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THE ART OF THE LONGSWORD

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1. **swords**
2. **metallurgy**

History of Metallurgy:

The metal that a sword can be made out of has varied throughout the entire existence of the sword. Some of the early swords were made of bronze (although there were swords of different metals before this "bronze age"). Bronze is an alloy of copper and tin that is harder than iron, has a relatively low melting point that allows it to be cast easier, and is more resistant to corrosion than iron. (www.britannica.com) However it was iron that eventually became the metal of choice for the sword blade. The benefit of iron was that it was much more readily available. It is also a more ductile metal meaning that it would not shatter as easily as bronze would. However, this is also a disadvantage because a soft metal does not hold a sharp edge for too long. Sword smiths eventually found that if iron was heated in the presence of leaves, grass, twigs, or other such objects they could increase the hardness. (Agricola. *De Re Metallica*. Book IX P423) What they were actually making was the metal known as steel, a combination of iron and roughly 2 percent carbon (plus some other trace elements) (www.britannica.com).

Steel is formed out of a lump of raw iron ore. There are several steps to get from the ore to the finished product and many ways of performing those steps were used over the years. An ore is a material the contains a metal in such quantities that it can be mined and worked. In an ore, the metal is usually contained in chemical combination with some other element. In all commercial iron ores the metal occurs as an oxide, a carbonate, or a sulfide. Converting iron ore into a form of useable iron is called iron smelting. There are many different forms of iron and steel the main classes being pig iron, wrought iron, Bessemer steel, open-hearth steel, crucible steel, alloy steel, cast iron, and steel castings.

For our research we are mostly concerned with pig iron, wrought iron, cast iron and crucible steel.

Pig iron is the product into which the iron ore is first converted in a blast furnace. Iron ore is placed in a blast furnace along with limestone, which is used as a flux[1] and melted with either coke[2], or charcoal used as fuel. The metal obtained is “pig iron.” It is drawn from the furnace and cast into small bars, known as “pigs.” It is from this that most other types of forged iron and steel are formed.

In the making of wrought iron, pig iron is melted in what is known as a puddling furnace, in which most of the remaining undesirable elements are separated from it, forming a puddle. The temperature of a puddling furnace is kept high enough to melt pig iron but not high enough to keep the wrought iron in a liquid state. On account of this difference small particles of iron, when they have become free from impurities, will partially congeal, forming a spongy mass. This mass is divided into puddle balls or lumps weighing 200 pounds each, which are formed into “blooms” and then, while still hot, rolled into bars.

Crucible steel is made by adding carbon to wrought iron. Small pieces of wrought iron are placed in airtight crucibles containing the required amount of charcoal. This is then melted in a furnace and the metal cast into ingots, which are hammered and rolled to the required size. The adding of carbon to wrought iron in order to convert it into steel

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[1] Flux is crushed stone which melts and either prevents the formation of oxides and other undesirable elements, or dissolves oxides and facilitates their removal

[2] a refined form of coal that is strong and almost smokeless

gives the steel the property of being capable of hardening; that is, of assuming greater hardness if heated to a given temperature and then quenched in water or oil.

Cast iron is made from pig iron by melting the pig iron in a cupola furnace and adding certain percentages of cast iron scrap. It is then poured in the molten state into molds shaped according to the required size and form of the castings it is desired to make.

According to one of the older texts on metallurgy, *De Re Metallica* by Agricola, the easiest and oldest method of iron smelting is the direct reduction of malleable iron from ore. The ore was smelted in a large crucible on a furnace. First charcoal was thrown into the crucible and heated, and then crushed iron ore mixed with unslaked lime was sprinkled over that. Then more charcoal was thrown on, followed by more iron ore; this process was repeated until a pasty heap was produced. The mass was then cooled and hammered until all of the slag, the impurities of the ore, was removed and the iron was condensed and flattened. It was then beaten by a water powered iron hammer and cut into pieces small enough to be reheated by the blacksmiths. Basically this was the standard method at the time of roughly forming wrought iron.

Another method of iron smelting was used to make a form of cast iron. Using iron ore that melts when heated, they removed the metal and eliminated other substances, through the use of a large blast furnace. The furnace was filled with small lumps of ore and charcoal. The high temperatures of the furnace allowed molten metal to be yielded, allowing malleable wrought iron to be formed from the iron ore. The charcoal and temperatures would cause the earthy materials to form a separate material called slag; this would float near the top while the partially reduced iron gathers at the bottom. This is the cast iron, which when drained and cooled is generally brittle, fusible, and has variable properties.

In the 1700s they began seeing the relationships between iron ore and charcoal and in the type of cast iron they formed, as seen here in an excerpt from *On the different metallic states of Iron.* (1768)

> The white cast iron is brilliant in its fracture and is crystallized in large facets; it is harder and more fragile than the others. It is never used for works that must resist a certain stress.
>
> Gray cast iron, whose fracture is matte and grainy, is more flexible than the preceding one and is more easily cut. This substance is also crystalline, but it crystallization is more confused.
>
> Finally black cast iron is even more rough in its fracture; it is composed of less adherent molecules, which crumble more easily. It has no use other than to be remelted with the white cast iron.
>
> These three states of cast iron have no relation to the qualities of the wrought iron. Whatever color the cast iron may be, it is impossible to judge from a glance the nature of the wrought iron that will be obtained from it; and whatever the nature of the ore it is always possible to give to the cast iron whichever of the characters is desired. If in the smelting of the ore as little of the charcoal is used as possible, the cast iron is white; it becomes gray when the amount of charcoal is significantly increased in charging the furnace; and finally becomes black when the use of that combustible is greatly increased. Thus charcoal is the only cause of the color shown by the fracture of cast iron and largely determines its imperfect ductility and the greater or lesser ease with which it's machined.

