Hand Tools in History
Steel and Tool Making Strategies and Techniques before 1870

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Preface: Center for the Study of Early Tools

One of the primary missions of the Davistown Museum is the recovery, preservation, interpretation, and display of the hand tools of the maritime culture of Maine and New England (1607-1900). The Center for the Study of Early Tools uses the museum tool collection and resources to document the science of ferrous metallurgy, particularly as expressed in the art of the edge tool. The museum collection and publications explore the development of metallurgy in colonial America, which culminates in the American factory system and the florescence of American toolmakers and their manufacture of hand tools in the 19th century. Museum curator and writer Skip Brack has utilized the most important information sources on early toolmakers, including the publications of the Early American Industries Association, research by Mercer, Goodman, Smith, Gordon, and many others, and information provided in museums, libraries, and historical societies to research material for the Hand Tools in History series. The Davistown Museum combines the new publication series, its exhibition of hand tools, and bibliographic and library resources to construct an historical overview of edge tool and steel making techniques, thereby providing opportunities to learn about the evolution of toolmaking technologies in America up to the end of the 19th century.

In studying the tools in the museum collection, curator and series author Skip Brack found that, in many cases, tools found in old tool chests and now on exhibit in the museum contradicted the popular misconception that all the edge tools of the shipwright used before 1800 or 1830 originated from Sheffield and nearby English tool-producing centers. His observations and the questions that arose from them led him to research and write the three new publications that explore these issues, Volumes 6-8, in the Hand Tools in History Series. The earlier series publications, Volumes 9 and 10 have been updated and will be reprinted.

Volume 6: *Steel and Tool Making Strategies and Techniques before 1870* explores ancient and early modern steel and tool making techniques and strategies, including those of ancient, Roman, medieval, and Renaissance metallurgists and toolmakers. Many of their technologies play a role in the florescence of American ironmongers and toolmakers in the 18th and 19th century. Brack refers to archaeometallurgists such as Barraclough, Tylecote, Tweedle, Wertime, Wayman, and many others who are useful guides for the journey through the pyrotechnics of ancient metallurgy. Volume 6 includes an extensive bibliography pertaining to steel and tool making techniques from the early Bronze Age to the beginning of bulk processed steel production in 1870.

Volume 7: *The Ferrous Metallurgy of the New England Shipsmith* explores the indigenous adaptation of these tool and steel making techniques by New England's shipsmiths and edge toolmakers from 1607-1882. This volume focuses on the construction of Maine's first ship, the pinnace Virginia, at Fort Popham on the Kennebec River in Maine (1607-1608) as the iconic beginning of a poorly documented, but critically important, component of colonial and early American history. This volume explores the roots of America's indigenous iron industry in the bog iron of southeastern Massachusetts and the many forges and furnaces that were built there in the early colonial period. It was these bog iron deposits that supplied the shipsmiths who forged the iron fittings for the many ships built in southern New England between 1640 and 1740. This milieu forms the context for the later evolution of New England's many edge toolmakers and shipsmiths, including the final flowering of shipbuilding in Maine in the 19th century. Volume 7 also includes a bibliography of sources cited in the introductory essays.

Davistown Museum Special Publication 42: *Glossary of Ferrous Metallurgy Terms: A Voyage through the Labyrinth of Steel and Toolmaking Strategies and Techniques 2000 BC to 1950*, originally an appendix in Volume 7, has grown too large and is now published separately. This glossary defines terminology pertaining to the origins and history of ferrous metallurgy, ranging from ancient metallurgical techniques to the later developments in iron and steel production in America, the foundations of which were laid in the colonial era. It includes a bibliography of sources for the glossary and a metallurgy bibliography.

Volume 8: *The Florescence of American Toolmakers 1730-1930* considers the wide variety of toolmaking industries that arose during and after the colonial period and its robust tradition of edge toolmaking. It discusses the origins of the florescence of American toolmaking not only in English and continental traditions, which produced gorgeous hand tools in the 18th and 19th centuries, but also in the poorly documented and often unacknowledged work of New England shipsmiths, blacksmiths, and toolmakers. This volume explicates the success of the innovative American factory system, illustrated by an ever-expanding repertoire of iron and steel making strategies and the widening variety of tools produced by this factory system. Volume 8 traces the rapid growth of American toolmaking that was, in turn, based on a rapidly expanding economy, the rich natural resources of North America, and continuous westward expansion until the late 19th century. It also includes an extensive bibliography on the Industrial Revolution in America, special topic bibliographies on a variety of trades, files on specific New England toolmakers, and chronologies of the most important developments in this toolmaking florescence.

Volume 9: *An Archaeology of Tools*, contains the ever-expanding listings of tools on display in the Davistown Museum tool collection, which now includes important tools from many sources. During 37 years of searching for New England's old woodworking tools for the Jonesport Wood Company's stores, Brack collected many different tool forms with numerous variations in metallurgical composition, which provided the impetus for researching and writing the *Hand Tools in History* publications. In many cases, the tools recovered by the Liberty Tool Co. in New England tool chests and collections and dating from before the Civil War appear to be American-made rather than imported from English tool producing centers. This observation applies to tools made in the early 19th century as well as to many of the tools recovered that date from the colonial period. The tools in this exhibition thus tell a much more complicated story about the diversity of tool and steel making strategies, techniques, and locations of manufacturers of the tools used by American artisans in the colonial period and up until the Civil War. This tool collection, along with our library and publications, forms the core of the Center for the Study of Early Tools. Our Web site provides internet access to the collection of tools in the Davistown Museum, allowing increasing awareness of the role of hand tools in Maine and American history, its shipbuilding industry, and an exploration of the many ways in which hand tools constitute an important information source about our sociocultural and mercantile history.

And, finally, Volume 10: the *Registry of Maine Toolmakers*, the last volume in the Hand Tools in History series, fulfills an important mission of the Center for the Study of Early Tools, the documentation of the Maine toolmakers and planemakers working in Maine. The *Registry of Maine Toolmakers* includes an introductory essay on the history and social context of toolmaking in Maine, a bibliography of information sources on Maine toolmakers, and appendices on shipbuilding in Maine, the metallurgy of edge tools in the Museum collection, woodworking tools of the 17th and 18th centuries, and three appendices on Maine and New England toolmakers. This registry is part of the Davistown Museum Web site and can be accessed by anybody wishing to research the history of Maine tools in their collection. We greatly appreciate receiving information about as yet undocumented Maine toolmakers working before 1900.

Hand Tools in History Complete Series:

- Volume 6: Steel and Tool Making Strategies and Techniques before 1870
- Volume 7: The Ferrous Metallurgy of the New England Shipsmith from the Construction of Maine's First Ship, the Pinnace Virginia (1607), to 1882
- Volume 8: The Florescence of American Toolmakers 1713 - 1930
- Volume 9: Davistown Museum Exhibition: An Archaeology of Tools
- Volume 10: Registry of Maine Toolmakers
- Special Publication 42: A Glossary of Ferrous Metallurgy Terms: A Voyage through the Labyrinth of Steel and Toolmaking Strategies and Techniques 2000 BC to 1950

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Introduction: European Precedents and the Metallurgy of Early Tools

Steel and Tool Making Strategies and Techniques before 1870 explores ancient and early modern steel and tool making techniques and strategies, including those of ancient Roman, medieval, and Renaissance metallurgists and toolmakers. Many of their technologies play a role in the florescence of ironmongers and toolmakers in 18th and 19th century America. I have used sources such as archaeometallurgists Barraclough (1984), Tylecote (1989), Tweedle (1987), Wertime (1962, 1982), Wayman (2000), and many others who are useful guides for the journey through the pyrotechnics of ancient metallurgy. Volume 6 includes an extensive bibliography pertaining to steel and tool making techniques from the early Bronze Age to the beginning of bulk processed steel production in 1870.

The Davistown Museum exhibition "An Archaeology of Tools" ends with the classic period of the Industrial Revolution (1865 - 1900) and the rapid expansion in the variety of iron and steel alloys, manufacturing processes, and tool designs that characterize this industrial florescence. As we move back to earlier periods of America's technological history, the further we go, the more tools in early settlers' tool kits were imported from Europe, either by immigrants or commercial trading companies. This process naturally raises questions about the origins of early tools in our collection that were found in New England not only in archaeological sites but also in workshops, cellars, old factories, and other industrial environments, which are in many cases one or two centuries old.

