods (about 1200–1500), formalized schools (*ryuha*) began to develop, and by the 15th century five regional traditions existed: in Kashima-Katori, in Kyushu, the capital (Kyoto), in the Kamakura area, and in the north-east.

The warrior courts also fostered Zen studies, as the austere principles suited warfare well. The Zen teaching of quick and spontaneous action while at the same time maintaining one's calmness and peaceful mind formed the centre of effective fighting strategies, and Zen practice assisted the fighters in achieving this realization.

For instance, the famous swordsman Ittosai Ito Kagehisa, who lived in the 17th century, was also famous for his deep philosophical thoughts. In fact, he named himself Ittosai (or 'one sword man') and founded Itto-ryu, the one sword school which still exists and has influenced modern kendo. Miyamoto Musashi, probably the most famous Japanese swordsman in the Western world, collected his thoughts in his *Book of Five Rings* as 'a guide for men who want to learn strategy', in 1645.

During the Tokugawa period (1603–1867), formalization of Japanese culture took place further, and the philosophical principles, once meant to encourage the warrior to face death in fierce combats, elaborated into the moral code of the samurai: the Way of the Sword did not only include training in the techniques, but also living by the code of honour of the samurai elite. The fighting techniques now became a vehicle for advancing the way of Zen. However, since there is no separation of mind and body in the Zen philosophy, the cultivation of the mind is, in fact, improvement of the techniques, and vice versa.

Since the 17th century, all Kendo schools have emphasized Kendo as a means of cultivating one's mind, and the proper code of practice is influenced by the Confucian philosophy: the primary goal of Kendo is to improve oneself through the study of the sword, and kendoka 'wield a sword not to control their opponent, but to control themselves'.

The meaning of life and death by the sword was mirrored in the everyday life of the feudal Japanese, and the one who understood and accepted death at any moment in his everyday life was a master of the sword.

Since the late 16th century, the sword became the symbol of the samurai. Only samurai were allowed to carry two swords: while the short sword (*kodachi*) was allowed for everyone, only the samurai were also allowed to carry the long sword (*daito*). The sword thus became an object of reverence and respect (through the respect for the samurai class), and it must be treated appropriately, in a graceful and dignified manner.

According to Zen, one must treat one's fellow beings (enemies included) as honoured guests, and the respect naturally applies to the sword too. The sword is often called the soul of the samurai, and the respect for the sword thus symbolizes respect for the owner: e.g. one does not step over somebody else's sword or touch it without the permission of the owner.

The respect also includes appreciation for the maker and the blade itself, e.g. when bowing to

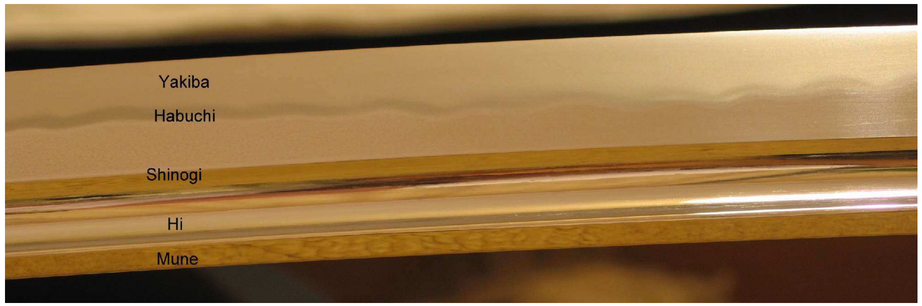
Toshin	**Sword blade.**
Nakago	Tang of blade
Mekugi-ana	Holes for *mekugi* to pass through and attach blade to *tsuka*.
Mei	Signature or inscription on tang.
Yasurime	File marks on *nakago*.
Ha-machi	Notch on *ha* side of blade
Mune-machi	Notch on *mune* side of blade. These are what the *habaki* press up against.
Ha	The sharp edge of the blade.
Mune	The back of the blade.
Hi	Groove used to lighten or improve balance; can also hide defects.
Hamon	Pattern of the differentially hardened edge.
Nioi	Small crystals of hardened steel (martensite).
Nie	Larger crystals of martensite.
Hada	The grain of the metal formed by repeated forge folding.
Yakiba	Hardened area of the blade.
Habuchi	The transition zone from soft to hard steel (defines *hamon*).
Hira	The surface from *ha* to *shinogi*.
Shinogi	Ridge line along side of the blade.
Shinogi-ji	Surface between shinogi and mune.
Yokote	Ridge line dividing kissaki from the rest of the blade.
Boshi	The hardened area of the kissaki.

