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Stasis in complex artifacts: The Japanese Sword

Most of this volume is concerned with mechanisms for the generation of new knowledge, particularly the type of knowledge of the world around us which helps us to create new resources.

During the long history of Homo Sapiens - a timeframe subject to much debate, but certainly in excess of 40,000 years - a great deal of resource - product - innovation has taken place, embodying much new tacit and reliable knowledge, but the rate of innovation has been far from constant.

Periods of change have been punctuated by long periods of stasis, so that for most of history the world would seem to be pretty much the same when a person died to the time when they were born.

This phenomenon, of high rates of innovation followed by stasis extending over many generations is not confined to the less developed, hunter-gatherer or early farming societies, but is also exhibited in advanced and sophisticated civilizations which had learned to beat the Malthusian trap, to produce resources to provision steadily rising populations.

Japan provides us with one such example of a sophisticated society many of whose artifacts - resources - had remained largely unchanged, apart from decorative variation for many centuries before substantial contact with the Western world.

We shall examine here one of the most famous of Japanese artifacts embodying extraordinarily high levels of craft skill but which remained virtually unchanged in form, function and manufacturing process for over seven hundred years, the Japanese sword.

We will show how the complexity of the manufacturing process, and its sequential nature in which each step is crucially dependent on the meticulous and precise completion of the previous stages tends to produce 'lock-in'.

Variation and innovation become increasingly hazardous and are confined to minor decorative features which, while largely irrelevant from a functional point of view, assume great social importance.

Steel swords have been found in tombs in Japan datable to the fourth or fifth century A.D., but it is probably that these were made in China and brought to Japan through Korea.

Swords were being made in Japan by the Heian period (794-1185 A.D.) but the special characteristics which made the Japanese sword such a formidable artifact were not developed until the Kamakura period (1185-1333 A.D.).

The functionality and processes of manufacture remained virtually unchanged from this time until 1876 - eight years after the Meiji restoration - when the warrior class, the Samurai were formally abolished.

Within a century the sword had become obsolete, except for the small numbers produced purely as art objects and mass produced swords of much lower quality for army officers.

The Japanese sword is a cutting tool originally developed for use from horseback with a slashing action, not the thrusting action of many Western swords.

The blade is typically 24 to 30 inches long, and has a handle suitable for two-handed operation. It is slightly curved, with a sharpened edge on the convex side of the curve. The concave side is not intended for cutting, and is blunt.

The functional requirements are straightforward - that the cutting edge be capable of extreme sharpness neither dulling nor chipping when striking violently armour of cotton, leather or maybe steel, often flesh and bone..

(Good reader, at this point I ask for your sympathy and understanding; we are discussing an object constructed with consummate and loving skill, revered, collected and exhibited in the world's greatest museums but whose sole purpose is to violently cut up living human beings. I cannot start to reconcile these conflicting attributes).

The second important functional requirement is that the blade remains straight and in one piece in use, even when struck hard by, say, another sword in battle. There can be few occasions more embarrassing than to be left holding a handle alone.

There are other slightly subsidiary requirements; the shape of the blade should assist a slicing action. The weight distribution should be such that the sword has plenty of momentum on the one hand, but is balanced and not awkward to use on the other; and the surface is of a composition and finish that does not encourage rusting, as long as care is taken.

The requirements of hardness and toughness don't normally go together, particularly in steels. To remain sharp, an edge must remain very hard - certainly much harder or resistant to deformation than the thing it is intended to cut. But hardness usually goes with brittleness, the opposite of toughness.

The strength - literally - of the Japanese sword blade is that it combines these two qualities, hardness and toughness in a most successful manner, using steel in its hardest form for the cutting edge but using steel in its toughest form to back-up the cutting edge and to form the body of the blade.

The creation of this combination of properties requires the most extraordinary skill on the part of the sword smith, and it is the recognition of this level of skill that ensures the blades a special place in our museums, and the accolade of 'Loving National Treasure' to the best of their makers in Japan.

Of all the metals, it is iron which has had the most profound effect on the course of history. It is abundant comprising around 5% of the earth's crust - 200 times more abundant than copper and 3000 times more abundant than tin, the two constituents of the alloy which gave us the bronze age.