These questions lead us back to a robust tool manufacturing milieu in continental Europe, which arose in conjunction with the construction of larger and more efficient blast furnaces for smelting iron. Peel back the palimpsest of hand tool production one more layer, and, in the medieval period, we encounter the blacksmiths, who would use a hit or miss procedure to produce their iron or natural steel tools from the bloom of melted iron that was produced by the earliest furnaces.

Our journey through the labyrinth of Hand Tools in History moves both forward and backward in time. In this volume, a return to the earliest roots of the Iron Age brings us, ironically, to the height of the Bronze Age. The earliest steelmaking strategies of four-thousand years ago shed light on the now forgotten toolmaking techniques and forgings of the earliest colonial shipsmiths and help us understand the irony in the decline of the quality of edge tool production in the age of sophisticated tool steels. Our journey ends with the fluorescence of American toolmaking between 1870 and 1930. We are hopeful that the post 1930 decline in the quality of woodworking edge tools may yet be followed by a revival of highly skilled bloomers and edge toolmakers to meet the needs of the creative economy heralded by states such as Maine, where the Davistown Museum is located, and that this renaissance will be informed by the Hand Tools in History series.

In the medieval period, we come to an interesting discontinuity in iron and steel production. The first blacksmiths would use a hit or miss procedure to produce their iron or natural steel tools from the bloom of melted iron that was produced by the earliest furnaces. Because iron absorbs carbon from the fuel, at rates which differ according to fuel-ore ratio and other factors, the very first blacksmiths could produce wrought iron (very low in carbon < 0.8%), malleable iron (0.8 through 0.2% carbon), nodules of steel (0.2 through 2.2% carbon), or cast iron (2.2 to 5% carbon) all in the same primitive bloomery forge. If the bloom of molten iron being reworked on the forge had absorbed just the right amount of carbon, the lucky blacksmith, whether in Assyria in 2000 BC or in ancient Sheepscot (Maine) in 1650 AD, would have a bloom of raw steel, ready for reforging, which was often done in a forge in the same location.

The very essence of the ancient craft of blacksmithing was, in fact, the knowledge that the continued hammering, reheating and quenching of the bloom of raw steel would expel unwanted slag, joining the heterogeneous mix of wrought iron and steely inclusions into a steel tool. The forge welding (further mechanical and thermal treatment) of natural steel was one of the earliest strategies for making weapons and edge tools. Central European blacksmiths, especially those using iron ore naturally high in manganese in their high-shaft Stuckofen bloomery furnaces, were aware that if they ran the furnace with a higher proportion of fuel to ore, resulting in a higher furnace temperature, the carbon, and thus steel content of their bloom increased, with a concurrent decrease in low carbon wrought or malleable iron. Archaeometallurgical evidence indicates that many early furnaces produced blooms containing a combination of wrought iron, natural steel and cast iron, along with slag and other contaminants (Barraclough 1984a).

The alchemy of blacksmithing included the knowledge that rapid quenching of a forged steel tool (just the right amount of carbon absorbed from the fuel by the molten iron) in cold water would result in an extremely hard tool. The magic of making natural steel edge tools included an intuitive knowledge of selecting the hard globular inclusions of natural steel from the bloom of iron, or even better, smelting a bloom of raw steel, and then employing the right sequence of hammering, quenching, reheating, tempering, and again cooling the edge tool being produced. The wide range of the quality of swords produced in Europe's early Iron Age, which ranged from implements fashioned only of iron to beautiful pattern-welded steel swords, illustrates the lack of knowledge of the chemistry of edge tool production. The lack of scientific knowledge was offset by a widespread sophisticated subtle “rule of thumb” knowledge of forging techniques (Barraclough 1984a). The large number of steel or steeled tools that survived from the early Iron Age indicates the wide variety of products that could be produced from a heterogeneous bloom of iron or raw steel. For production of high quality natural steel edge tools and weapons, many hours of laborious hammering, careful reheating, and quenching were required for each tool. The knowledge of the significance of the coloration and a feel for the texture or consistency of the bloom, bar stock, or tool at each stage of the forging process was the key to learning how to produce edge tools. It was the intuitive understanding of this process that allowed individual blacksmiths to forge usable steel tools from bloomery iron, and which allowed a select few blacksmiths to create art out of iron.

Beginning around 1300, the direct process of producing wrought iron and then natural steel edge tools from the blooms of primitive furnaces was supplemented by the development of more complex procedures for producing iron and steel. The key element in this historic change in iron producing technology was the evolution of the blast furnace. Development of this new manufacturing process marks what some historians consider to be the beginning of the first Industrial Revolution.

The introduction of the blast furnace to produce cast pig iron with a high carbon content was the accidental result of the gradual construction of larger furnaces, which ran hotter and in which iron absorbed more carbon, producing what at times in the past had been considered to be useless cast iron. To be made into useful hand tools, cast iron had to be reheated or fined to remove its excess carbon, producing malleable iron or wrought iron from which so many tools and implements were made in the early Iron Age.

The new technology smelted iron ore into pigs of cast iron, which were then reheated and remelted to remove carbon and slag, producing purer and more refined types of bar iron and blister steel. It was the village blacksmith who first made tools and other implements by the direct process of taking the bloom of iron from a furnace and pounding and hammering the iron to produce the desired artifact. It was also the role of the village blacksmith during the early Industrial Revolution to use the wrought or malleable iron from the finery and chafery, which shaped the fined iron into useable bars and anconies, to produce the tools and artifacts of his trade. Blacksmiths, shipsmiths, and edge toolmakers often utilized imported steel from Germany and England to make the edge tools of the first colonists by welding this steel to the iron handle of a chisel or the iron poll of an ax.

The unsolved mystery of the early colonial period is when and where was steel first produced in the colonies? To what extent was the European supply of tools for the shipwright supplanted by colonial toolmakers during the remarkably productive period of ship building in New England that began in the 1640s and resulted in the construction of thousands of fishing and coasting vessels in the next 100 years?

In 1700, Boston was one of the busiest ports in the British Empire outside of England itself. The vigorous New England shipbuilding industry was about to get a boost in the form of a new type of steel, blister steel, produced in cementation furnaces that appeared in the American colonies a few decades after their widespread use in England. This new form of steel, often welded onto iron shafts to create "steeled" edge tools, is the key technological link between early colonial shipbuilding and shipbuilding tools, and a second more robust Industrial Revolution that was spreading across England and Europe in the 18th century.

Five major innovations in the 18th century, constituting a second stage in the Industrial Revolution, paved the way for the full blown Industrial Revolution that evolved in the United States after 1865:

- In 1709, Abraham Darby I determined that coke could be used as a substitute for charcoal as the fuel in a blast furnace. The gradual changeover from charcoal to coke was completed in England by 1760, and was responsible for the rebirth of what was in the previous decades a fuel starved English iron and steel producing industry.
- In 1742, Benjamin Huntsman, in his search for higher quality steel for watch and clock manufacturing, adapted the ancient process for manufacturing crucible steel to his mercantile endeavors, making a major contribution to the evolution of the Industrial Revolution by producing pure steel that had none of the slag and contaminants, including sulfur, that made blister steel produced by the cementation process an often inferior product. Sheffield cutlers quickly adapted cast steel for the production of high quality edge tools, challenging the centuries old hegemony of German steel made from fined (decarburized) cast iron and the recent perfection of making shear steel from blister steel.
- In 1769, James Watt, noticing the wastefulness of the Newcomb steam engine as a water pump, patented his improved version of the steam engine. Production was delayed for four

years but by 1775 Watt had entered in business with Mathew Boulton to mass produce an engine that revolutionized industrial production by the direct conversion of heat to work. In 1781, Watt introduced a mechanism to convert reciprocating motion to rotative motion allowing machinery operation of every kind. In 1783, Watt designed yet another improvement, the double acting steam engine, which allowed the alternative application of steam then vacuum to each side of the piston. The modern Industrial Revolution was underway.