Their main fault was that in explaining the difference between the irons, they did not even notice that the main distinction was a structural one, namely whether the carbon was present in the elemental state of graphite or whether it occurred in crystals of iron carbide.

Also described in *De Re Metallica* is the process for making steel by cementation. A large crucible and bellows are set up, so that the nozzle of the bellows is directed at the center of the crucible. The crucible is then filled with high-quality charcoal and surrounded by rock to keep the iron and charcoal in place. When the charcoal has been kindled and the crucible is glowing, a mixture of iron and flux is poured into the middle of the crucible. Into the middle of this mixture is then added four masses of iron. This is then heated for 5 to 6 hours in an intense fire. Afterwards the mass is taken and pounded on an anvil, and quickly tempered with water. When tempered, it is replaced on the anvil and broken into fragments. Out of the fragments pieces of iron that have been partially or wholly changed to steel are removed and broken up. These pieces are put back into the crucible and made purer. They are heated and each mass is removed and formed into bars. These are immediately placed in the coldest running water available. Being suddenly condensed the bars are changed into a more pure form of steel, harder and whiter than iron. The science behind cementation is that the iron has experienced at least the beginning of fusion; the bars have absorbed carbon for the charcoal in which they were packed. They are more brittle that they were before; their fractures are brilliant and no longer fibrous, which is the natural effect of the high temperatures they have undergone favored by contact with carbonous material. The iron has also changed in nature and composition, increased in weight, and its properties are changed. It has become a form of steel called blister steel due to its surface being covered with blisters and its mass shot through with cavities.

By the late 1700s the processes of refining steel had become even more of a science rather than a craft. They took the blistered steel and forged it to compact it by blows with a hammer and to hot-weld together the parts that the bubbles of effervescence had separated. This mechanical operation changes the texture of the parts of the metal, but does not give fibers to the steel, it gives it grain. After having being forged the fracture of the steel is no longer shiny, it is gray and granular. In being converted to steel, not only does the iron become harder and more brittle but also it becomes fusible. There was a lot of superstition and lore passed down from master to apprentice surrounding steel making, methods that people knew did a certain thing but they didn't know why, so the methods were often full of ideas that worked but were odd and unrefined. This is one method for hardening iron from a pamphlet printed in Nuremberg in 1532:

> Take the stems and leaves of vervain, crush them, and press the juice through a cloth. Pour the juice into a glass vessel and lay it aside. When you wish to harden a piece of iron, add equal amount of a man's urine and some of the juice obtained from worms known as cockchafer grubs. Do not let the iron become too hot but only moderately so; thrust it into the mixture as far as it is to be hardened. Let the heat dissipate by itself until the iron shows gold-colored flecks, then cool it completely in the aforesaid water. If it becomes very blue, it's still too soft.

Many odd items and ideas were used to change the hardness of iron and make steel. The instructions in the pamphlet tell of many things that can be distilled in ordered to make a mixture to quench the iron in: human excrement, red land snails, root of oxtongue, dragonwort and vervain, mustard and vinegar, human hair, varnish, juice of earthworms and dragons blood. Recipes tell which items to mix to harden, soften, solder, and etch steel. The early process of hardening iron to steel was a single-stage one, an interrupted quench so that the steel came out of the bath at the desired hardness. Much of the mystery and concoctions were associated with this, because what they did know is that pure cool water cooled steel too fast. It may be that the organic matter in the bath also prevented too prompt a reoxidization.

We know now that quenching does not change the nature of steel, it does not alter the composition, it is a mechanical operation. The rapidity of the cooling, or the sudden retreat of the matter that held the molecules of the red-hot steel a certain distance apart from each other, leaves a greater energy to the force that brings them together. These molecules join together with a greater acceleration force that is less restrained. They come closer together and have a greater adherence to each other. But since the force that causes this only acts at insensible distances, the entire mass does not participate in the condensation. It retains a greater volume and a lesser density, it becomes more fragile. In hardened steel the contacts of the molecules are closer together but less numerous, the secondary elements are harder, and their adherence is less.

In Italy the book *De la Pirotechnia* was printed in 1540 by Vannoccio Biringuccio. It took a more scientific approach to making steel than some of the earlier works. Steel at the time was generally made in hearths by holding wrought iron in prolonged contact with the charcoal fuel, however this required a lot of skill, and because it was so difficult, in many smelting areas little steel was intentionally made. In *De la Pirotechnia* the author describes the secrets of using herbs and other items as discussed earlier, but in more depth and also somewhat more scientifically and described the color of the steel at different stages of tempering;

> Other secrets are the various tempering with water, herb juices, or oils, as well as the tempering of files. In these things, as well as in common water, it is necessary to understand well the colors that are shown and thrown off on cooling. It is necessary to know how to provide that they acquired these colors well in cooling, according to the work and also the firmness of the steel. Because the first color that is shown by steel when it is quenched while fiery is white, it is called silver; the second which is yellow like gold they call gold; the third which is blueish and purple they call violet; the fourth is ashen gray. You quench them at the proper stage of these colors as you wish the more or less hard in temper. If you wish it very hard, heat your iron well and quench it rapidly in the tempering bath that you have prepared or in clear cold water.

