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Tutorial review

Archeometallurgy related to swords

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ABSTRACT

This tutorial describes the development of swords, their influence on the evolution of materials, and their impact on society. Swords can be dated to the Bronze Age and over time came to be found in many different cultures. They evolved not only geographically, but also with respect to their design and the materials used for manufacture as the nature of conflict evolved. Some of the most advanced materials and manufacturing techniques prior to the modern age find expression in sword manufacture. Carbon dating of ancient iron and steel weapons, and even their oxides in some cases (which retain iron carbide particles), can be used effectively to resolve the date of manufacture. Coupled with their range of styles and compositions, the study of swords is an extremely valuable archeological tool.

1. Introduction

Archeometallurgy is the study of the history of metal production and use by mankind. This tutorial refers to the subfield of study surrounding the production and use of metals for the purpose of making swords. Swords are weapons that have blades that may be of various lengths and shapes. For example, they may be straight or curved, and may have none, one, or two, cutting edges. Swords evolved from knives and daggers and have been made for thousands of years transitioning from the Bronze Age to the Iron Age. Swords appear to have evolved simultaneously in many different cultures. In addition to metals, there are examples of swords that were made of wood. Bone, horn, and stone were also used for related short weapons and in some cases for the cutting edges of wooden swords. Indeed, the curved wooden swords of Egypt are themselves derived from the ancient wooden boomerangs or throw sticks, and the famous Indian Kukkri or Ghurka sword-knife is also derived from that shape [1]. Swords are still manufactured today, largely for ceremonial or collection purposes, but not exclusively so. The sizes, shapes, and weights of swords evolved to counter changes in warfare such as the development of cavalry techniques and the evolution of other weapons.

Because of their long history and ubiquitous use, swords represent an excellent opportunity to study the evolution of technology and materials, and the concurrent advancement of societies. This is because prior to the widespread use of firearms in the 1800's A.D., they were a key element of weaponry.

Naturally, a great deal has been published about the evolution of sword design, the different types of swords found in different cultures [1–3], and the various metallurgical and manufacturing aspects of swords [4–6]. There are huge sub-fields of study concerning the materials and design of handles, scabbards, inscriptions and so on as well as popular accounts of the history of the sword [7–9]. The purpose of this tutorial is to try and capture some essential elements of the archeometallurgy of swords with appropriate references.

The author's personal interest in this topic stems from his study of Damascus swords [10–12]. This was initiated following the recognition that these ancient materials had similar compositions to modern high carbon steels being developed for industrial applications. This initial area of interest expanded to both monolithic and layered sword materials [13–17]. Ultimately the work led to the carbon dating of ancient steels [18–21]. It should be pointed out that the study of ancient materials and explanations for their origins are often controversial [4,6,22, 23] and there are instances of uncertainty of manufacturing methods even in relatively recent times [24].

2. Metallurgical evaluation techniques

Methods to study ancient swords fall broadly into two camps. The first is non-destructive and the second involves destructively using a part of the artifact. Polishing the surface of a sword without damaging the metal falls somewhat in between the two extremes, and great care is taken before any marks or changes of any kind are made to ancient artifacts. However, in many cases there is the opportunity to study damaged materials or segments that have already been studied by others.

Metallurgically, the approach to studying an unknown metal, object, or artifact is to ask what is the composition? And, then, what is the microstructure, how was it made, and when? Subsequently it may be important to know in the case of steels if the object can be carbon-dated. Accurate determination of composition usually needs wet chemical analysis that is destructive, but non-destructive techniques such as

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X-ray spectroscopy can provide information as can micro Raman spectroscopy.

Metallurgical analyses usually require samples to be cut and polished although some work can be done in-situ, but there are difficulties with the scale of a sword when it comes to scanning electron microscopy, for example, and transmission electron microscopy of necessity requires removing a piece of the object. Structural information can then be gleaned by Energy Dispersive X-ray Analysis. Basic metallography can provide considerable information such as grain size and shape, and implications regarding cold work and recrystallization, heat treatment and transformation histories, and composition.

Evaluation of mechanical properties such as tensile strength and ductility inevitably requires destructive techniques, although surface microhardness measurements can yield useful information and are relatively non-destructive.

3. The origins of materials for swords

The generally accepted historical sequence of basic metal development (excepting native copper and meteoric iron) is from pure copper to arsenic bronzes, to tin bronzes, and then to iron and steel [25]. The earliest uses of manufactured metals, that is, smelted copper or arsenic bronzes, date from the chalcolithic age, largely in Anatolia or neighboring areas, starting in 4000–3500 B.C. The early Bronze Age (3000–2500 B.C.) saw increases in arsenic and antimony bronzes (although there are tin bronze axes found in Ur from 3500–3200 B.C.). Examples of products include weapons such as a dagger from melted native copper in 3500 B.C., a flat ax from cast, worked and annealed copper from 3000 B.C., and an early Iberian copper halberd from 3000 to 2500 B.C. There are no examples of long swords during this early period, although short swords are documented [7,8].