Geometry.

Sori	Depth of curvature.
Nagasa	Length of the blade measured from *munemachi* to *kissaki*
Omote	Exposed side of sword (as shown here).
Ura	Hidden side of sword.
Saki-haba	Width at *yokote*.
Kata-haba	Width at widest point.

Random.

Kizu	Flaws in the blade.
Shinken	Real (sharp) sword.
Shinsakuto	Newly-made sword.
Nihonto	Japanese sword.
Iaito	Sword used for iaido.
Tsukamaki	Art of applying tsuka ito.
Shaku	30.2 cm.
Uchiko	Powdered limestone, used for cleaning sword.
Choji	Clove oil, used for protecting sword from air.



the katana.

I must admit that, in my ignorance, it took me many years to understand the extreme worries that sword collectors seemed to harbour about possibly contaminating or scratching a katana. A blade that used to cut flesh and bones and clash with armour and steel in the battlefield should certainly survive, I naïvely thought, being touched by an innocently admiring finger or even being dropped on the floor. The effects of such treatments ought to be insignificant compared to the battle scars of a genuine sword. Only on visiting the polisher's workshop did I begin to understand the collectors' motives.

Of course the katana is strong enough to withstand being handled, being dropped and being thrust through a suit of armour. However, in so doing, it may scratch; with a particularly strong blow, it might exceptionally even dent or chip. The duelling samurai will go through all this without a second thought, but the battle-worn sword will bear the scars of the battle, just like the suitcase that accompanied you around the world for the past ten years isn't as shiny as when it came out of the shop. To restore the battle-worn katana to its former beauty and deadly cutting efficiency, its samurai owner would periodically entrust it to a sword polisher for maintenance.

It must however be realized that the maintenance that a polisher may carry out is exclusively *destructive*. Polishing is ultimately nothing more than removing steel from the sword using abrasives. The polisher can never actually return a worn-out sword to its original state. A shallow scratch will be cleaned out by abrading a microscopic layer of steel from the whole surface, making that area of the sword thinner by at least the depth of the scratch. A small notch will be smoothed away by abrading away enough metal from the edge of the blade that the line is again straight; and a deep notch will be impossible to undo, since removing it would force the polisher to remove so much metal that he would change the overall geometry of the blade.

Therefore one of the primary goals for the polisher is to do as little as possible, since anything he does is irreversibly taking away some of the irreplaceable metal of the original sword. It then makes sense to avoid any unnecessary scratches, dents and even fingerprints that might in the long term lead to corrosion from the acid in the sweat; the restoration of each of these minor blemishes would require some polishing, therefore removing some metal from the sword and ultimately reducing its lifetime.

Witnessing the polisher at work allowed me to understand how much more is really involved in his job beyond merely sharpening the edge of the blade. Way beyond this purely utilitarian function, the skillful polishing of the blade reveals the beautiful texture of the metal and allows you to admire the complex internal structure that makes the katana the unique weapon that it is.

As previously mentioned, the blade must be made of hard (high carbon content) steel in order to hold a sharp edge. Hard steel, however, is brittle: a sword made of high carbon steel would soon chip and break in combat. The peculiar technique perfected by the Japanese swordsmiths around 10 centuries ago combined a core of soft steel, for shock-absorbing resilience, with a jacket and edge of hard steel. The complex forging process, resulting in thousands of microscopic layers, and the elaborate and carefully controlled heat treatment for hardening, which added not only extra strength but also the distinctive artistic pattern known as *hamon*, are too complex to describe in this short essay; Yumoto [4] and particularly Kapp et al. [2] give copious details. What matters here is that the surface of the blade, when properly polished, silently tells the story of all the activities that took place during the forging process.

The polisher works on a short section of the sword at a time, perhaps 10–20 cm. He sits on a low stool in front of a bucket of water in which he soaks several sharpening stones. The sword blade is naked, the tsuka and all the fittings having been removed beforehand. The polisher handles the sword with his bare hands. The sword, while very sharp, is not quite as sharp as a razor, primarily because of the much sturdier geometry of the cross-section. The blade won't cut the polisher's hand if held firmly. It would, however, cut his hand very deeply if he were foolish enough to slide his grip along the edge.