De la Pirotechnia was one of the first texts that could really be used as a guide and truly comprehensive book on metallurgy.

> Steel can be made from any kind of iron ore or prepared iron. It is indeed true that it is better when made from one kind than from another and with one kind of charcoal than with another; it is also made better according to the understanding of the masters. Yet the best iron to use for making good steel is that which by nature is free from corruption of other metals and hence is more disposed to melt and has a somewhat greater hardness than the other. Crushed marble or other rocks readily fusible in smelting are placed with this iron; these purify the iron and almost have the power to take from it its ferruginous nature, to close in porosity, and to make it dense and without laminations.
>
> Now in short, when masters wish to do this work they take iron that has been passed through the furnace or obtained in some other way, and break it into little pieces the quantity that they wish to convert into steel. Then they place in front of the *tuyère* of the forge a round receptacle, half a *braccio* or more in diameter, made of one third clay and two thirds charcoal dust, well pounded together with a sledge hammer, well mixed,

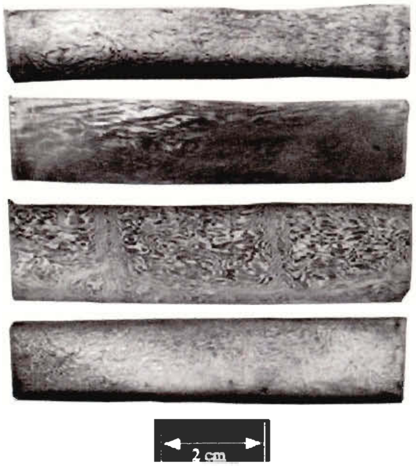
> and then moistened with as much water as will make the mass hold together when it is pressed in the hand. And when this receptacle has been made like a cupeling hearth but deeper, the tuyere is attached to the middle so that its nose is somewhat inclined downwards in order that the blast may strike in the middle of the receptacle.
>
> Then all the empty space is filled with charcoal and around it is made a circle of stones and other soft rocks which hold up the broken iron and the charcoal that is also placed on top; thus it is covered and a heap of charcoal is made. Then when the masters see that all is afire and well heated, especially the receptacle, they begin to work the bellows more and to add some of that iron in small pieces with saline marble, crushed slag, or other feasible and nonearthy stones. Melting it with such a composition they fill up the receptacle little by little as far as desired.
>
> Having previously made under the forge hammer three or four blooms weighing thirty to forty pounds each of the same iron, they put these while hot into a bath of the same molten iron. The masters of this art call this bath “the art of iron”. They keep it in this melted material with a hot fire for four or six hours, often stirring it up with a stick as cooks stir food. Thus they keep it and turn it again and again so that all solid iron may take into its pores those subtle substances that are found in melted iron, by whose virtue the coarse substances that are found in the bloom are consumed and expanded, and all of them become soft and pasty. When the masters have observed this they judge that the subtle virtue has penetrated fully within; and they make sure of it by testing, taking out one of the masses and bringing it under a forge hammer to beat it out, and then, throwing it into the water while it is as hot as possible, they temper it; and when it has been tempered they break it and see whether every little part has changed its nature and is entirely free inside of every layer of iron. When they find it has arrived at the desired point of perfection they take out the lumps with a large pair of tongs and they cut each one in six of eight small pieces. Then they return them to the same bath to heat again and the add some more crushed marble and iron for melting in order to refresh and enlarge the bath and also to replace what the fire has consumed. Furthermore, by dipping that which is to become steel in this bath it is better refined. Thus at last, when these pieces are very hot, they are taken out under the forge hammer, and made into bars. After this while they are still very hot and almost white of color because of the heat, in order that the heat may be quickly quenched they are suddenly thrown into a current of water that is cold as possible.

Also mentioned in that text are the kinds of steel that are highly praised from different areas. A type called Valcamonica from Italy, and also the famed Damascene is mentioned along with guesses as to how the Damascene is made.

> I do not know how those people obtain it or whether they make it, although I was told that they file it, kneed it with certain meal, make little cakes of it, and feed those to geese. They collect the dung of these geese when they wish, shrink it with fire, and convert it into steel. I do not much believe this, but I think they do is by virtue of tempering, if not by virtue of the iron itself.

Although early metalworkers had many different "recipes" for making steel, in their fundamental level they were all the same. Iron was heated in the presence of high-carbon materials allowing the iron to absorb the carbon and become harder. Some of the more relevant processes of steel production for the manufacturing of swords were those of making wootz and crucible steel.