The transition from stone knives and axes to copper or bronze was a natural one. And knives could be fashioned into spears by the addition of a shaft. Swords developed from daggers, although there is no real definition of the length of a sword, but it seems that the relative softness of early metallic materials did not lend itself to long weapons because of the ease of bending. The first swords appear in the late Bronze Age, i.e., 1600–1200 B.C. [2]. Interestingly, although an incredible variety of detailed changes took place, for almost 3000 years the basic form of a sword was sustained. A handle, often with a pommel to balance the weight of the blade, either integrated or attached, is connected through a guard to a blade of about at least 60 cm. There are often grooves, or fullers, in the blade to reduce weight without sacrificing key strength properties. Over time, thrusting weapons became cutting and thrusting weapons, narrow blades became broad, one-handed became two-handed, and so on, depending upon the niche of usage.

The date of the transition from the Bronze Age to the Iron Age is a complex topic. In some respects, making iron should be relatively easy compared to tin bronzes because melting is not needed to manufacture iron, whereas three melting steps are needed for high-tin bronzes. In fact, the earliest examples of iron manufacture are similar in time to those of bronzes, but in far less quantity as described next.

Waldbaum [25] is a compelling authority on the earliest man-made iron. (There are ancient artifacts made from meteoric iron but these are readily identified by their high nickel content.) Smelted iron objects, in very small quantities, have been found (in Mesopotamia) from dates as early as 5000 B.C. Additional objects are found from this date continuously in other locations such as Egypt and Anatolia, including some notable historical items. Waldbaum has documented 14 iron objects at sites dating to 3000 B.C., for example. However, it is generally accepted that the start of the Iron Age is between 1200 B.C. and 1000 B.C., but there are complexities with this general statement including the late development of the Iron Age in Egypt (600 B.C.). Because of its initial scarcity and hence value, iron was first used for ceremonial purposes and because it was weaker than bronze, its use as either a tool or a weapon had to await the use of carbon in iron. The evolution from tin bronzes to iron (and steel) involves geography, shortage of ores, the relative strengths of bronzes and irons, the carburization of iron, and the quenching of steels. Clearly, ferrous materials eventually replaced bronzes first as tools and then as weapons — primarily as the benefits of carburization of iron were discovered.

The relative hardnesses of early metals and alloys readily illustrate the driving force to move to steels. The hardness of copper and early bronzes is low with a DPH (Diamond Pyramidal Hardness) of 50–70. To compensate, Bronze Age swords often included features such as ribs for extra strength. Annealed wrought iron has a similar hardness (DPH 100) to worked copper or bronze; but, cold working wrought iron doubles this hardness, i.e., to a DPH of 200 and similar values can be found for complex bronzes. The addition of significant carbon starts to dramatically demonstrate the advantage over bronze so that even in the annealed condition, a Damascus Sword of 1.5% C has a DPH of 320–370. Once heat treatment is introduced, the hardness increase can be profound leading to values of DPH 1000. Thus, improvements of the order of 10 to 20 times are found over copper. Although hardness is only one measure, it is a useful surrogate for strength; but of course, ductility and toughness are also of paramount importance.

The development of steel swords can be contemplated within two basic groups. In the first, the sword is made from a monolithic piece of steel and there are many examples including Damascus swords — albeit with some unusual features such as their unique patterns. In the second group, the sword is made by solid state bonding, usually through forging, of dissimilar metals, and by folding or twisting in a manner that creates a layered or laminated structure. In the development of early wrought iron, the bloomery process led to the necessity for lamination in order to form larger pieces from the bloomery product. Thus, hammer forging and folding led to laminated structures from the earliest times. Often, such processes lead to surface patterns after polishing and etching and hence the term “pattern welded” is sometimes used to describe them. Examples include early Merovingian blades, the Toledo blades, the Indonesian kris, the Japanese sword, and some Chinese swords. (It should be noted that in Damascus steels the surface patterns confused early observers and indeed some believed that these patterns resulted from lamination of different steels.)

In Table 1, key dates and events are listed in the evolution of materials for swords, and their development in various parts of the world. This table is far from comprehensive and is only a top level view, but it does capture key approximate dates of major events. To build on the development of swords this paper will focus on first, the role of swords made from monolithic steels including Damascus steels; second, the evolution of layered steels for swords; and third, the role of carbon dating in determining the age of ferrous objects.