- In 1776, John Wilkinson invented a boring machine to manufacture precision ground cylinders, the first of which was used as a blowing engine at his ironworks at Broseley, allowing the expansion of cast and wrought iron production utilizing coke instead of charcoal. James Watt immediately adopted Wilkinson's design to the manufacture his improved versions of the Newcomb engine, building steam engines that allowed rapid expansion of industrial production. The steam engine increased the efficiency of the blast furnace and allowed industrial activities at locations without water power.
- In 1784, Henry Cort introduced an improved version of the reverbatory puddling furnace, which kept iron separated from the carburizing fuel in a chamber or container above the heat source. The development of the puddling furnace allowed production of large quantities of high quality wrought and malleable iron, some of which was converted to blister, and then to crucible or cast steel. In the same year, Cort designed and built rolling mill equipment that allowed the rapid and efficient conversion of wrought and malleable iron produced in the reverbatory furnace to bar and sheet stock, which was then shipped to special purpose forges and mills to be made into iron products and tools of every description.

In America, where crucible steel was not produced until the Civil War due to lack of access to high temperature resistant crucibles and artisans trained in the subtleties of smelting cast steel, the development of the puddling furnace supplemented America's numerous bloomeries and stimulated the production of large quantities of high quality iron bar stock. Domestically produced iron and steel, along with imported cast steel, allowed American blacksmiths to forge their exquisite timber framing and shipbuilding tools. After 1830, the puddling furnace was also used for steel production by decarburizing cast iron, supplementing blister steel, German steel (also now made in puddling furnaces), and crucible steel in the era before bulk steel production finally satisfied the rapidly growing market for steel (after 1870).

The combination of these five advances in metallurgy, the use of coke instead of charcoal, the production of crucible steel, the development of the steam engine, the invention of precision ground cylinders, and the production of high quality wrought iron in puddling furnaces, were the essential ingredients in a vigorous English industrial expansion (1785 - 1840). Textile machinery and machine tool invention paved the way for the replacement of craft based industries with a factory system that was ironically perfected in America in the fourth and fifth decades of the 19th century before being more slowly adapted in England and Europe. These advances in metallurgy and machine tool design joined with the invention and application of the steam engine and Henry Cort's grooved rolling mills to radically change the manner in which machinery and hand tools were manufactured, increasing their uniformity, efficiency, and quality.

Ancient Toolmaking Techniques

The Origins of Metallurgy

The robust English tool industry of the 18th century, their continental predecessors, and their unacknowledged siblings, the edge toolmakers of colonial New England, have roots in iron and bronze tool production technologies that can be traced back to millenniums before the Christian era. A familiarity with the origin and history of metallurgy before 1350 helps us understand the tool manufacturing techniques that changed very little between 1350 and 1700. This continuity contrasts sharply with the increasing pace of technological change that characterized tool manufacturing processes after 1700. A review of the origins of metallurgy and the history of edge tool and weapons production provides the historical context for understanding the challenge the first European settlers in America faced in manufacturing or importing the edge tools so crucial for their survival. For thousands of years before the Industrial Revolution edge tool production, including weapons such as swords and knives, was an esoteric, alchemical, and even magical process, the efficiency of which determined the rise and fall of empires.

The terms "copper age", "bronze age", and "iron age" can be misleading. They denote historic eras during which one tool form or another dominated the surviving remnants and relics of a particular culture. In this context, the age of metallurgy -- the smelting and casting of metal bearing terrestrial ores -- can be traced back to at least 4500 BC, and possible 6000 BC (Renfrew 1973). All of the many writers on early metallurgy (Ceram, Forbes, Swank, Tylecote, Barraclough, Piggott, Percy, Smith, Snodgrass, Wertime, and Plenier) concur in noting the rise of a major center of iron and natural steel production (circa 2000 BC) in the Caucasus Mountains of northern Turkey and on the shores of the Black Sea, a body of water providing convenient transportation for the metal products of this resource-rich mountain region. Of particular interest is the fact that the Black Sea is lined with self-fluxing iron sand with a magnetite content as high as 80% (Wertime 1980). This sand washes down the rivers from the mountains that lie above the Black Sea on the Turkish coast. The Chalybeans appear to be the first ironmongers to utilize this sand for manufacturing iron and steel implements, circa 1900 BC. Wertime, citing Piaskowski (1982), indicates that at this time they "were making a high nickel steel by adding the nickel arsenide, chloanthite, consisting of iron, nickel, cobalt, arsenic, and sulfur, to the smelt." (Wertime 1980, 20). Piaskowski, in the last chapter of Early Pyrotechnology (Wertime 1982), cites classical sources including Xenophon, Euripides, and especially Aristotle, as noting the evolution of the Chalybean Age of Steel, at the height of the Bronze Age. Aristotle notes, "that a stone called pyrimachos is thrown" into the furnace during the smelting of iron to help produce the steel tools characteristic of the Chalybean smelting process. Piaskowski suggests that the additive used in the smelting process, possibly as a flux, is Chloanthite, a complex iron-nickel-cobalt-arsenic sulphide. The nickel content of this additive or flux, 9.44%, helps explain why tools made by the Chalybeans had been frequently mistaken for meteor iron derived tools, and also explains their tendency not to rust, a phenomenon also cited by Aristotle. Piaskowski notes that Chloanthite is a sulphide, also in agreement with the observations of this steel producing culture made by Euripides.

The iron and steel tools and weapons produced along the edge of the Black Sea were exported to nearby communities during the succeeding centuries. An Assyrian colony was established at Kanes, which continued manufacture of ironware, later supplying the Hittite Empire to the southwest. At no point during the first half of the second millennium BC were sufficient quantities of iron weapons and tools produced to overshadow bronze tool production. The Anatolian coast was, in fact, the location of a polymetallic culture, which exploited local resources of copper, silver and gold as well as iron. The location of tin deposits essential for the manufacture of bronze tools has not yet been established with certainty. Wertime (1980), Snodgrass (1971, 1980), and others note the extensive trading networks necessary for obtaining tin in distant locations, as well as the possibility that the disruption of the tin trade played a major role in bringing the late Bronze Age to an end. The inability to continue large scale production of bronze weapons combined with longstanding knowledge of iron smelting techniques to give rise to the Iron Age and its steeled edge tools and weapons after 1200 BC. Many of the high nickel content iron artifacts noted throughout Egypt and the Near East after 4000 BC, though only occurring randomly in the context of bronze tool production, may have derived from the Chalybean nickel alloy natural steel produced accidentally as early as 1900 BC by the smelting of the iron sands of the Black Sea shoreline. Archaeometallurgists as recent and Tylecote (1976) have previously assumed that these high nickel content iron tools were wrought from meteorites high in both nickel and iron.

The innovative iron smelting and fining techniques of the residents of northern Turkey followed almost three millennium of copper working and smelting. Wertime (1980), among the foremost of pyrotechnical historians, notes the fundamental fact that the use of fire for smelting copper as well as producing pottery, glass, and concrete from lime is the fundamental element in the evolution of civilizations and their urban environment. The first and foremost products of the Caucasus region, including the Black Sea coastline, were copper implements (tools, utilitarian metalware, and ornamental metalwork) produced as early as 4500 BC. Renfrew (1973) also notes the florescence of a copper smelting culture in the central Balkans (Vinca – Yugoslavia) as early as 6000 BC. The evolution of a polymetallic culture in the central Balkans may be autochthonous and the first such example of a pyrotechnic culture; its influence on the later Black Sea coastline polymetallic community is unknown and undocumented. Heskel (1980) also notes the rise of an early copper smelting culture at Tepe Yahya, Iran, with copper awls appearing as early as 4500 BC.

The abundance of copper containing ores made the Caucasus region a center of metallurgy for over a millennium prior to the appearance of bronze tools. Copper implements and tools have two forms: those produced from the cold hammering of the easily shaped raw copper and those cast from smelted carbonate and oxide ores such as azurite and malachite. These copper products were produced in the southern Caucasus region and imported in large quantities to Sumer by 3000 BC. At this time, copper metallurgy can be documented as well established in Egypt, China and India. It is also at this date that bronze tools and artifacts begin appearing in large quantities in many cultures. The key transition point in the evolution of a non-pyrotechnic culture to a polymetalic pyrotechnic urban culture occurred when the hammering and shaping of found or mined copper, silver and gold was supplanted and, in fact, replaced by smelting of copper in furnaces, which reduced or extracted the pure metal from their oxide ores. In the case of copper smelting, at least in southwest Asia including Anatolia, iron oxide was sometimes used as a flux, producing “bears” of iron slag at the bottom of furnaces, many of which were retrieved and recycled during the Iron Age for the valuable metal they contained. Knowledgeable coppersmiths therefore had early experience with iron – it just took a few centuries or longer to figure out useful applications for the iron slag left at the bottom of the copper smelting furnaces. The presence of this iron slag helps explain the occasional appearance of iron tools and implements throughout the Bronze Age.