Wootz was made by heating crushed iron ore heated by a charcoal fire in a cone shaped furnace. While being heated, the iron is separated from the ore and it forms a lump of metal. This lump is removed from the furnace and beaten repeatedly to remove any impurities such as coal from the fire. After this process it was reheated again and hammered while still glowing hot. This further purified the metal. While it was still hot, it was broken into smaller pieces that were put into crucibles with the aforementioned leaves, twigs, etc. and heated for a few hours at very high temperatures. These were then air cooled to form little "cakes" of steel (Gogan. *Fighting Iron*. P45). These cakes would eventually make it to the sword smiths where they were "hammer welded" into the actual blades. The process of hammer welding is for the most part given away by the name. Bars, or in this case, cakes, of steel are heated until they are bonded. Then they are repeatedly folded, hammered, heated, folded, hammered, heated, etc. until for all intents and purposes they were combined into one alloy. This would then be quenched (quenching is the rapid cooling of a metal) and occasionally treated with a weak acid to bring out the contrast in the different types of steel. This is shown well in the following picture:



From The Key Role of Impurities in Ancient Damascus Steel Blades. http://www.techfak.uni-kiel.de/matwis/amat/def_en/articles/key_role_impurities/the_key_role_in_damascus_steel_blades.html

The reason these blades could perform so well (as in having both flexibility and rigidity) was that they were not composed of one type of steel. As is seen in the images, there are darker and lighter bands of steel. This is because of the differing amounts of carbon from one “cake” to another. This allowed the properties of the hard and soft steel to in essence be blended together, thus creating both a flexible blade and one that would hold an edge well.

Crucible steel is produced in nearly the same way as wootz is. Its difference is that it is created with wrought iron and carbon objects or previously carbonized iron. Like wootz, it is heated at very high temperatures in crucibles. But because it is heated in a closed environment, there are no impurities that are absorbed into the steel as it is formed. (Gogan. *Fighting Iron*. P47) This crucible steel could then be cut into bars and sent off to sword smiths where they would undergo the same process of blade making as with wootz.

There is further evidence that sword smiths obtained steel from a supplier rather than making their own steel. "Carburisation of iron is a slow process and it was not economical for the individual smith to produce his own steel, which was expensive and sparingly used. It was usually imported from Sweden, Russia, or Spain, since native ores were generally unsuitable for conversion during the medieval period." (Cowgill. *Knives and Scabbards*. P8). This is pertaining to a period that is before the industrial era, and deals specifically with knife blades. However, it is known that in this time period many blade smiths made blades for both swords and knives.

We have found many reports and methods of how to use steel from different ironworks differently. Steel from all of the regions of Europe had different properties and thus there was different advice as to how to forge with each and different techniques for quenching the different steels.

The common steel in France was Soret, Clamecy, or Limousin steel; sold in small square pieces, the texts I have found say that it was good for heavy pieces. But it was cheaply produced and therefore probably used more for plows and other farming implements. The recommended quenching process for this type of steel was to heat it to just beyond cherry red, douse the steel with salt and put it into fresh water until cold; this would generally yield a steel that was less likely to break.

Piedmont steel was reportedly good for forging cutting implements, but one had to watch to make sure the pieces didn't feel stiff when handled and there were no yellow-looking spots in a fracture, which was proof that the steel would be difficult to use. There is also mention of an alternative kind of Piedmont steel formed from an unusual method that was particularly strong and good for making things used for violent and forceful work. There are warnings about quenching this type of steel too hot, and ruining it.

Reports are that some of the best steel available was from Germany, called Carme steel or steel with a rose. It had a reputation for being of excellent quality and was used to make swords and other cutting tools. There are extensive instructions on how to quench this type of steel, probably because it was good quality and hence expensive, and it was imperative to do it right the first time. Recommended techniques include, greasing the blade or putting wooden shavings on it and allowing the grease or wood to burn on the piece before putting it into a running stream or river. The German ironworks in Innsbruck seem to be famed for making some of the highest quality iron. Why isn't clear but one theory is that it might be possible that the German iron-smelters had discovered the uses and properties of manganese, which hardens steel, without knowing it. Knowing only that when they mixed a certain type of rock into the steel in a certain way, better steel was produced.

You may find evidence of its appreciation even in Shakespeare's time in *Othello, "a sword of icebrook's temper."* In the early editions of the play the word is Isebrook which is the anglicized version of Innsbruck.

The Spanish ironworks were also reported to produce steel in large sized bars that took a lot of work to properly temper and quench. But the steel was good for a lot of heavy-duty tools such as anvils and heavy hammers. Also produced was another kind of steel from Spain called acier de Grain or acier de Mondragon. It was a preferred source of steel for the exterior parts of the Toledo blades.

The Weald of southeast England is largely in Sussex, Kent and Surrey. Ironstone in the clay formations was exploited for iron smelting from about the 2nd Century BC until early in the 19th century AD. In 1496 the first documented blast furnace was established in England, on Ashdown Forest in Sussex, and within fifty years the bloomery furnaces had been superseded by the technology of the blast furnace. Making use of water power derived from the many streams in the Weald, a massive expansion of the industry during the second half of the 16th century resulted in over a hundred blast furnaces and associated finery forges being established in the Weald, a number unequalled in any other region of Britain. In the seventeenth century reports are that the iron works in Sussex produced close to 8 tons of iron each "founday", a founday being about 40 weeks which was how long they kept the furnaces burning. The metal was cast into "sows" weighing 600lb to a ton. They then melted off a piece of the sow and beat it with sledges and treating it with water bringing it to a bloom, thus making a plate of iron approximately 33 sq. ft. It is unclear however, the size of plate delivered to the armorer or sword smith.