The available literature on sword development from the viewpoint of shape and historical evolution is tremendous. A cursory search by the interested reader will unearth literally hundreds of publications. Some of these are the previously referenced classic works such as Burton's *The Book of the Sword* [1], and others in this scholarly category [2,4–6]. There are also many examples of popular compendia of swords and a few recent examples are selected as references [7–9]. Withers [7] and Withers and Capwell [8] document with excellent pictures the chronological evolution of swords from the early Bronze Age through to modern times with examples from many cultures and detailing the sword lengths, weights, and features. Additionally, there are many magazines devoted to the subject of edged weapons. In the balance of this tutorial, the focus will be on the metallurgical aspects of sword development.

A feature of the manufacture of ancient steels and other complex alloys such as cast bronzes is the lack of written accounts. Perhaps because of this, in cases in which marginal changes in heat treatment or composition can lead to disaster, there is sometimes the association with sacrifice or ephemeral influences. For example, there are ancient writings about human sacrifice associated with quenching Damascus swords. Some of the quotes in this arena have been reported previously

Table 1
Some historical developments in swords (dates are approximate).

Date	Event	Comments
7000 B.C.	Pure copper	Axes, tools
7000 B.C.	Meteoric iron	Knives, Tools
5000 B.C.	Smelted iron	Very small quantities
4000–3500 B.C.	Smelted Cu, As-bronzes	Use of manufactured materials
3500–3200 B.C.	Sn–bronze	Axes found in Ur
3000–2500 B.C.	Early Bronze Age	As-, Sb-, bronzes
1600–1500 B.C.	Late Bronze Age	First swords appear
1350 B.C.	Tutankhamun grave	Daggers of iron and gold
1200–1000 B.C.	Iron Age	Generally accepted date
423–223 B.C.	Shang Dynasty	First Chinese bronze swords
206–220 A.D.	Han Dynasty	Iron replaces bronze in swords
224–651 A.D.	Parthian, Sassanid	Iron replaces bronze in swords
250–450 A.D.	Late Roman Empire	Long sword (Spatha) replaces the Gladius
400 A.D.	Saxons enter England	Swords buried with dead
500 A.D.	Periplus of Erythraean Sea	Indian iron swords exported
793–1066 A.D.	Viking Age	Standardized production, pattern welded
900–1100 A.D.	Seljuq Dynasty, Persia	Curved shamshir
900 A.D.	Japan Tachi	Precursor to the katana and wakizashi
1000 A.D.	Quenched, tempered steels	High quality swords
1100 A.D.	Norman swords, mounted knights	Cross guard on double edged broad sword
1300 A.D. and on	Japanese samurai	Range of sword types
1300 A.D.	Muslim curved swords	Tulwar, khanda, and shamshir Indian swords
1400 A.D.	Chain mail to plate armor	Sword piercing points
1500 A.D.	Germany Zweihander	Two handed, huge guards
1600–1700 A.D.	Europe, Asia	Damascus steels popular
1600–1700 A.D.	Europe side-swords	Rapiers, dueling
1804 A.D.	U.S. Marine Mameluke	Capture of Tripoli
1800's A.D.	Ottoman empire spreads	Curved swords introduced
1800's A.D.	Firearms replace swords	Swords for ceremony and hunting

[16]. A relatively modern quote from the Japanese sword maker, Akihira Miyairi, summarizes the issue: "our work is not done by measuring and talking…all the processes are performed by intuition…experience, yes, repetition, trial and error; but it is *kan* (intuition), the flame, the color of the steel, the thickness of the clay…I adjust these by *kan*. People say swordsmiths have secret formulas. I think it is *kan*, and this sort of thing can never be explained." He goes on to disdain written records, explaining that "true craftsmen don't like to write things down…and any of the ones who did never produced a decent sword."

3.1. The role of monolithic steel swords and Damascus steels

The lengthy history of monolithic steel swords, as described above, maybe starts with the Ancient Roman "Gladius" short stabbing weapon of the infantry (800 B.C.–476 A.D.) which evolved to the longer "Spatha" of the cavalry from the 1st C A.D. onward. There are famous Scandinavian steel swords found at Nydam Moss in Denmark that are dated to ca. 200 A.D. And, folklore abounds with references to swords from the Dark Ages, many of which have names (for example, Excalibur, Joyeuse, Durandal, Altecar, Tizona, Gramr, Fotbir, Meofainn, and Colada) [5]. In a description of Celtic iron swords in the Early Iron Age, Tylecote [6] divides them into two broad groups. The first is monolithic iron with the edges hardened by cold hammering and the second is those made by piling or layering low and high C layers followed by carbonizing.