The polisher starts with a coarse-grained stone for the strongest abrasive action: this is the foundation work that has the effect of sharpening the edge, repairing repairable notches and scratches and cleaning out rust. This process, however, leaves evident scratch marks on the blade. The next stage, with a slightly smoother stone, is not so much for polishing any blemishes of the blade but rather for cleaning away the scratches left by the first stone. In order to keep track of the amount of abrasion, the polisher uses each stone at a particular angle: the coarsest stone is rubbed perpendicularly to the blade, while subsequent ones are used at different angles. That way, from the direction of the scratch marks still remaining on the blade, he can tell precisely when the new stone has finished removing the scratches of

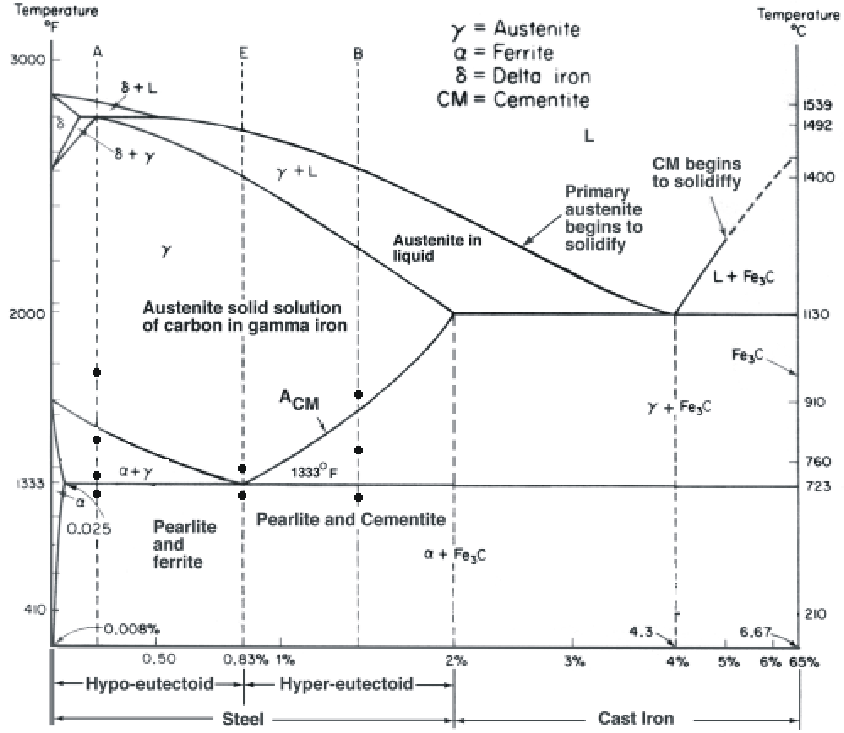


Figure 1: The iron-carbon equilibrium phase diagram

Hyper-eutectoid steels, in which the network is of cementite, will then be harder than hypo-eutectoid steels. In addition to this distinction, increasing the carbon content will decrease the proportion of ferrite formed, and harden the steel.

2.3 Quenching and martensite

Martensite is a less stable, faster-forming alternative to pearlite. It can be formed by cooling austenite rapidly to about room temperature. In martensite, the iron has adopted the ferrite crystal structure, but the carbon has not had time to escape. It stays in place, distorting the ferrite lattice and forming a very hard structure. The distortions also mean that this phase is less dense than a mixture of ferrite and cementite would be.

2.4 Tempering

If the temperature is raised above room temperature, but not high enough that austenite is stable, the carbon can diffuse. This will allow pearlite to coarsen, or even form spheres. The carbon trapped in martensite can also escape, allowing the structure to soften.

3 Combining hardness and resilience

3.1 Using high-quality materials

Imperfections in the steel provide starting points for cracks, and so must be removed. This presents something of a problem to a Japanese smith: Japan, while blessed in many respects, is almost devoid of good iron ore. The repeated folding, perhaps the best-known part of the sword-making process, serves to homogenize the steel. It also allows fine control of the carbon content. Carbon will escape as carbon dioxide from the hot metal in air. Exposing the hot metal to carbon (for example, some smiths use rice ash) will increase the carbon content.

3.2 Combining hard and soft material

It is possible to weld high and low carbon materials together. In this configuration, the energy of bending the sword will be absorbed by the softer steel bending, rather than by the harder steel shattering. There are several patterns in which the Japanese sword combines hard and soft steel [3]. They all have soft steel (*shigane*, containing roughly 0.2 % carbon by weight) for the core, with harder steel (*hagane*, containing roughly 1 % carbon by weight) for the edge.