The start of the Bronze Age is marked by the use of arsenic containing ores in the copper smelting process, which resulted in the first production of a bronze alloy, i.e. arsenic bronze. Arsenic bronze could be hammered, heated, and reforged into edge tools and weapons, which were superior in strength to hammered copper tools. At some point in the late 4th millennium, copper smelters and coppersmiths discovered that if they added tin as an alloy to smelted copper, tin bronze tools were superior to both the arsenic bronze and pure copper tools and implements formerly being produced.

R. J. Forbes (1950) in *Metallurgy in Antiquity* provides this historical sketch of the history of metallurgy. Of particular importance is the transition between stage II, the hammering of native metals, and stage III, the smelting techniques of polymetalic societies that soon gave rise to experiments with alloys and forging techniques, which greatly expanded tool forms, availability, and quality.

Evolution of Metallurgy

I	Native metal as stones [no alterations]
II	Native metal stage ([altered by] hammering cutting etc.) (copper gold silver meteoric iron)
III	Ore stage ([altered] from ore to metal alloys [in a furnace;] composition as primary factor) (lead silver copper antimony tin bronze brass)
IV	iron stage (processing as primary factor) (cast iron wrought iron steel)

(Forbes 1950, 9, Fig. 4)

Initially, the direct reduction of metal from ore was the objective of this industrial activity. Smelters, forge masters, and metal smiths soon learned that direct process metals production was not their only option. The deliberate production of arsenic-bronze, followed by tin bronze, was only the first step in experimenting with alloys and additives that led to the more sophisticated refining processes necessary to produce carburized iron, i.e. steel. For 3,000 years the strategies and processes for producing steeled edge tools and weapons were based on what Barraclough (1984a) called “rule of thumb” procedures. During this entire period the critical role of charcoal derived carbon as a component of steel, and the chemistry of fully martinized steel, were unknown. The spread of the Iron Age into central and finally coastal Europe was the result of the growing intuitive knowledge of techniques and technologies that could produce steel edge tools and weapons superior to the bronze implements that had been used for thousands of years. The appearance of the blast furnace after 1400 AD in Europe, 2000 years after its first appearance in China, marks the beginning of the emergence of sophisticated pyrotechnical polymetalic empires, well armed and ready to settle and exploit the new-found-lands of North and South America and the East Indies.

The Bronze Age

8. Egyptian Copper Adzes, 17th and 18th Dynasties

Trustees of the British Museum

Figure 1 (Goodman 1964, 18).

This Egyptian adz has either a copper or bronze blade with long handles attached to the tool with leather bindings. The adz was not only one of Egypt's most important tools, but was the universal ship carpenter's tool until the advent of the water powered rotary saw (1825) and steam and electric powered woodworking machinery (1860). The evolution of the forms and metallurgy of the adz lead to an Industrial Revolution that manufactured exquisite crucible steel adzes while also rendering obsolete the sailing ships they built.

The use of a technological model to describe the chronology of history can be misleading. This is especially true of prehistoric societies and protohistoric cultures with cuneiform texts that were difficult to interpret. Bronze tools in large quantities began appearing in the Near East and in China at or before 3000 BC. Iron artifacts fashioned from nickel laced meteor iron, or from the addition of nickel-containing chloanthite into the iron smelting process, have been found in Egypt and Mesopotamia dating well before 3000 BC. Fisher (1963) notes the anomalous discovery of non-meteoric forged iron in the Great Pyramid of Greh in Egypt, c. 2900 BC. Other anomalies include the production of malleable cast iron in China after 500 BC and steel producing bloomeries in south eastern Africa (500 AD).

The occasional appearance of forged iron artifacts during the Copper and Bronze Ages raises intriguing questions about the alchemy of metallurgy. The chemistry of bronze and iron smelting was unknown until the very last decade of the 18th century. Yet the art of smelting as a mysterious ritual produced bronze weapons far superior to those made of copper by 3000 BC. Did the metallurgical mountain magicians of this period also smelt forged iron but discard it as too dull for weapons? Did the art of metallurgy arise at different times and places, as in early Egypt or the central Balkan highlands, only to be lost again and rediscovered? Because of the secrecy surrounding the magic of steel production, did the knowledge of the techniques of producing natural or raw steel arise in some other location, only to return to the Caucasus region around 2000 BC? Did production in India of Wootz steel, an early form of crucible steel, predate iron smelting in the Caucasus?

The knowledge of casting bronze from copper and tin pre-dates the broad awareness of how to produce steel tools from primitive iron furnaces and bloomeries that arose after 2000 BC, despite the fact that the smelting of bronze is a much more sophisticated process than the smelting of iron. Hammered bronze edge tools and weapons retain a harder and sharper edge than any edge tools and weapons made from wrought iron. Early metallurgists smelting bronze probably also knew how to smelt iron; the bronze weapons and tools they were making simply had more durability and usefulness than the same artifacts made from wrought or malleable iron. The length of the Bronze Age, as defined as a period of time characterized by the predominant use of bronze tools, varies among geographical locations. In northern Mesopotamia, a robust steel producing culture, the Chalybeans, arose at the height of the Bronze Age, circa (2000 BC). Natural steel tools suddenly appeared in large quantities, but were not sufficient in their patterns of distribution or their variety of applications, to constitute an alternative to the bronze tools commonly used throughout western Asia. After 1200 BC, there was however, a sudden disruption in the availability of tin, which brought a rapid end to the Bronze Age. At this date, the fluorescence of a Chalybean natural steel producing culture was ancient history; the dominant forms of the new ferrous metallurgy were wrought and malleable iron and natural steel, and the weapons and edge tools that were derived from their production. In continental Europe, the Bronze Age ended in 750 BC. In Britain, a gradual end came between 500 BC and 100 BC. Denmark and Iceland continued the use of bronze tools until 100 AD.

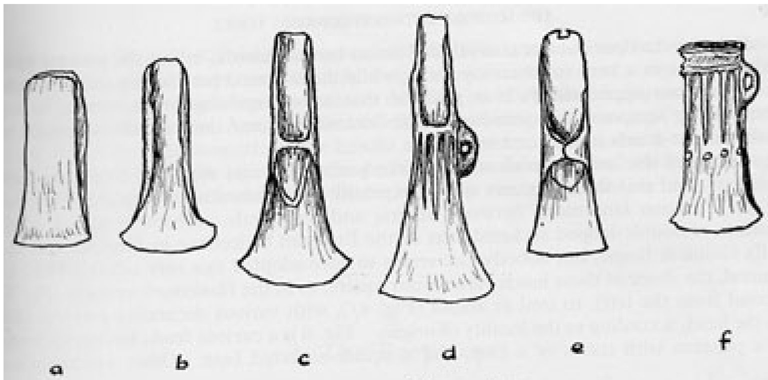
One fact stands out with respect to the era of bronze metallurgy: the single most important result was improved weaponry, as with all later developments in metallurgy. Bronze swords and daggers were far superior to copper weapons. It was the availability of these weapons that must have played a major role in the relative ascendancy of one civilization over another in Mesopotamia during the millennium and a half after 3000 BC. Historians may argue that other factors, such as soil fertility, language development, social organization, or religious values, in a subsistence economic model of the development of early societies, played an equally important role as weaponry. In the long run of history, however, the quality and efficient use of the weaponry more than any other cultural factor determined the viability and fate of the society.

Weapons were not the only edge tools being produced by early pyrotechnic societies. Hand tools familiar to 18th and 19th century shipwrights have their roots in ancient tools forms, including those made of stone, copper, and bronze. The earliest stone adze was an eolith, a found stone edge tool, later sharpened by grinding. Many tool forms still used by American colonists to build their coasting vessels had forms that can be traced back thousands of years, as for example, shaft hole adzes and axes, frame and whip saws, and augers. Early modern strategies for making the steel (e. g. German steel) for edge tools were only a few centuries old in 1608, when Maine’s first ship the Virginia was built. The production of blister steel for steeling edge tools was still decades in the future.

Other issues related to metallurgy are also important. The various sources on the history of tools and metallurgy disagree about a diffusion model of history. Did advances in bronze casting start in the Caucasus and gradually advance to China, where bronze casting of religious statues achieved a remarkable degree of sophistication in the second millennium? Or was this art independently developed within China? And how far in the past will future archaeometallurgists be able to trace China’s use of cast iron, which Barraclough (1984a) dates back to at least 700 BC?