Many of the modern accounts focus on sword shape and design versus the metallurgical details of their origin or manufacture. Oakeshott [2,3], for example, writes extensively about medieval swords. He starts with the basic design being the blade, the cross guard, and the pommel, and examines the evolution using this three-piece assembly as the classification system. Thus, the blade length and weight and cross sectional shape are key. The evolution from the basic design to the larger "war" sword and then the two-handed sword is defined by the evolution of war practices, armor, and the use of horses. Interestingly, inlaid iron (and subsequently silver, tin, and copper) markings that were hammered into the blades of Viking swords were essentially controlled by the shape of the section of the blade which itself was controlled by the development of armor. So as chain mail became replaced by impenetrable plate armor, the sword evolved from a flat cutting shape to a thrusting shape to penetrate the areas between the armor plates. As the cross section evolved, so did the area available for inscription. The names and variety of swords are remarkable. As an example, the "Landsknechts", mercenaries of old Europe from the late 1400's to late 1600's A.D. or the elite doppelsöldners (so named as "double" mercenaries because they were expensive to hire), used the zweihänder, a 6′ long monolithic steel sword.

Damascus steels are one of a number of interesting examples of monolithic steels; that is, they were made from a single casting rather than being manufactured from layered steels. Their early history is uncertain, but they are believed to have been in use as early as the time of Alexander the Great (323 B.C.). They include scimitars (curved saber-like blades) such as shamshirs (Persia), Kilijs (Turkey), and Tulwars (India). They were certainly in use by the Islamic period (620 A.D. onward) and notably in the Crusades (11th–13th C A.D.). Much has been written [4,10–13,22,23,26–30] about this class of materials and it will not be repeated here, but some highlights are as follows.

Damascus steels are identified not only by their outstanding properties, including superior toughness and cutting edge, but also by the unusual patterns found on their surfaces after polishing and etching, and sometimes gruesome legends regarding their heat treatment or testing. The origin of the patterns has intrigued blacksmiths and metallurgists over time and has been the subject of investigation by luminaries such as Michael Faraday (who was a blacksmith's son), as well as famous scientists in Russia and France. The legend of the steels and the mystery surrounding their manufacture have caused them to be featured in famous novels such as *The Talisman* by Sir Walter Scott, for example, and in movies such as *The Crusades*, directed by Cecil B. DeMille, see [16]. Although the steels were traded to Europeans in Damascus, and carry that name from the European association, their likely origin was from India where the original castings, known as wootz, were made, exported, and then forged in different locales.

Damascus steels have very high carbon contents of between about 1.3 and 1.8% C. The carbon is responsible for the development of the characteristic patterns on the surface of the swords, which consist of aggregated iron carbide particles (cementite). The size ranges of the individual carbides and the spacing between the bands of aggregated carbides have been measured and experimentally reproduced in several different ways, although the precise mechanism for their formation continues to be the source of debate and significant differences of opinion exist regarding the metallurgical origin of the patterns [22,23]. The very high carbon contents can lead to a material that is intrinsically very hard with an associated sharp cutting edge, but one that can also be brittle. The development of the patterns on the steels is a manifestation of extensive hot and warm working, and the subsequent properties exhibit excellent toughness as well as hardness and strength. Because the mysterious patterns could not be reproduced by European blacksmiths, and the excellent properties of the swords were superior to contemporary weapons, Damascus swords developed a reputation for invincibility. The legends and history of the swords have been covered extensively [4,6,10–13,26–30]. Examples of the surface patterns often found in the swords are shown in Fig. 1(a) and (b).

3.2. The evolution of laminated or layered steels for swords

A different manufacturing process for swords involves the layering or laminating of steel of either similar or dissimilar composition. An example of a pattern welded Chinese sword blade is shown in Fig. 1(c).