History of Sword Manufacturing:

Sword making has been a "science" that in the past was thought of as having almost mystical qualities. Sword smiths who forged high-quality swords were viewed as mystics, and their names would be well known throughout the surrounding lands. Even in more modern times, the sword or blade smiths who could repeatedly create highly effective blades would earn themselves a highly revered name. Some of the more famous sword smiths were those of Toledo in Spain, Solingen in Germany and the Damascus smiths. It is said that Damascus Swords can be bent so that the tip touches the hilt, and yet still hold a fine cutting edge (Gogan. *Fighting Iron*. P37).

Now although saying the word "sword" can almost instantly bring up images in one's mind, there are literally thousands of variations. To get it clear what a sword is (if anyone is confused), Encyclopedia Britannica defines it as "a preeminent hand weapon…consisting of a metal blade varying in length, breadth, and configuration, but longer than a dagger, and fitted with a handle or hilt usually equipped with a guard." (www.britannica.com).

The processes for manufacturing crucible steel were some of the main methods of steel production for sword smiths before the industrial era. However, once the industrial period came around, the method of sword making was increasingly more exact as knowledge of metallurgy and material science became greater. The swords of the British military were made by following a strict set of rules for example. The following is the list of steps that are documented in John Latham's *British Military Swords* (P53-54):

- A bar of steel 12 in X 1 in X 5/8 in is heated to red heat and drawn out by mechanical hammers (Ryder Hammers – a series of pistons driven by a belt, each bas equipped with a different shaped hammer-head impinging on complementary shaped anvil.) until it is 20 in X ¾ in X ½ in.
- Reheat steel and pass it through rollers that stretch and shape into required dimensions.
- Should reheated and goes back to Ryder Hammers and drawn out shaped into the tang. This is a more recent method. The previous method was: shoulder opened with chisel when hot and a soft iron tang is hammer-welded onto the blade.
    - All government specifications for swords up until about 1880 stated: "The tang to be made in best wrought iron, neatly and soundly shut on at the shoulders, the shoulders to consist of equal parts of iron and steel." Later specifications came with the above statement, with an addition: "… or the blade and tang made of one piece of steel, solid throughout."
- Blade taken to grinding mill. This removes excess metal and brings blade to final dimensions. The grinding wheel was continually fed with water to keep the blade cool.
- Blade returns to smithy and hardened by heating in gas oven to specified temperature then quenched in whale oil (a non-mineral oil that doesn't change steel and cools at the required rate). The blade is now very brittle.
- Next it is tempered in a bath of molten lead until the temperature of the steel is equal to the temperature of the lead. The blade is also straightened at this stage (done by hand on an anvil using a fixed fork and hammer and checked by eye).
- Blade then cooled in open air.
- Blade polished.

This process was done on a large scale, as it had to fill the government contracts that would include hundreds of swords at a time. The steel used for these more modern swords would most likely be crucible steel as it could be produced in very large quantities for a relatively low cost.

For other swords from the 18th century onwards, a similar process was used. As Frederick Wilkinson describes the process a sword smith obtained a cast steel bar. This bar was then cut into lengths sufficient for two blades, and then fed through grinders until it is correctly shaped. After this the blade was heated and then tempered in warm oil, finished off by polishing on grinding wheels (Wilkinson. *Swords & Daggers*. P58).

The sword smiths themselves were well known among their respective communities. Mowbray tells of the LePage family in Paris, that "The name of LePage on a weapon became a mark of artistry, accuracy and dependability," and "… holders of this name acquired acclaim and wealth serving a variety of masters." (Mowbray. *American Eagle Pommel Swords*. P131). While the LePage family did not limit themselves to only making swords (they were an arms manufacturer, thus they manufactured swords and guns), their early success was due to their skill at constructing swords.

During the pre-industrial era in Western Europe, there were a few areas of noteworthy sword manufacturing that took hold around the 15th century. In Germany there were the smiths in Solingen, Passau, and Cologne. France had Poitou, Bordeaux, and Savoy. Italian swords were from Milan and Brescia. Spain had the Toledo smiths. Britain itself was a little slow in making a name for itself in the area of sword production, but eventually the Sheffield Cutler's Company was formed in 1624. (Wilkinson. *Swords and Daggers*. P57) In fact, British swords were not known for being quality swords. However, there was an Englishman that wanted to give Britain a name in the sword smithing industry. Frederick Wilkinson documents this in *Swords and Daggers* (P58):

> "Blade making in Britain had fallen off so much that in 1783 the London Cutler's Company sought government permission to import blades duty free from the Continent and this provoked a Birmingham tool maker, Thomas Gill, to declare that he could produce British blades of equal quality. In 1786 the Honourable East India Company ordered 10,000 blades and each was to be subjected to a bending test. Of the 2,700 English-made blades 1,084 failed the test; of 1,400 German blades only 28 failed, and of Gill's 2,650 only 4 failed. In addition to the bending test Gill had his blades struck flat, as hard as possible, on a block of cast iron and edgeways on a block of wrought iron and it is reported that some cut through the block."