Pure iron - rarely encountered even today - is quite soft and bendable, and has very few practical applications.

The properties of the metal change markedly, however, with the incorporation of quite small amounts of carbon. As small an amount of 0.4% carbon permits the material, which we call steel, to be capable of heat treatment to a greater hardness than the best bronze tools with which the Egyptians carved their huge granite statues.

Japanese swords typically have an edge of iron containing 0.6% or 0.7% carbon, which permits, with suitable heat treatment, a hardness sufficient to scratch glass. Higher amounts of carbon are used in a variety of applications in Western industry - the massive tools used for moulding plastic or forming car bodies may have around 1% carbon and the 'cast iron' which used to be the standard material for stoves and grates, manhole covers, railings etc. had up to 3%.

The percentage of carbon for any given application, and its distribution in the iron and the heat treatment the iron/carbon material (steel) has undergone are crucial to the satisfactory functioning of the artifact - in our case, the blade.

The Japanese knew nothing of carbon - neither did anyone else in the heyday of the sword - it was not identified as a separate material, an element, until the end of the 18th century.

Nor did they know that they were adding this all-important material accidentally to the iron during the process of extraction of the iron from its ore, iron oxide. (See note at end of paper).

The extraction of iron (many other metals are extracted in a similar manner) entails mixing pulverized ore with charcoal, igniting and blowing air - oxygen - through the mixture in a furnace large enough to ensure a very high temperature is attained.

The charcoal burns to carbon dioxide and carbon monoxide; the carbon monoxide reacts with the ore at high temperature, removing the oxygen and leaving iron.

The temperature was not high enough to actually melt the iron which stays in the fired mass as friable lumps, to be picked out when the furnace had cooled down. These lumps were then reheated and hammered repeatedly to produce a usable and workable material.

During this process hot iron, extracted from the ore comes into contact with hot charcoal - which is essentially carbon - and absorb it quite readily. However, the amount of carbon absorbed cannot be controlled, and the process is quite haphazard, producing a carbon content range from less than 0.5% to over 1.5%.

The swordsmith is highly skilled at sorting the lumps of raw steel from the furnace and judging from appearance and texture their suitability for the hard outer shell of the blade, including the cutting edge, and the softer, more ductile core.

To do this, he takes lumps of the raw, friable, steel from the furnace, reheats it to a bright red heat and hammers it into sheets about a quarter of an inch thick. While still hot, the sheets are dropped into water; the rapid cooling leaves them in a very hard and brittle state. They are then broken up with a hammer to form flat but rough shaped pieces each with an area somewhat less than one square inch.

The finished sword needs steel with 0.6% to 0.7% carbon at the cutting edge, but many reheats are required during the forging processes, and each time the steel is reheated in the forge a little carbon is burned away.

For this reason, the smith starts the whole process with steel containing 1% to 1.5% carbon and the carbon content gradually drops during the long and many times repeated heat and hammer, heat and hammer.

It is worth remembering here that the smith has no real knowledge of what he is doing in metallurgical or chemical terms. Only in this century has he been able to think in terms of percentages of carbon - indeed, he was unable to think in terms of carbon, or some unidentified substance being present in the iron and dramatically altering its properties, at all.

In Europe, for instance, in the middle of the 18th century it was widely thought that steel was a particularly pure form of iron, purified by the heating process.

Cyril Stanley Smith, in **A Search for Structure**[1] quotes **Dictionnaire de Chymie** by P.J. Macquer, published in 1776 -

[1]See bibliographical note at end

'From what we have said, we may judge that steel is much better purified iron than any other iron impregnated with a larger quantity of the inflammable principle, and hammered by the temper.' And yet, by observing tiny clues in the process and thoughtfully relating them to the properties of the finished article, Japanese swordsmiths produced a remarkable consistency in composition and hardness.

The little chunks of hammered and broken raw steel are carefully examined at their fractured edges and those which are heavy and dense, with a fine crystalline structure and a bright silvery colour - which we now know to have between 1% and 1.5% carbon and a few other minor impurities - were then just known to be the right material to start the blade making process. They were carefully sorted out and stacked in a pile 6 or 7 layers high and 3 to 5 inch side, heated to a bright yellow colour (around 1300oC) in a charcoal forge and hammered to a solid mass.