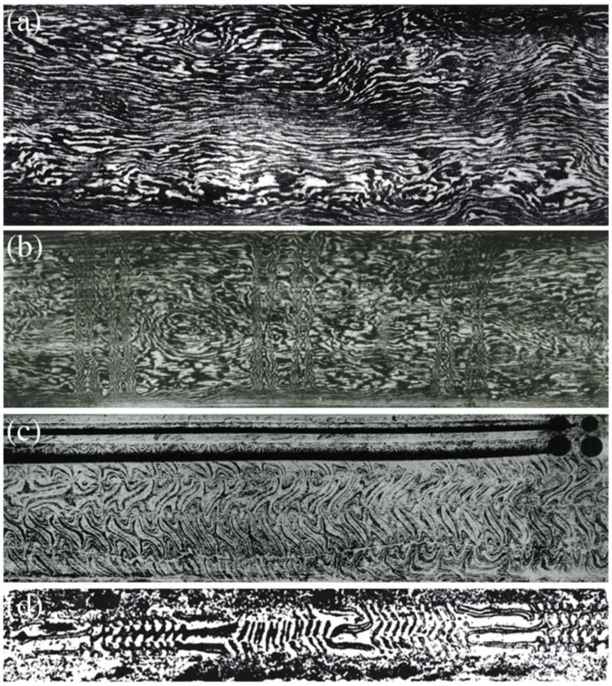

Fig. 1. Examples of blades having patterns are shown. (a) The typical wavy patterns on Damascus blades and (b) the special "Mohammed's Ladder" pattern of repeated vertical markings. In both (a) and (b) the light regions are agglomerations of iron carbide particles in a matrix of eutectoid pearlitic steel. The blades are from the 17th or 18th C. In (c) a 17th C A.D. Chinese pattern welded blade is shown. In this case, the pattern arises from two steels of different carbon contents being folded and hammer forged. In (d) is shown an X-ray image of a Merovingian blade from Finland ca. 650–700 A.D. The patterned structure arises from two low carbon steels twisted together in the center of the blade and encased by folded steels.

The concept of lamination has a very long history. There is controversy surrounding the origin of a laminated iron plate found in an air passage in the Great Pyramid of Gizeh in 1837; the pyramid dates back to 2750 B.C. but iron-making in Egypt was not practiced until two thousand years later. The age of the plate, and how it became contained in the air passage, remains unknown. There is a specific description of Achilles's shield in Homer's *The Iliad* written in 800 B.C., in which a five layered (bronze, tin, gold, tin, and bronze) structure prevents Aeneas's spear from penetrating, suggesting that the concept of lamination for toughness was understood. The existence of a laminated adze blade from 400 B.C. found at Al Mina on the coast of Turkey is well documented and consists of a medium carbon cutting edge with a backing plate of low carbon steel. Laminated composites are found in many other cultures over a very broad time horizon, including the early Merovingian and Viking cultures and sword makers from Japan, China, Indonesia, Persia, India, and several European countries.

The motivations behind laminating metals are varied. Inserting a layer of a rare metal between two layers of a more common metal is one example. The limits in carburizing thick pieces of iron can be overcome by carburizing thin layers and then stacking them to form bulk material. Mechanically, there are a number of potential benefits including strength, toughness, resistance to corrosion, and retention of a sharp edge. There is also the esthetic appeal of visible layers and the visible demonstration of the skill of the sword maker. In Tables 2 and 3 [15] are shown two interesting sets of results. In Table 2, examples of ancient laminated composites are presented with their approximate era of manufacture, and the compositions of the different layers are given. In Table 3, the possible motivations for laminating these materials, and some modern examples, are listed. Some highlights from these products are as follows.

A Chinese saying dating to the 2nd C A.D. refers to "hundred refinings makes quality steel." A blade of 30 refinings was examined [31] and it was concluded that the term referred to the number of layers after repeated folding [likely to be 16, 32, 64, etc.]. Another example is of a sword from North India made of 100 to 150 layers of iron with C contents from 0.04 to 0.3% that was finally quench hardened (6). The issue of folding of metals occurs in several different artifacts, and especially in the Japanese sword. The purpose of folding can result in lamination by decarburization of outer layers during forging, which are then solid state welded back on themselves leading to high and low carbon layers. Multiple folding can also lead to homogenizing of the steel. Laminations are often claimed or assumed to result in improved toughness over bulk material, but this is perhaps only the case in limited examples and will be discussed in the paragraph on the Japanese sword.

Merovingian blades were originally manufactured on the Rhine [4] and date back to the 2nd C A.D., although when found they are usually severely corroded and difficult to examine metallographically. In situ X-ray examination and metallographic studies have demonstrated that they consist of strips of pure iron and low-carbon steel or carburized steel, and instead of simple folding as in the above examples, there is a twisting component that leads to the pattern welded surfaces. An example is shown in Fig. 1(d). The high carbon piece is adjusted to become the cutting edge and apparently, in at least some cases, can be martensitic [4]. Aitchison [5] discusses swords from the Ruhr, the Rhineland, and the district of Noricum, and their manufacture by twisting rods and forging flat strips onto the twisted and hammered pieces. Another process involved "concertina folding" of carburized iron strips.

The special area of the Japanese sword is one that has received enormous attention with many scholarly works as well as fine publications

Table 2
Examples of ancient laminated composites.