In a study of the archaeology of tools, did the invention and use of copper and bronze woodworking tools also originate in the Caucasus Mountain region? When the metal products of the Caucasus region were transported by sea to other locations, were the ships used built by stone adzes or bronze adzes, or did similar tools forms arrive spontaneously in several locations? What impact did the use of bronze edge tools have on the woodworkers of pre- and protohistory? Did the spread of bronze woodworking edge tools accompany the spread of bronze weapons? Was there a time lag, with stone edge tools lingering in use after the appearance of bronze weaponry? Were bronze edge tools superior to the ground stone axes and adzes used by the first shipbuilders, either Mesopotamian or northern European?

The following illustrations are of typical Bronze Age edge tools. In Figure 2, the socket hole tools illustrate an anomalous tool form that lingered until the beginning of the Iron Age in northern Europe without further development. The earlier shaft hole edge tools in Figure 3, in many cases far older than the socket hole bronze edge tools, are prototypes for modern edge tools. In several cases (Figure 3: c, e, and h), these ancient tool forms are similar to modern American axes.



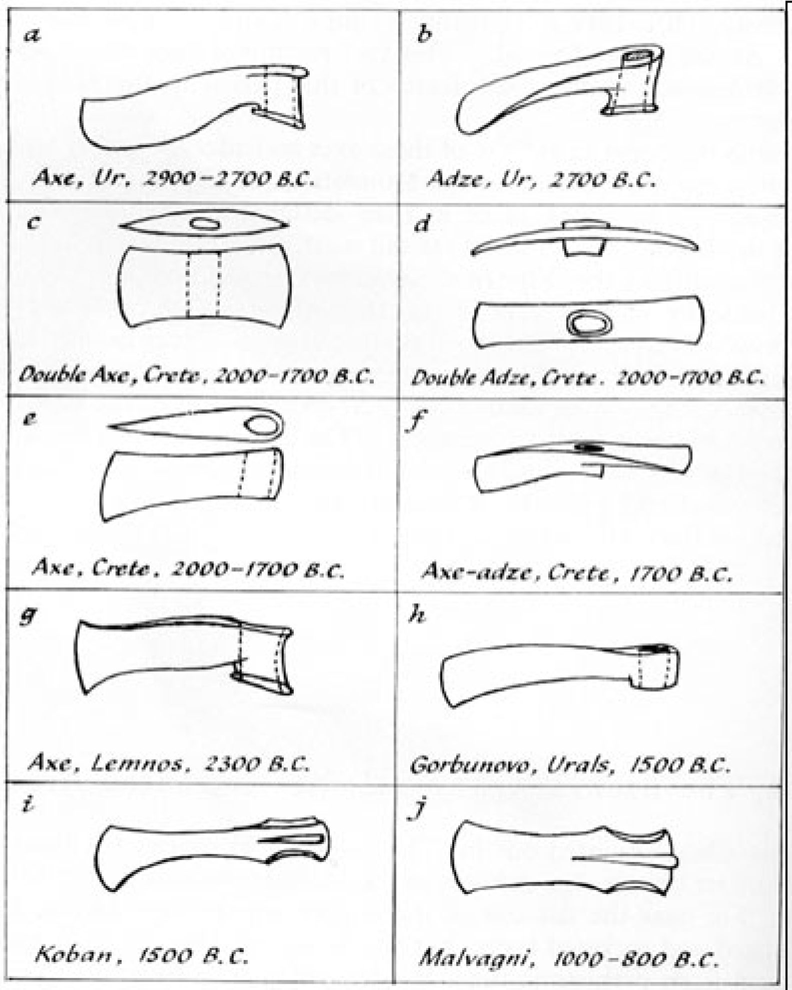
4. Development of Bronze Axes

5. Hafted Bronze Axes

Haslemere Educational Museum

Figure 2 (Goodman 1964, 15).

W. L. Goodman in *History of Woodworking Tools* illustrates an interesting cul de sac in edge tool design: northern Europeans clung to an obsolete model of socket hole bronze edge tools throughout the European bronze age, requiring the hafting of the tool a knee-shaped handle, as illustrated to the left.



9. Bronze Shaft-hole Axes and Adzes: (*a* and *b*) *British Museum;* (*c*, *d*, *e*, and *f*) *Heraklion Museum, Crete;* (*g*) *National Museum, Athens;* (*h* and *i*) *Material and Researches in 'Archeology', No. 35, Moscow, 1953;* (*j*) *Museo Nazionale, Syracuse, Sicily*

Figure 3 (Goodman 1964, 20).

The modern design of the shaft hole ax or adz first appears in the tool kits of Sumerians circa 3000 BC. The Goodman illustrations depict shaft hole edge tools used throughout Mesopotamia, the Mediterranean and the Russian Steppes. These edge tools were much more efficient than the socket hole edge tools used in Barbarian Europe during its bronze age. These illustrations also show the wide variety and relatively modern design of Bronze Age edge tools during this period. The ax illustrated in (h) is a type encountered in Rome a millennium later. The axe-adze from Crete illustrated in f is reminiscent of the combination tools characterizing the tool kits of Vikings two millenniums in the future. In both cases, these tools were made of iron, but their prototypes are illustrated here. Why European Bronze Age toolmakers never utilized the design of the earlier shaft hole style stone tools remains an unsolved archaeological mystery.

The Evolution of Iron Metallurgy

The origins of iron smelting appear to have the same geographical Indo-European roots as copper and bronze metallurgy: the Caucasus region. Snodgrass, Wertime, Plenier and other writers note the florescence of a full fledged Iron Age characterized by steeled edge tools and weapons centered first at Cyprus in the mid-13th century BC with major centers at Crete, the Peloponnesus and Athens by 1200 BC. The earlier isolated ironworking technology associated with the iron sands of the Black Sea is the source of this florescence of a pyrotechnic society utilizing iron ore rather than copper and tin as its major source material. At the same time ironworking technology was working south into the land of the Hittites and the Phoenicians and then west to Cyprus, possibly with the help of the mysterious Sea Peoples, knowledge of ironworking and steeling techniques spread north from the Chalybeans into the Eurasian steppes of southern Russia, resulting in the Scythian Iron Age. After 1000 BC the Iron Age spread rapidly into southern and central Italy and then into Austria and Germany by 700 BC. Knowledge of ironworking technology in central Europe after 700 BC appears to have roots both in the Scythian ironmongers of the Russian Steppes and in the sophisticated ironworking centers of southern Italy and Etruria. Phoenician traders and ironworkers also spread knowledge of iron smelting and steeling techniques to coastal France and especially to Spain during the early years of the last millennium BC (Plenier 1980).

As noted, iron smelting technology originated in the milieu of copper and bronze edge tool and weapons production, but may have been discounted or ignored due to the superiority of bronze edge tools and weaponry over duller wrought iron implements. Practical methods for providing large quantities of "steeled" or natural steel edge tools may have been lacking. Whatever the case, when production of iron tools and implements became widespread sometime after 1200 BC, the result was a rapidly expanding technological revolution. This revolution was the result of the growing knowledge of two alternative strategies for producing steel edge tools and weapons. The first was the realization that smelted iron could be made into "natural" steel by halting the decarburization process prior to a bloom of iron becoming low-carbon wrought iron. This was done by operating a shaft furnace or even a bowl furnace as a higher temperature by lowering the angle of the tuyere and increasing the ratio of carboniferous fuel to iron ore. Wertime (1980) notes the control of ancient shaft furnaces was difficult; carbon re-absorption often resulted in the production of cast iron (higher carbon content resulted in lower melting temperature). The many examples of cast iron artifacts he cites suggests cast iron and natural steel were two well known byproducts of the attempt to smelt low carbon wrought iron.

The second method of making steel was based on an awareness that inserting an iron tool into a charcoal fire for long periods of time in a manner that excluded contact with oxidizing flames, resulted in the absorption of carbon and then the formation of a steel edge on the tool being forge welded. The cutting edge of the tool was carburized by submergence in the charcoal, then hammered and again reheated; forge welding a steely cutting edge on the tool. Forge welding is a toolmaking strategy that has endured in various forms throughout history and is still utilized to produce many tool forms. Blacksmiths of the early Iron Age learned they could make not only forged iron tools, but primitive steel tools by these methods. To further improve the quality, the natural steel or carburized steel implement had to be reheated and hammered to expel slag inclusions. Blacksmiths soon noted that rapid cooling (quenching) produced extremely hard and brittle edge tools. This brittleness could be relieved by tempering, reheating the tool at a temperature below its critical (melting) point, which alleviated the brittleness and produced durable, yet malleable edge tools, especially swords and knives.