Iron and steel in this carbon content range (but not with above 1.5% carbon) may be welded one piece to another by heating to a high temperature and then hammering them together.

The hammering is done in a manner that elongates the block and after a long flat bar has been obtained it is folded over on itself and the process repeated, rather as one might do making pastry, but in this case with white hot metal and a heavy hammer.

Yoshindo Yoshihara, a modern swordsmith who describes this process in great detail[2] folds and hammers out the steel about 13 times (producing around 16,000 layers per inch of thickness)

The repeated heat - hammer - fold, heat - hammer - fold homogenizes the material, distributing the carbon evenly, while a little is constantly being lost.

Eventually the material has reached a stage at which the smith considers it ready to fashion, by again heating and hammering, the rough shape of the blade.

However, this would produce a blade of uniform material, and a blade more able to resist shock can be produced by inserting a core, right down the length, of a softer more ductile steel.

Just as the original broken chunks of raw steel were selected to produce a steel that would give a hard edge, so other chunks are selected - those with a darker, muddy looking fracture - which have a much lower carbon content. These are destined, after their own heat - hammer - fold processing to form the softer, ductile core.

This is done by chiselling a deep V-cut along the length of the edge steel, performed when the steel is white hot. The softer core material is forged to a shape suitable for insertion into the V and the two are, at very high temperature inseparably hammered together, the core inside and towards the back of the blade.

The composite blade is now reforged into its final shape.

Next comes the final heat treatment, to bring out the strength of the blade and the hardness of the edge. The degree of skill required for this stage may be judged by the length of time devoted to it during a swordsmith's apprenticeship.

All the preceding stages would be taught in two to three years. A further two to three years would be devoted to the final crucial hardening and the production of a blade ready for, but excluding, the fine grinding of the surfaces and the edge sharpening.

[2] Ref. Bibliography

While the presence of a small percentage of carbon - in the case of a sword, 0.6 - 0.7%, as we have seen, to produce a very hard steel a careful and closely controlled heat treatment is required.

This is done by heating the steel to a temperature above about 720oC (which the smith would have to judge entirely by eye), a bright cherry red, and then cooling rapidly, normally in a tank of water - an operation called quenching. If the steel is allowed to cool slowly - just held to cool in the air for instance - it will not develop the degree of hardness required for a cutting edge.

Quench hardening has been recognized for many centuries - Roman swords exist that show evidence of quenching - but the underlying theory of just what is happening in the crystals of steel, that gives hardness with fast cooling and softness with slow cooling (dislocation theory) has only been understood within the last few decades.[3]

The swordsmith wishes to make a blade which is very hard at the edge, much softer and tougher immediately behind the edge. This is quite apart from the use of soft steel in the core.

To achieve this, he ensures that the edge cools very rapidly but that the rest of the blade cools much more slowly, ending up much tougher.

The method is to coat the blade with a layer of clay, very thinly applied at the edge, much thicker towards the back.

When the blade is thrust, red hot, into water the edge cools rapidly through its thin clay coating, the back more slowly.

After final grinding and finishing of the blade, the difference in colour and texture between the hard edge and the softer rear steel can be clearly seen, and many centuries ago this dividing line was taken, by the client warrior to be good evidence that the blade had been made out of the correct materials and properly hardened.

Over the centuries swordsmiths have learned to slightly contour the clay coating, producing patterned effects in the steel behind the edge. Different schools of swordsmith, and different individual smiths would develop different patterns that have become important, though almost entirely decorative, features in the assessment of the sword.

If you take a piece of steel, two or three feet long and approximately 1/4 to 1 1/4 section, heat it to a bright red heat and suddenly thrust it into a tank of cold water you can expect trouble.

The whole think can bend or twist, or cracks can form through the body of it or at the surface.

After all the work that has gone into the blade up to this stage, the average swordsmith would expect to lose over half of his work and an extremely skilled smith may lose a quarter.

Some correction of faults may be possible - not the closing of cracks, but a little judicious straightening or correction of curvature, but the loss figures just given would apply after any such corrections had been attempted.