Artifact	Approximate era	Composition (where known)	
		Layer A	Layer B
Giza Pyramid plate	~2600(?) B.C.	~0.2% C	Wrought iron
Achilles' shield	700–800 B.C.	Five-layer composite: bronze/tin/gold/tin/bronze	
Adze blade (Turkey)	400 B.C.	Edge: ~0.4% C	Backing plate: ~0.1% C
Chinese blade "hundred refinings"	A.D. 100 onward	Negligible C	Low C
Merovingian blade	2nd–12th century A.D.	Low C	"Pure" iron
Japanese sword	A.D. 400 to present		
Overall blade		Outer layer: 0.6–1.0% C	Inner layer: 0–0.2% C
Outer sheath		1.6% C to ~0.8% C	Interlayers: low C
Thailand tools	A.D. 400–500	Negligible C	0.13% C, 1.8(?)% C
Toledo blades	500 B.C. onward	0.8% C outer sheath	Soft iron central layer
Indonesian kris	14th century A.D.	Tool steel, ~1% C	Low C; meteoric iron with 5–7% Ni
Halberd	14th century A.D.	High C	Low C
Chinese pattern-welded blade	17th century A.D.	Unknown C content	Unknown C content
Shear/double-shear steel	19th century A.D.	High C	Mild steel
European gun barrel	19th century A.D.	Steel, ~0.4% C?	Low C or pure iron
Persian dagger	19th century A.D.	~0.8% C	~0.1% C

Table 3
Possible motivations for laminated materials.

Laminated Artifact	Limited Material	Processing to Make Bulk Material	Tensile Strength	Improved Toughness	Improved Damping	Attractiveness Quality
Giza Pyramid Plate	√	√				
Achilles' shield				√		?
Adze blade (Turkey)	√	√		?		
Chinese blade "hundred refinings"	?	√	?	?		
Merovingian blade	√	√	?			√
Japanese sword			√	√	√	√
Thailand tools	√	√	√	?		
Toledo blades	√	√	√	√		
Indonesian kris	√	√	?	?		√
Halberd	√	√		√		
Chinese pattern- welded blade			?	?		√
Shear/double- shear steel		√	?	√		
European gun barrel			√	√		√
Persian dagger				?		√
FSU* materials			√	√		
Modern knives						√
Modern chisels				√		

* Former Soviet Union.

available detailing the sword surfaces and shapes and handles [32–36]. It is believed that they evolved from Chinese swords such as the Jian, which had initially bronze and then steel forms. The Dao sword was exported to both Japan and Korea, and influenced Japanese swordsmiths. Sword types evolved through the Heian, Kemakura, and Muramachi periods with the high point of Samurai sword making in the Kamakura period (1192–1333 A.D.). Indeed, noted historian Cyril Stanley Smith described the Japanese sword as "the supreme metallurgical art". The swords are composites at several levels and have unique surface markings following heat treatment. The sword is essentially comprised of a high carbon (about 0.6–0.8% C) sheath surrounding a soft low carbon steel core. The high carbon sheath is made by reducing iron ore with carbon in such a way as to produce very high carbon (2% C) brittle pieces called *tama-hagane* that are then hammered together and repeatedly folded. This has the effect of reducing the carbon through repeated decarburization and homogenizing the structure and refining it. The product at this stage is called *kawagane* and because of the repeated folding is often described as containing thousands of layers. However, work by the author and his colleagues demonstrated that discretion of individual layers is lost at about a thickness of a few microns [16], see Fig. 2. The high carbon outer sheath is folded around the soft core (*shingane*) and hammered into the final shape. Clay is then selectively arranged around the blade in such a way that the cutting edge is the only part containing transformation products following heat treatment and quenching. Following polishing, the surface of the sword contains patterns, sometimes extremely elaborate, on the cutting edge reflecting the different transformation zones.