3.3 Changing the quench rate

One of the more impressive techniques used by Japanese sword-smiths to give their swords resilience and strength is to change the rate at which different parts of the blade are quenched. The blade is coated with clay, but the coat is made thinner at the edge than elsewhere. The sword is then quenched from the austenite regime to room temperature. The thinly-coated edge cools fastest, forming martensite. The rest of the sword cools more slowly, and forms the tougher ferrite and cementite mixture.

As well as mixing toughness and hardness, this step also gives rise to some of the other notable properties of the Japanese sword. The lower density of martensite means the edge of the sword becomes longer than the back, giving the sword its distinctive curve. The painting with clay also allows the edge of the martensite region to be precisely controlled, allowing the smith to express himself in the form of the *hamon*.

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A visit to a sword polisher's workshop

Frank Stajano

The Japanese sword is renowned for its sharpness. The unstoppable cutting power of the katana is an essential component of its mystic appeal. A Muramasa-forged katana plunged in a mountain stream, says a well-known legend [1], would cut in two any dead leaves that touched it as the water carried them downstream. Modern legends, in the form of samurai movies, show Japanese swords that chop down tree trunks or even split stone statues. Beyond such often exaggerated imagery, historical records tell us that, in the Edo era, new swords were tested on the live bodies of condemned criminals and that a good sword, handled by a good swordsman, would cut a human torso in two with one stroke, flesh and bones and all [1, 3].

What was the secret that allowed a sword to be this sharp? How was this sharpness obtained? And just how sharp were the real samurai swords, legends aside? After years of exposure to so many movies, books, comics, works of fiction and scholarly tomes, I got some first-hand experience of the topic in 2003 when I finally had the privilege of spending a whole morning with a sword polisher in Japan, in his traditional workshop, and could admire him at work on an authentic katana.

Most of the people who find the katana fascinating will have at one point or another owned a small blade such as a Swiss Army knife and will have had the experience of attempting to re-sharpen it. They will be familiar with the feeling of gently feeling the edge of the blade with the thumb, with the classic test of cutting through a sheet of paper and with the usually futile attempts to cut the hair on the back of one's finger—a task that only a new razor blade seems to be able to do cleanly.

For most of us, the sharpest blade ever used is indeed the razor blade—or, equivalently, the blade of the snap-off paper cutter. Both of them slice cleanly through hair and paper respectively; however, even against such undemanding materials, they very soon lose their sharpness. This is due to two factors: geometry and materials. As for geometry, these blades are sharpened to a very narrow angle; this makes them very sharp but also makes the edge of the blade very thin and therefore incapable of bearing much mechanical stress without deforming and wearing out. As for materials, these blades are made of soft steel: the metal can be sharpened easily but it wears off equally easily with use.

The edge of a sword blade cannot be sharpened to an angle as narrow as that of a razor blade, otherwise it would never be able to withstand the much heavier mechanical stresses to which a sword is subjected in combat. It must also be significantly harder, as it would clearly not be possible to indulge in continuous re-sharpening in mid-battle. So the sword polisher must sharpen a blade whose edge is much harder than either the razor blades or the penknife blades with which we may be familiar.

The experience of penknife sharpening may have made you aware of at least three more important points. First, the abrasive stone leaves small sawtooth marks on the edge of the blade, which cause the blade to get stuck and rip through the paper instead of neatly slicing through it. Second, it is not trivial to keep the desired angle between blade and sharpening stone all the way through the polishing. Third, it is very easy to scratch the blade if one allows its flat surface to come into contact with the stone. As you might expect, all these problems also occur in sword polishing, greatly amplified by the fact that the blade is over ten times longer. This is in part why the skill of sword polishing takes many years of apprenticeship to master.

A modern-day polisher of Japanese swords faces two main kinds of jobs: first, the polishing and restoration of antique swords; second, the sharpening of newly-made swords. In the first case, the sword edge may have been damaged in use (whether by actual combat or by over-enthusiastic modern-day handling) and the blade itself may have been ruined by rust. In the second case, the blade as produced by the swordsmith needs to be sharpened in the first place. In both cases, skillful polishing, way beyond anything you and I might have imagined from the experience of sharpening penknives, is required to reveal the unique texture of the steel of