America also had a need for swords, and many domestic sword smiths took up shop in the 18th century. The main location for sword production was in Philadelphia. An interesting fact was that, despite many domestic sword smiths, most of the blades of American swords were actually Solingen-produced blades (Mowbray. *American Eagle Pommel Sword*. P142). The domestic sword smith businesses were for the most part either family-run affairs, or immigrants that had been smaller-time smiths in Europe. As stated above, they all seemed to set up shop in Philadelphia. A little background information is given on many of these Philadelphia smiths in Mowbray's *The American Eagle Pommel Sword*. There was Lewis Prahl, who worked as a blacksmith, yellow smith (working with brass), gunsmith, and sword smith although his sword smithing was limited (Mowbray. *American Eagle Pommel Swords*. P160). The Rose family were sword smiths only. They were well known for producing high quality blades, with no surface blemishes (Mowbray. *American Eagle Pommel Swords*. P171). Emmor T. Weaver was known for his silver mounted straight-bladed swords. These were not as dressy as some of the other products of the time, but were known to be reliable. He was also involved in Freemasonry (Mowbray. *American Eagle Pommel Swords*. P173). There was also a man named Frederick Widmann, a German immigrant and a "mystery man" historically. He produced high quality swords, but unfortunately never became too successful. He never married and thus had no children to assist him with his work, so he had to stick to smaller jobs (Mowbray. *American Eagle Pommel Swords*. P180).

The sword as a weapon of war did manage to survive for quite a long time. Its origins date back to around 1000 BC and possibly even earlier. However it became less favorable as long-range fighting started to take hold. Gun barrels are also made of steel and as steel could be mass-produced, so could guns. Due to the higher demand for pistols and rifles, weapon-smiths chose to manufacture gun parts rather than swords or other bladed weapons because of the profitability of guns. Because of this, fewer swords were manufactured and they moved more to being decorative pieces than functional weapons.

Metallographical Analysis of Swords:

Metallographical analysis is an analysis in which either optical microscopes or electron microscopes are used to examine metals at very high resolutions, in the case of swords the metal is steel. These tests reveal the composition and characteristics of steel, the temperature at which the steel was hardened or tempered, and any mechanical treatment the steel has undergone (Oberg. *Iron and Steel.* P 95). In this case, the tests can be used to prove if historically documented procedures for the manufacturing of swords are correct. The three most common meteallographic tests are: scanning electron microscopy, optical microscopy, and x-ray analysis.

Due to the precision of these metallographic tests, the equipment needed is usually very expensive. However, WPI has facilities of its own to do such testing. Included in WPI's Metal Processing Institute (MPI) are:

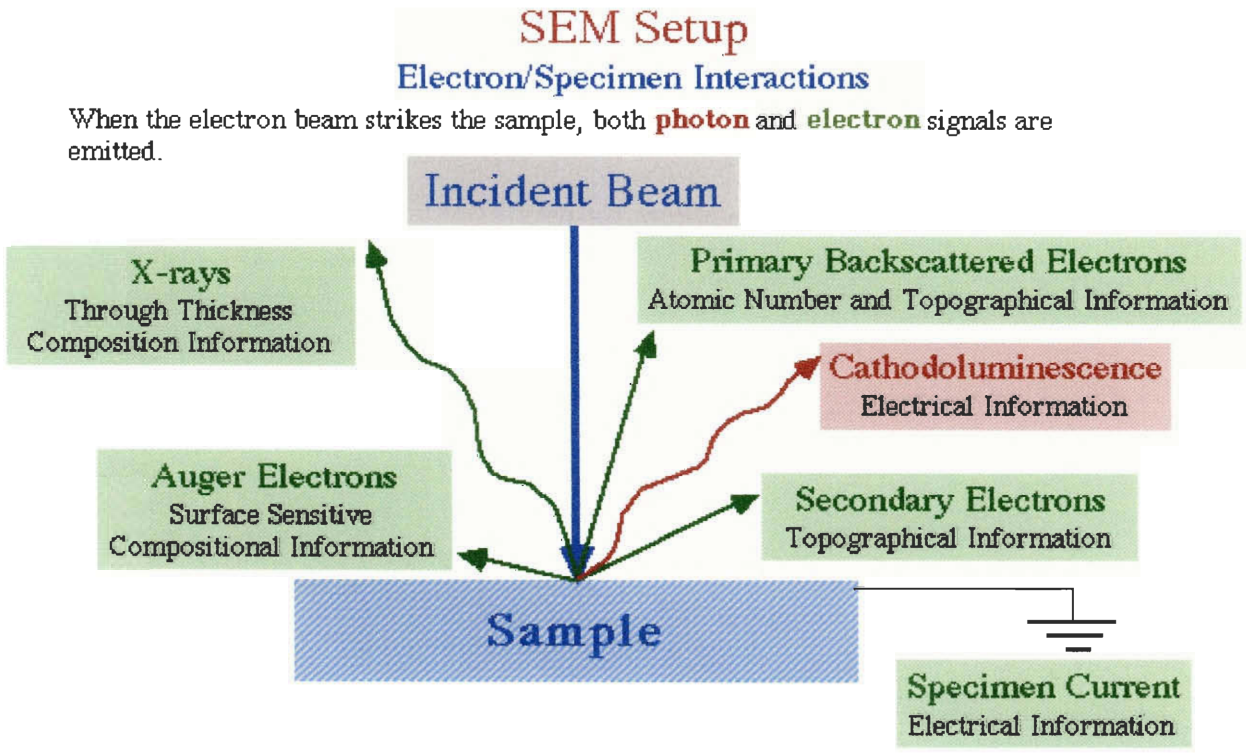
Two scanning electron microscopes (SEMs), an analytical scanning transmission electron microscope (AEM), optical reflection and transmission microscopes, and supporting sample preparation and photographic equipment are the major facilities available for microstructural analysis. The AMR1200 (SEM) is equipped with a Kevex 7000 Energy Dispersive X-Ray (EDX) Analyzer. The JSM840 (SEM) is equipped with stage automated digital image analysis, a light element (Uranium down to Boron) Quantum X-Ray detector with a Kevex Delta system, and a wavelength dispersive x-ray analyzer. The JEOL 100C (AEM) is equipped with a Devex 8000 EDX system. These facilities are used primarily for microstructural analysis and determination of crystal structures of fine phases present in metals and ceramics (from http://www.me.wpi.edu/MTE/optical.html).