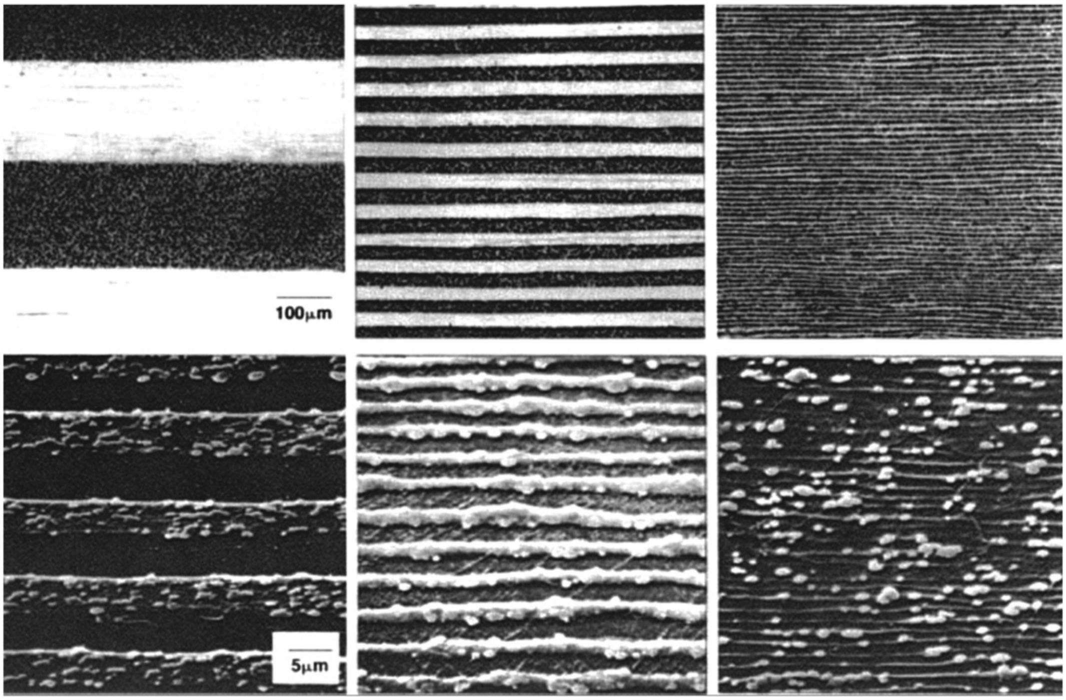

Fig. 2. Top: Light microscope photomicrographs of laminated composites of alternating layers of 1.6% C steel and Fe–3Si alloy. From left to right are images after processing to produce 25, 250, and 2500 individual layers. Bottom: Scanning electron microscope photomicrographs of the 2500-layer composite after processing to have individual layer thicknesses of 5, 2, and 1 μm. At the 1 μm thickness level the carbides are uniformly distributed and individual layer discretion is lost. (The selection of the Fe–3Si alloy was designed to minimize carbon interdiffusion between layers.)

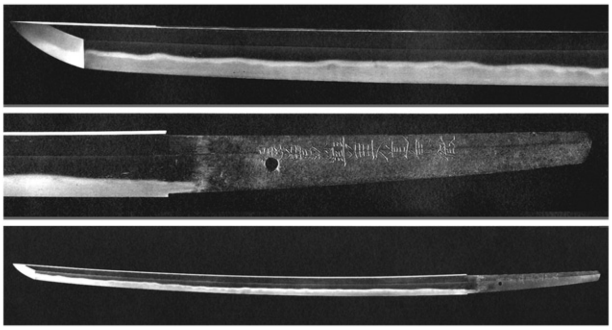

Fig. 3. A Japanese Katana from 1660 to 1670 A.D. Many of the characteristic external features of the Japanese sword are evident. At top, the transformation zone at the edge of the blade following quenching is clear. In the center, the inscription on the tang is evident and in the bottom the shape of the point of the blade and the graceful arc of the blade are hallmarks of Japanese sword making from this period.

An example is shown in Fig. 3. Occasionally the layers from the most recent of the folds in the outer layer can be seen. It has been pointed out that in many respects the Japanese sword structure is similar to the shear steel structure of Western Europe [6]. The Toledo steel swords also consist of a high carbon sheath hot forged around a soft iron core and then quenched and tempered. Toledo steels have a long history dating back to pre-Roman times [37].

In Europe, the art of using different steels forged together to form patterns also found expression in the manufacture of "Welded Damascus" shotguns. The skill level achieved in making these barrels was such that the incorporation of a name into the barrel pattern was possible through the correct initial setup of the starting steel pieces. In Indonesia, there is a class of knife originally invented in the 14th C A.D. called a kris which is unusual in that it can have wavy blades (between 5 and 15 waves) or straight blades. An executioner's kris in this case is made by piling 3 layers of iron or soft steel separated by thinner ones of meteoric iron called pamir. In Fig. 4, examples of both types of kris are shown [16].

As a final note on this section, there are many publications dealing with the modern manufacture of pattern welded blades [38–40]. A remarkable range of materials are incorporated in modern blades often for their esthetic appeal and to demonstrate the skill of the bladesmith [24]. (The pattern welded variety of Damascus steel is even used today in luxury watches; a limited edition of five Aurora watches, retailing for $16,500, boasts a dial face and a case made from 128 layers of two different steels [41]).

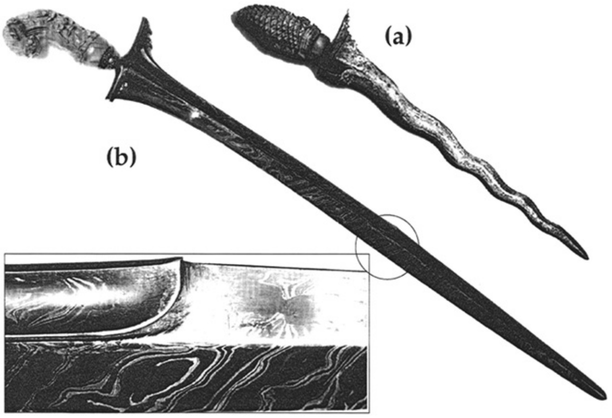

Fig. 4. The Indonesian kris is a pattern welded blade that can be either wavy as in (a) or straight as in the executioner's kris in (b). In the case of (a) the layers are alternating low and medium carbon steels. In (b), the steel layers are interspersed with meteoric iron (pamir). After etching the Ni-rich meteoric iron layers appear bright against the steel background.