The one tool at a time recarburization and forge welding of the outer iron surface of the tool in a charcoal hearth was time consuming and the danger of oxidizing the carbon content by burning the steel was an ever present problem. The key to forging steel edge tools was to prevent surface contact with combustion gases; primitive methods to protect the steel from being oxidized included dipping the iron tool in pig fat and wrapping it in goat skin prior to submerging it in the charcoal fire, or variations of covering it with leather, mud and clay. The fundamental principal was "enclosure" - keeping the wrought iron implement being carburized isolated from combustion gases. The basic principal of early forging techniques was then similar to that employed in making Wootz, Damascus or Toledo steel in crucibles, where the iron was reheated in direct contact with carboniferous materials in crucibles, which protected the tool from combustion gasses.

A third primitive method for making edge tools and weapons was case hardening, a variation of carburizing and then hand forging steel tools and weapons. A lump of wrought iron from the bloom was pounded into thin sheets of iron, which were then buried in a bed of charcoal, possibly even a desert campfire. After hours of baking, the outer layers of the sheet iron would be carburized sufficiently to become steel. These sheets of steel could be piled and hammered together and interspersed with sheets of wrought iron. These alternating sheets of steel and wrought iron could be forge welded into the pattern-welded swords and weapons of the early iron age. Victory in warfare often went to the warriors with the best blacksmiths who produced the highest quality weapons by the tedious carburization of wrought iron or the even more difficult pattern-welding of sheet steel and wrought iron. The intuitive knowledge of hardening by sudden quenching followed by tempering to relieve brittleness was the secret to successful production of steel edge tools superior in quality to hammered bronze weapons.

With respect to this revolution in metallurgy, the diffusion model of technological change as advocated by Childe (1925) appears to help explain the spread of ferrous metallurgy, at least in the Mediterranean region. Aside from the isolated appearance of forged meteor nickel-iron, iron production was isolated or restricted to the Caucasus until taken up by Hittites in eastern Turkey, close neighbors of the iron mongers of the Caucasus, sometime after 2000 BC. At this time, iron smelting and forging technology spread northward from the Caucasus area to the Scythians on the vast expanse of the steppes between the Carpathian Mountains and the Don River. Iron working in this area included a robust tradition of animal art work, conical footed iron cauldrons and short iron swords and daggers, prototypes of forms to later emerge in the timber frame burials of central Europe.

Iron smelting technology in India, which evolved into a sophisticated crucible steel making (Wootz steel) capability, may have originated in the Caucasus. Wootz steel had its limitations, however, as it was produced only in 1 to 3 Kg batches and required mixing into the crucible just the right amount of pure wrought iron and a carboniferous material such as granulated charcoal. Wootz steel was later traded to Damascus, where the famous Damascus steel swords were produced, probably as early as 1500 BC. The forge welding of Damascene steel swords involved the same technique of pattern-welding thin sheets of crucible steel and pure wrought iron, producing malleable steel swords of amazing durability and quality. The Damascene sword was of a higher quality than any weapon produced from wrought iron, natural steel, forged steel or case hardened steel. Archaeometallurgical analysis indicates many swords were "refined" as many as 25 or 50 times (Barraclough 1984a). While Barraclough is referring here to pattern-welded weapons made in China circa AD 77 - AD 189, the same pattern-welding techniques were universally used throughout the Near East and central Europe to make the highest quality swords of the early iron age. Examples of pattern-welded swords were produced almost as soon as the first iron and natural steel tools were produced; in the area of the Caucasus this may have been as early as 2000 BC. The Damascus steel industry was a component of the spread of iron smelting technology to northern Palestine, which was well established over a broad area by 1250 BC. The extensive references in the Bible to iron (90) and steel production (5) illustrate the spread of this technological process.

Bronze edge tools still dominated Mycenaean culture until its demise circa 1100 BC when Dorians, probably armed with iron or steel swords, overwhelmed the Mycenaean civilization. Iron production also appears on Crete and in Greece at this time; Homer makes numerous references to the production and use of iron and steel during the Trojan Wars. The Greeks cite the Chalybeans on the south side of the Black Sea as their source of iron smelting technology and the iron swords, spears and horse bits that followed. With the fall of the Hittites in eastern Turkey and northern Iran, military dominance in northern Mesopotamia evolved to the Assyrians, famous for their use of iron swords and especially, iron chariots, probably the most important technological innovation of the Iron Age.

One of the enduring mysteries of Mediterranean protohistory is the extent of use of iron and steel weapons by the invading "sea peoples" during the great migrations of 1250 - 1150 BC. It was these migrations by numerous small bands of warriors from locations as diverse as Libya, Anatolia, Greece, and possibly more northern locations that put an end to late Bronze Age civilizations from Egypt to Troy. Once iron smelting technology became widespread after 1200 BC, it spread to Greece and Crete (1200 BC), Etruria (1000 BC), southern Italy (900 BC) and continental Europe by 750 AD, but not necessarily in the logical sequence indicated by the dates.

The Chinese Iron Age

K. C. Barraclough (1984a) in his classic *Blister Steel: The Birth of an Industry* provides a sketch of the many strategies the Chinese used to produce steel. Following the pioneering research of Joseph Needham (1958), who wrote *The Development of Iron and Steel Technology in China*, Barraclough notes that the rise of a robust cast iron industry in China can be dated at least as early as 700 BC and appears to be nearly concurrent with the use of the direct process bloomery furnace to produce iron and steel. There is no readily identifiable period of bloomery iron and steel production that can, as yet, be identified as preceding the rise of cast iron production in China. Perhaps the most significant evidence for the sophisticated steel producing capacity in China at this time is the existence of a white cast iron adz with a decarburized cutting edge. The cutting edge of this adz has been carefully heat treated; illustrating a sophisticated ability at malleableizing cast iron. Barraclough notes that by the Menchuis era (4th century BC) there is ample evidence of the widespread production and use of malleableized horticultural tools throughout China. Of particular interest is the fact that the process for malleableizing cast iron apparently went out of use in China around approximately 700 AD. A millennium passed before this process was rediscovered by the French metallurgist R. A. F. de Réaumur (1722). In the ethnocentric world of American metallurgy, Seth Boyden is considered to have been the inventor of malleableizing cast iron in the 4th decade of the 19th century.

Barraclough describes the fully developed Chinese version of the blast furnace, which was widely used during the Han Dynasty (202 BC – 220 AD). This relatively small furnace with a circular hearth was typically 13 feet in height, 8 feet in diameter, and was charcoal fired producing approximately a half ton of cast iron per day. Coal was also used as a fuel source but at a later date. By the third century BC, enough specimens have been recovered from gravesites to illustrate that a wide diversity of techniques existed for producing swords at this time, including sophisticated pattern welded swords. Barraclough notes in particular that the steel produced in China was made by the charcoal fining of pig iron by a process very similar to that used in Germany and Austria (the Styrian process) fifteen hundred years (or more) in the future. Barraclough, after Needham, also notes widespread production of wrought iron as well as the first documented evidence of what is now known as the Brescian process, which was in evidence at least as early as 125 AD. Several variations of producing steel by submergence in liquid wrought iron can be dated as early as 1116 AD from written sources, which note:

> Now for making steel, they take bars of soft iron and fold them up in coils, inserting pieces of cast iron between the layers. Then they seal up the furnace with clay and heat it. (Barraclough 1984a, 32)

Barraclough describes this as a solid-diffusion method, which was widely practiced at this time. The resulted heated mass of raw steel was then forged into a more coherent mass and then subject to further forging and heat treatments to produce some of the fine steel swords that can also be dated from this period. Barraclough also quotes Needham's citation of a 1637 manuscript describing the technique of fusion:

> The wrought iron is beaten into thin plates or scales as wide as a finger and rather over an inch and a half long. These are all wrapped within wrought iron sheets and tightly pressed down by

> cast iron pieces placed on top. The whole furnace is then covered over with mud matted with worn out straw sandals. The bottom of the pile is daubed with mud as well. Large furnace piston bellows are then set to work and when the fire has risen to a sufficient heat the cast iron comes to its transformation first, and, dripping and soaking, penetrates into the wrought iron. When the two are united with each other they are taken out and forged; afterwards they are again heated and hammered. This is many times repeated. The product is usually called “lump steel” or “irrigated steel”. (Barraclough 1984a, 33)

Barraclough notes this method anticipates later western methods but omits the ingot casting stage. The fact that this particular strategy for making steel was in use in China at this late date (the manuscript is dated 1637), and follows almost two millenniums of use of variations of the Brescian method, suggests the wide variety of steelmaking options available to continental European, English, and colonial American immigrant ironworkers in the 17th century. We now think of blister steel production via the cementation furnace as the source of our early steeled edge tools. The use of the cementation furnace is a relatively late development in steel producing strategies. The many and varied older options for making steel were well known at this time.