As it shows, there are scanning electron microscopes and an X-Ray analyzer. These two pieces of equipment can be used for the tests. Also, optical metallography is also an option, and there is equipment on campus for that as well. As stated above, there are three more common testing procedures for looking at the structure of steel under at very high resolutions. The first one to discuss is Optical (or light) Microscopy. This is more of the basic approach to examining the crystalline structure, as it is based solely on using "traditional" light microscopes. Its first drawback is that it does not have as high a resolution as electron microscopy would have. The next drawback is that in order to obtain the best image of the crystalline structure of steel, the preparation of the specimen must be destructive. The following is an excerpt from Structure of Metals Through Optical Microscopy by Avinoam Tomer on the method of preparation for optical microscopy:

1) Locating region of interest (region of specimen representative of the bulk or one that contains a local area of interest)
2) Sectioning (specimen must be removed while minimizing the effects of over heating, under cooling, or deformation)
3) Mounting (to embed a representative specimen within a housing or mold that will allow specimen to be conveniently held during remaining grinding and polishing steps)
4) Fine grinding (use progressively finer grit sand papers to produce a flat defect free surface)
5) Mechanical/chemical polishing (removes thin damaged layer that remains after grinding and produces a virtually scratch free surface so that the true structure of the metal is exposed for etching)
6) Etching (the surface of the polished metal is attacked during etching using reagents such as acids and bases in a solvent such as water, alchohol or glycerin. Because certain regions of the polished surface are attacked preferentially the structure of the metal becomes visible)

Then, by examining the specimen under the microscope, a high resolution and contrasted (due to the etching) image of the crystalline structure can be created. Looking at this image can give evidence as to how the metal was cooled and the percentage of carbon in the metal. This can help to prove or disprove documented methods of production, or at least documented methods where methods of heating, cooling, and other processes are described. For example, if it is stated that the sword was heated in a certain type of furnace, the statistics on what temperature that type of furnace can reach can be compared to what the metallographic image of the crystalline structure of the sword reveals about what the heating (or cooling) rates and temperatures were.

The Scanning Electron Microscope (SEM) is a microscope that uses electrons



SEM Setup

Electron/Specimen Interactions

When the electron beam strikes the sample, both **photon** and **electron** signals are emitted.

rather than light to form an image. The electron beam comes from a filament, made of various types of materials. This filament is a loop, generally of tungsten, which functions as the cathode. A voltage is applied to the loop, causing it to heat up. The anode, which is positive with respect to the filament, forms powerful attractive forces for electrons. This causes electrons to accelerate toward the anode. Some accelerate right by the anode and on down the column, to the sample. A beam of electrons is generated in the electron gun located at the top of the column. This beam is attracted through the anode, condensed by a condenser lens, and focused as a very fine point on the sample by the objective lens. The scan coils are energized (by varying the voltage produced by the scan generator) and create a magnetic field which deflects the beam back and forth in a controlled pattern. The varying voltage is also applied to the coils around the neck of the Cathode-ray tube (CRT) which produces a pattern of light deflected back and forth on the surface of the CRT. The pattern of deflection of the electron beam is the same as the pattern of deflection of the spot of light on the CRT.

Three requirements for preparing samples for a regular SEM are:

1) Remove all water, solvents, or other materials that could vaporize while in the vacuum.
2) Firmly mount all the samples. Any specimen must be firmly attached to the specimen support before being viewed in the SEM. Attention to detail in the mounting procedure is very important if a researcher desires a quality result.
3) Non-metallic samples, such as bugs, plants, fingernails, and ceramics, should be coated so they are electrically conductive. Metallic samples can be placed directly into the SEM.

There are many advantages to using the SEM instead of a light microscope. The SEM has a large depth of field, which allows a large amount of the sample to be in focus at one time. The SEM also produces images of high resolution, which means that closely spaced features can be examined at a high magnification. Preparation of the samples is relatively easy since most SEMs only require the sample to be conductive. The combination of higher magnification, larger depth of focus, greater resolution, and ease of sample observation makes the SEM one of the most heavily used instruments in research areas today.