For the blades which survive this ordeal by fire and water, the long process of grinding and sharpening commences. Again extreme skill is called for, using carefully selected natural stones in many degrees of fineness and hardness so that the final product emerges with sharply defined contours, a smooth sweeping curve and a very finely textures, though not polished, finish.

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[3]See Callister, pp 148-53

The swordsmith's skills evolved over centuries. Having evolved, they remained virtually static for many more centuries.

Enormous experience and skill has been accumulated in the choice of materials for each stage of the process - the choice and concentration of the original ore, the cleaning away of impurities, the firing with carefully prepared charcoal to extract the first raw steel, the hammering and quenching and fracturing, leading to skilled assessment of 'suitability' which we now call carbon content, the refinement by many times repeated forging and folding; the meticulous coating with clay to insulate one part of the blade more than an immediately adjacent part during the hardening and quenching process.

The reader may care to think through this last stage in detail. Imagine that you take a large carving knife from your kitchen and that you must cover it with a coating of clay, as think as a visiting card close to the edge, stepping up to the thickness of half a dozen cards towards the back of the blade. You must scour the countryside for your own suitable clay (you will have to try many) you must learn to refine it and prepare a thin slurry.

You must heat the blade with its think envelope of clay to a bright red heat over a bed of burning charcoal, so that it has the same high temperature right along the length and on each side - all without disturbing anywhere the clay. And, when you have made the temperature both even and correct, you must immediately thrust it into a tank of cold water.

If any of the clay comes away from the steel, a whole month's work is instantly lost - and there are children with hungry mouths in your house next to the forge.

Having found a clay that work in spite of this violent treatment, you treasure it. You lay hands on enough to last you through your career. You take great care to make sure there are no oversize particles to give little drag lines as you apply it with a spatula to the blade, no minute specks of organic matter which could burn with the heat and life the layer. You will develop extreme caution in the surface finish of the steel to which you apply the slurry - not a hint of grease, not too smooth, a nice even oxide coating, but not a scale which could become detached.

And when you have got it right, you adopt one golden rule; **don't change anything**. Use exactly the same materials - even though you don't know in any rigorous way what they are - prepare them and process them in exactly the same way each time. Suppress variation, suppress innovation, teach your apprentices to stick rigidly to the rules.

This type of complex, sequential process leads almost inevitably to lock-in, to stasis.

Even when using the best and most careful techniques a high failure rate occurs and the only way to achieve a success rate that can be lived with is to repeat each stage as exactly as possible. Innovation is extremely risky and is likely to lead to expensive failure.

The Japanese sword has been used as an example of this phenomenon, but there are many others. Particularly susceptible to lock-in are processes in which slight changes in one ill-understood variable produce large changes in the product.

This occurs frequently, for instance in early glass manufacture, in which the absence of a small percentage of calcium oxide (accidentally incorporated in Roman glass by shells in the silica sand deposits used as the raw material - very similar to the accidental incorporation of carbon in iron) leads to an unstable, water sensitive glass.

Suggested further reading

The purpose of this paper is to bring attention to a complex process requiring a sequence of precisely performed and interdependent stages; the description of each stage is kept to a minimum needed for this purpose.

For those interested, much more complete descriptions of the processes may be found in:-

The Craft of the Japanese Sword
Knapp and Yoshihara, Kodansha International, Tokyo & New York 1990, ISBN 0-87011 - 798 X

This is unusually informative, being a book about a craft by a man who actually practices it.

Those interested in the science and technology of historically important artifacts, including detailed laboratory examination of the Japanese sword will gain much from:-

A Search for Structure
Cyril Stanley Smith, MIT Press 1981, ISBN 0-262 - 19191 - 1

Modern theory of the structure of materials at an atomic level, with fundamental explanation of hardness, brittleness and ductility are presented in:-

Material Science and Engineering
William D Callister, John Wiley 1997, ISBN 0-471 - 13459 - 7

[Diagrams to be inserted in the text at points both appropriate and convenient, with short captions. All from Kapp & Yoshihara p.31
Diagrams of the hanon (the line or pattern between the hard and less hard part of the blade), p.39 or 44.
The forging processes pp.72, 75, 77, 78, 80]