The European Iron Age: Halstadt 750 - 450 BC

(The German spelling is Hallstatt)

One of the curiosities of the iron age in Europe is that it did not spread, as might be expected, from Greece to Rome to southern Europe and thence north, but from the east out of the vast Russian steppes of the Scythian horsemen with their iron swords and animal art, probably following the same pathway as the bronze swords that preceded them (2000 BC). The earliest examples of iron tools are found in Czechoslovakia wagon graves well to the east of Halstadt, Austria.

The rise of an iron smelting culture in Europe is time and site specific. The first evidence of widespread use of iron tools and implements comes from the vast graveyards (in excess of 2,500 graves) of the later periods of Halstadt culture. During the late Bronze Age (1200 to 800 BC), Halstadt graves contained a vast array of bronze tools, many similar to those in the tool kits of the Scythians to the east. After 800 BC, iron technology was introduced into proto-Celtic Europe and iron tools began appearing in Halstadt grave sites. A flourishing salt trade with southern Europe and the Mediterranean helped support a robust culture with elaborate hill fort burials, some containing four wheeled funerary wagons, and including rich hoards of tools, gold metalwork and other cultural artifacts. The Halstadt culture extended in the east to Bohemia and Czechoslovakia and thence westward to Switzerland and eastern France. The culture was named after its most important commercial center, the salt mine town of Halstadt in central Austria. The characteristic tool of the later Halstadt culture is a long iron sword, which first appeared in the Czech wagon graves replacing the decorated long bronze swords of the earlier Halstadt culture. Iron edge tools may have been used to the east to construct the larger plank-built burial chambers that contained so many of the iron tools recovered from this culture. A gradual westward shift of Halstadt culture lead to the establishment of new trading routes down the Rhine river with connections to the Rhone River, which provided access to the recently established Greek trading center at Marseilles (circa 600 BC).

A fundamental question remains unresolved with respect to Halstadt iron production. Etruria, located to the south of Austria in central Italy, possessed iron tools and artifacts as early as 1100 BC. Yet Halstadt, with its extensive mineral resources and its rich manganese containing iron ore was not an iron tool production center until 800 AD. Did it also import wrought iron or iron tools from the south in trade for salt, also having learned metallurgy from Scythian predecessors to the east? Could Halstadt's metallurgy skills have originated in the south and come via Etruria from Aegean and Mediterranean sources as a result of its Etrurian trade networks?

The European Iron Age: La Téne 450 - 50 BC

La Téne represents the next stage of Celtic culture in central Europe. La Téne was a village and ritual site on the edge of Lake Neuchâtel in Switzerland. Discovered in 1857, La Téne, lying northwest of Halstadt, was rich in archaeological artifacts indicating a fusion of styles of the earlier Halstadt chiefdoms to the east with Greek and Etrurian decorative styles to the south. La Téne reflects the gradual movement of Celtic influence to the west, reaching the Atlantic coast of France by 200 BC. La Téne styles in decorated metalwork, tools, and pottery appeared in Spain, throughout Gaul and eventually in Britain after 100 BC. La Téne burials contain more warrior related artifacts than the more peaceful Halstadt; these included the appearance of iron-axle chariots in aristocratic warrior burials. La Téne metalwork is characterized by distinctive curvilinear motifs; its iron swords and daggers were shorter than those made by Halstadt iron mongers but with greater decorative qualities. The La Téne culture obliterated Halstadt styles and forms. It spread south into Italy and to Britain, though why and how it spread remains unknown. One of the mysteries of the early Iron Age in both Britain and Gaul is that limited iron production may have preceded La Téne-related Celtic migrations by several hundred years, raising the probability of penetration by Halstadt metallurgical techniques as early as 500 BC.

A second mystery is the relationship between the relatively rich resources of the Sussex Weald, south of London, with its manganese laced siderite ores and the Roman invaders who took over the iron industry of the Weald from the indigenous Celtic iron mongers who had worked its ore deposits for centuries. Perhaps the Romans integrated this indigenous iron smelting community in their efforts to utilize the same resources for arming the legions of Roman warriors who were fighting or would soon fight the Gauls. The Sussex countryside is littered with remains of Roman bloomeries, usually located along streams directly adjacent to ore deposits, and always marked by the tell tale slag deposits of the smelting process.

By the beginning of the La Téne era, two different strategies for making steel were well established. The primary strategy was natural steel production from direct process bloomeries, which resulted from the finesse of the iron smelter’s control of the reducing process. As noted, changes in the fuel ore ratio combined with use of manganese laced ores facilitated natural steel production. The second principal steel production strategy of the early Iron Age involved the carburization of wrought or malleable iron by the time consuming process of submerging individual tools in the charcoal fire and then forge-welding a steel cutting edge on the shaft of the iron tool being steeled. An alternative process was case hardening an edge tool by submergence in a charcoal fire or fire pit. Only a few edge tools could be produced at one time by these tedious processes.

Bloomeries specifically designed to produce raw steel probably appeared sometime between the late Halstadt and early La Téne periods. Tylecote (1987), Pleiner (1962), and others note the presence of “currency bars” at locations throughout continental Europe in the early Iron Age. These portable and usually handled bars of iron often contain significant quantities of raw steel, that is, they had a highly heterogeneous carbon content. Whether initially accidentally or deliberately smelted with a high carbon content, currency bars were the raw material used to forge sheet iron and steel from thin bar stock made from these bars. The sole function of finers and forge masters was to create iron and steel tools and weapons from these currency bars, which were traded throughout continental Europe.

Iron Age in Britain and Rome 500 BC - 400 AD

Unlike the beginnings of the European Iron Age, the widespread use of iron tools in Britain cannot be pinned down to a specific time and location. Iron tools, weapons, and other implements begin appearing in British archaeological sites dated as early as 500 BC. By 100 BC, the Iron Age appears well established in England, but not in Ireland, where use of bronze tools lingered well into the era of Roman occupation of Britain (43 AD).

Caesar led the first Roman expedition to Britain in 55 BC, then again in 54 BC. During the preceding five centuries, Britain had been gradually settled with bands of Celtic farmers from Gaul -- the gradualism of their settlement may be reflected in the sporadic appearance of iron tools and weapons in Britain in the same period. By the time Caesar encountered Celtic Catuvellauni at Britain's most prosperous city fort at Colchester (54 BC), he found numerous well armed soldiers equipped with iron swords and horse drawn chariots.

Whatever remnants remained of a Bronze Age culture in Britain was quickly obliterated by the Roman invasion of Britain at Rusborough (AD 43). The 25,000 Roman troops brought with them iron implements of every description including natural steel and forged steel edge tools and weapons. This rich legacy of the British Iron Age during the Roman occupation is well illustrated in the many museum collections in England, most notably in the British Museum in London, the London Museum and regional museums throughout Britain. As Goodman (1964) also illustrates in his *History of Woodworking Tools*, prototypes for 18th and 19th century American hand and edge tools abound in these collections, in some cases (as with sheep shears, a primordial form of scissors) unchanged until the 20th century.

It is at this point in time that a diffusion theory of technology becomes inadequate. Roman iron and steel had two important sources. The most import source of Roman iron, steel and weaponry was "Noricum", the Roman province that was also the location of the Halstadt culture with its manganese rich iron so useful in the production of natural steel. Important iron and steel producing centers in Noricum included the trading centers of Magdaleneberg in southern Austria, Huttenberg to the north, and Linz, at the end of the “iron road” from the Erzberg (Iron Mountain) to the Danube River. Spain, Spanish mines, and Spanish metallurgists supplemented the famous natural steel tools made from the spathic ores of the Erzberg in Austria, also supplying iron and steel tools and weapons to the Roman Republic.