X-Ray spectroscopy is yet another choice for testing that can be done on the WPI campus. This method of testing can reveal the elements contained in a given specimen. This happens because X-Rays diffract at certain angles for different elements. The diffracted X-Rays are developed on film (in a similar way as typical photographs), or are stored on a CCD. The following are three methods of X-Ray spectroscopy (from http://www.andor-tech.com/x-ray.html):

> **Dispersion**
> The spectrum of the X-ray source can be determined in two ways: the X-rays can be dispersed before detection; or they can be detected directly. X-ray dispersion can be achieved either by using 'grazing incidence gratings' for low energy X-ray photons, or by using the periodic arrangement of atoms in a crystal as a grating for shorter wavelength photons. The dispersed X-ray spectrum can then be measured using the CCD as the detector. Dispersion techniques, although providing high resolution are relatively inefficient with typically only 10-4 of X-rays being dispersed.

> **Direct Detection**
> Using direct detection without a dispersing element does not necessarily mean that spectral information is lost. As we have seen, an electron is created for every 3.65eV of the absorbed X-ray. Therefore the size of read out signal from a CCD should be a direct measure of the X-ray energy. For example, a 5keV photon can generate 1370 stored charges. Depending

on the noise performance of the CCD we can easily determine the photon energy to better than 100eV. Therefore, by recording a CCD image in conditions where there are few X-ray photons - so that it is unlikely any one pixel absorbs two photons - we can generate a spectrum with moderate resolution by making a histogram of the output image.

Detective Quantum Efficiency & Event Splitting

The procedure for direct detection outlined above is complicated by issues relating to the detective quantum efficiency (DQE) and so-called 'event-splitting' (2). If a photon is detected in the depletion zone, the electrons generated are usually drawn into a single pixel where they are stored for read-out. If, on the other hand, the photon is absorbed deep in the substrate, the electrons and holes will simply recombine and the photon will not be recorded. However, if the photon is absorbed in the field-free zone just below the depletion layer then the low electric field present may allow expansion of the cloud. This can result in loss of some of the charge, which is not stored at all, or it can lead to storage of the charge in more than one pixel – the phenomenon known as event-splitting. This effect is more pronounced if the depletion layer is thin.

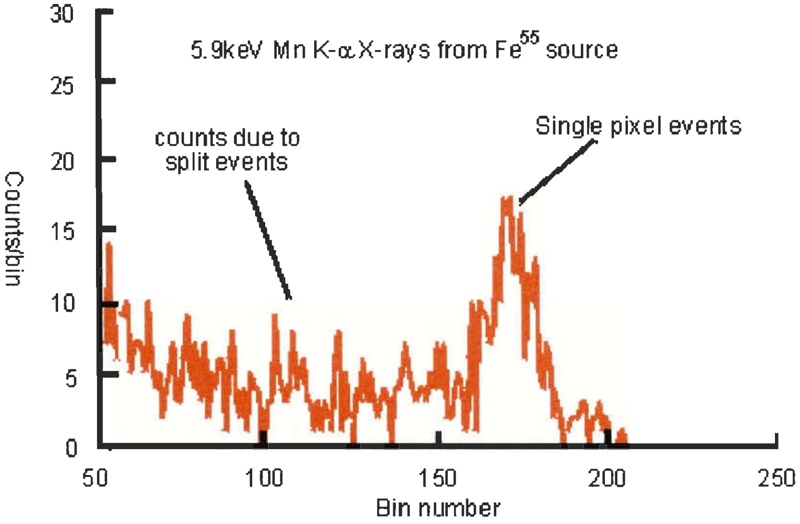


Figure 2. Histogram of CCD pixels for exposure to 5.9keV radiation from an Fe55 source. The long "tail" in low bin numbers is due to electrons from one photon being split into more than one pixel.

An example of event splitting could be seen when an Fe55 radioactive source was used to expose an Andor CCD camera (see Figure 2 above). The chip has 1024x256 pixels and, from the source strength and exposure time, only ~1500 photons at 5.9keV were expected to be incident during the integration time. The resulting histogram in Figure 2 indicates that there are quite a few pixels apparently recording photons with less than 5.9keV. These are due to event splitting. The height of the peak at 5.9keV shows that the quantum efficiency for single pixel detection is 0.17 at this photon energy. The overall detective efficiency, in terms of absorbed energy, is approximately 0.6. A great deal of effort has gone into exploring this behavior in CCDs. Kraft et al (3). have shown that for photons of more than about 4keV energy the single pixel detection

> efficiency can be related to the depletion layer thickness, d, by a simple slab absorption formula:
>
> $$DQEs \sim 1- \exp(-ad),$$
>
> where a is the absorption coefficient for silicon at the appropriate photon energy. Thus, by using the calibration at 5.9keV it may be possible to get an estimate of the single pixel absorption efficiency for other photons in the keV region.

Using these tests, the composition of the steel can be found. From there it is possible to analyze the different elements to determine where the metal originated, and also a limited view of the methods of production (from looking at the amount of carbon in the steel).

Combined, the three tests mentioned (Optical Microscopy, Scanning Electron Microscopy, and X-Ray spectroscopy) can determine the temperature at which the sword was produced, any mechanical treatment done to the sword, and the elemental composition of the sword. Using all the collected data, along with the historical documents, it would be possible to determine if the documented procedures are in fact correct.

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