3.3. The role of carbon dating in ferrous based artifacts

An issue of interest is the determination of the date of origin of ancient artifacts. Although there are many ways to establish a date, including accurate original inscriptions as are sometimes found on Japanese swords, or provenance, for some materials isotopic techniques are the best. Several isotopic methods are available, but the one of greatest interest to establishing the date of iron-based objects is carbon dating (^{14}C). The reason for this is that it covers a time span of interest from the earliest period of the Iron Age to several hundred years ago. Iron-based materials that contain C include wrought irons containing less than 0.05% C, steels that contain up to 2.1% C and cast irons over 2.1% C.

Radioactive carbon, ^{14}C, occurs naturally and is formed in the atmosphere when cosmic rays create neutrons that collide with nitrogen. The ^{14}C combines with O to form CO and CO_2 which then mix with the stable forms of ^{13}C and ^{12}C. Living matter absorbs C with the contemporaneous mixture of isotopes. Upon death, the ^{14}C is no longer absorbed and decays at a known rate (a half-life of 5730 years). If the ratio of ^{14}C to ^{12}C can ultimately be measured using accelerator mass spectrometry, then the age of the object can be deduced. For the technique to be applicable to iron-based objects, the C source found in the objects must be contemporaneous with the manufacture. Thus, the use of coal or coke in reducing iron ore (as is often the case in Chinese cast irons) does not allow for C-dating because they are both exhausted of ^{14}C, whereas charcoal and wood sources do work.

There are caveats: contamination from other C sources such as limestone and siderite, shells, or old wood that are depleted in ^{14}C can cause articles to appear to be older than they are. Additionally, complications can arise from the recycling of artifacts and one also has to be aware of the possibility of forgeries.

Work by the author and colleagues [18–21] led to some advances in carbon dating techniques and some discoveries. A new sealed tube combustion method for C extraction was developed that used CuO in a quartz tube. This led to simplification in sample preparation methods and reduction in sample size. In addition, it was determined that in many cases the corrosion product, i.e., rust, still contains the C in steel in the form of iron carbide (which is thermodynamically more stable than the pure iron matrix), and therefore in at least some cases rust can be used as a dating source. It is worth commenting that the examination of corrosion products can reveal ghost microstructures and rich structural information can be gleaned as demonstrated recently in 2nd C B.C. Celtic sword blades [42].

A summary of all work to date was compiled. There had been 63 previously published results for iron-based materials, and through discussions with other researchers, nine other results were located. New work by the authors added 20 new results, bringing the total of all known measurements in 2003 to 92. In summary, ages ranged from

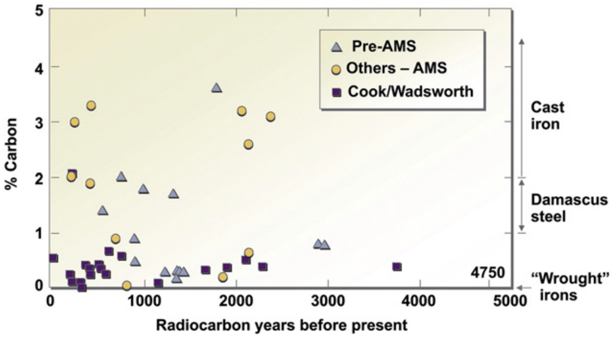

Fig. 5. A summary of carbon dating of iron based artifacts through 2004. The weight % C is plotted versus the measured radiocarbon years before present (BP). The major categories of compositions of cast iron, Damascus steels, and wrought iron (very low carbon) are indicated. Between wrought iron and Damascus steels are low, medium, and high carbon compositions.

very recent materials (1995 A.D. for a Japanese folded metal used for a standard), to materials from 350 BP (in C-dating BP, "Before present", is preferred to B.C./A.D. designations because BP data do not require the use of calibration assumptions [11]), to the commonly-accepted start of the Iron Age (4000–5000 BP). Materials ranged from very low-C wrought irons to cast irons. Sample sizes ranged from less than 0.05 g to more than 500 g. Sample conditions ranged from clean metal to severely corroded metal and rust. In principle, there is no period in Iron Age history that cannot be accessed using carbon dating. A summary of these data is given in Fig. 5.

4. Summary

Swords have been an integral part of society from the Bronze Age to the recent past. They evolved independently in many different cultures and as a result have many different forms, compositions, and structures, some of which are extremely sophisticated. Recent work on carbon dating has demonstrated the usefulness of the technique in determining the age of manufacture of steel swords. The developments of materials for swords, and the evolution of sword designs and structures, are powerful archeometallurgy tools.

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