The sacking of Rome by the Gauls in 390 BC may have been due to the gradual improvements in the metallurgy of Gallic swords, which may have increased in quality over several centuries. The Etruscans, who controlled northern Italy and the Rome area until 500 BC, also had a large repertory of iron tools and weaponry. As with the origins of the Etruscans themselves, the sources of their iron technology are unknown. Did their knowledge of iron smelting diffuse from the north in Gaul, where there may have been occasional iron production even before Halstadt, possible as early as 900 BC? Did the Etruscans, who overthrew the Romans in 500 BC, then bring their knowledge of iron smelting to Rome and central Italy before it filtered in from Greece? Did the knowledge of iron smelting reach Spain earlier than Italy, courtesy of Phoenician traders and iron mongers who were another source of knowledge of the secret alchemy of ferrous metallurgy? Or did Etruscan iron metallurgy derive from earlier Iron Age activity in Greece, Crete, and Cyprus, currently the conventional viewpoint (Snodgrass 1980, Wertime 1980)? Was the later defeat of the Gauls by the Romans, allegedly with superior steel swords, the result of obtaining superior Spanish steel *after* the first successful Gallic invasion of 390 BC? What role did Spanish steel swords play in the defeat of Carthage? Did the Romans further perfect the art of sword and armor making with the help of the manganese rich spathic ores from Noricum, which may not have been available in Spain? To what extent did the siderite ores from the Sussex Weald supplement natural steel from Noricum and Spain?

Caesar was assassinated in 44 BC, marking the end of the Roman Republic, the beginning of the Roman Empire, and the ascendancy of an Iron Age that used many of the basic woodworking tools found in 19th century woodworker's tool chests. These include cast iron jack and jointer planes, socket and tang chisels and gouges, axes, adzes, hammers, pry bars as well as blacksmith's tongs and other iron tools (Goodman, 1964). Iron production in many locations – Sussex, Carinthia, Spain – was underway on a large scale. The question remains: what about the quality of steel weapons and tools? Was all steel imported from England, Spain, and Noricum? What about steel swords from Damascus, which utilized the Wootz steel from India to produce the world's finest steel swords? Did the woodworkers' edge tools have weld steel cutting edges? Or were natural steel and/or forged steel edges hammered out by blacksmiths directly from the forge? Is the paucity of surviving steel edged tools due to the fact the steel is easily oxidized and didn't survive for 2000 years? Or that steel, as a rare and valuable commodity, was carefully hoarded and recycled? Whatever the case, by the time of the Roman Empire, the hegemony of an iron age culture with steel swords, natural steel edge tools, and iron chariot and wagon axles was established from the furthest reaches of Mesopotamia to the northernmost regions of Europe and the fringes of the British Isles. Hundreds of relatively low quality (by our standards) natural steel ax heads, highly contaminated with slag inclusions, and nearly as dull as a malleable iron ax, abound in private and museum collections throughout Europe. Five toolmaking strategies for making edge tools (knives and swords) characterize early Iron Age, Roman, migration period, medieval, and early modern metallurgy before the appearance of the blast furnace. Radomir Pleiner's (1962) pioneering work on early metallurgy is cited by Tylecote (1987) and provides a thumbnail sketch of these early toolmaking strategies.

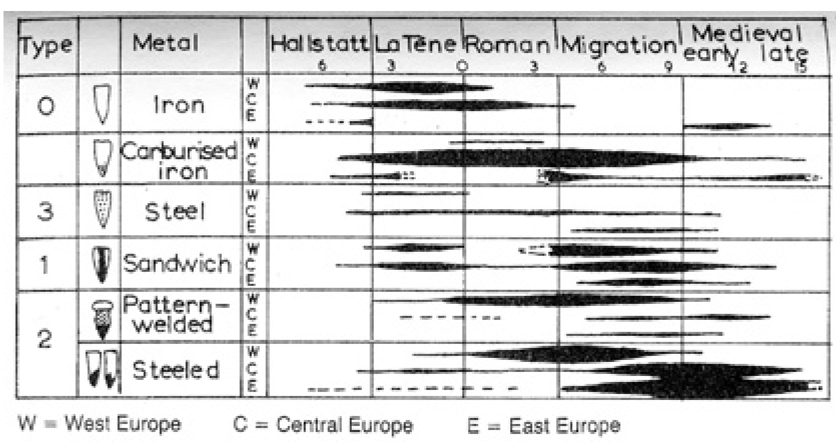


Figure 7.21 Chronology of knife forms (after Pleiner 1962).

Figure 4 Knife forms. From Tylecote, Ronald F. 1987. *The early history of metallurgy in Europe*. New York: Longmans Green. pg. 269.

These techniques for making weapons and edge tools characterize forging practices until the appearance of cast iron in the 13th and 14th centuries. Until that date, the best edge tools and weapons other than the Damascus sword were made from Spathic iron high in manganese, later the source of spiegeleisen (cast iron high in manganese). The manganese neutralized the deleterious impact of sulfur in the direct process bloomery, facilitating its expulsion within this slag and allowing the accidental and unintended production of iron with more uniform carbon content, i.e.

natural steel. A high proportion of early central European iron implements circa +/- 500 BC, especially those manufactured in southern Germany and Austria, were composed of natural steel rather than wrought or malleable iron. Most of the manganese was expelled in the flux with the sulfur as a waste product. Manganese remaining in natural steel tools, in cast iron implements and equipment, and in steely tools made from the partial decarburization of spiegeleisen (German steel), as typified by many of the late medieval tools in the Nuremberg Museum, gives them not only added strength but also a shiny appearance such that they appear to be made out of crucible steel.

The extent of use of iron tools during the late years of Roman occupation of Britain and the turmoil that followed, is illustrated not only by the wide variety of iron implements in museum collections from archaeological sites, but also by the startling number of pikes, spears, and other weapons found in the Thames River and other riverine locations. Luckily for archaeologists and historians, warrior votive rituals required disposal of articles of warfare in the river. The anaerobic environment of the river mud flats served to protect these iron and steel tools from oxidation, allowing systematic retrieval of these pikes, spears, and swords by British antiquarians who became knowledgeable about this tradition during the 19th century. The forms and styles of these implements provide a link between Roman Britain and the later florescence of a reinvigorated iron age that began during the period of cathedral construction (1100 AD).

Wrought Steel: The Zelechovice Furnace

One of the most famous of all writers on early ferrous metallurgy is Radomir Pleiner, a Polish archaeometallurgist. Few of his writings have been translated into English, but he is often cited by the also famous multilingual American archaeometallurgist Theodore Wertime. One important article by Pleiner (1969) is available in English, *Experimental Smelting of Steel in Early Medieval Furnaces*. Pleiner is an avid investigator of numerous bloomery forge sites from the early Iron Age to the late medieval period, particularly those which are commonly encountered in eastern and central Europe. Working in conjunction with the Archaeological Institute and the Institute of Iron Metallurgy, both in Prague, Pleiner investigated early medieval Slavic metallurgy including a Zelechovice type furnace located in northern Moravia and operated during the 8th century AD. Pleiner also correlated his experiments with investigations of the Scharmbeck low shaft bowl furnace commonly used in northwest Germany, Poland, and Czechoslovakia during the first four centuries of the Christian era.

To perform his investigations, Pleiner rebuilt a Zelechovice furnace, which was constructed in a rectangular trench approximately 13 meters long and 2 meters wide. These bloomeries often had wide slanting entrances in their midsections with nearby charcoal and ore piles and roasting hearths. Pleiner built three bloomery furnaces of this design, one of which was used for testing air circulation and the other two for the actual smelting tests. The most intriguing component of this type of furnace was the cavity in the lower furnace body, which extended in the ground to the right of the tuyère (see figure below). The iron ore being smelted was placed in this cavity on top of and adjacent too but not within the charcoal fuel being fired. The most important characteristic of this particular type of a bloomery furnace was that it was capable of the production of natural steel. The bloom of iron ore being reduced was sufficiently protected from the oxidizing influences of the combustion gasses of the burning charcoal by this cavity; the resulting product of these early Moravian furnaces was often either partially or primarily raw natural steel with a heterogeneous carbon content.

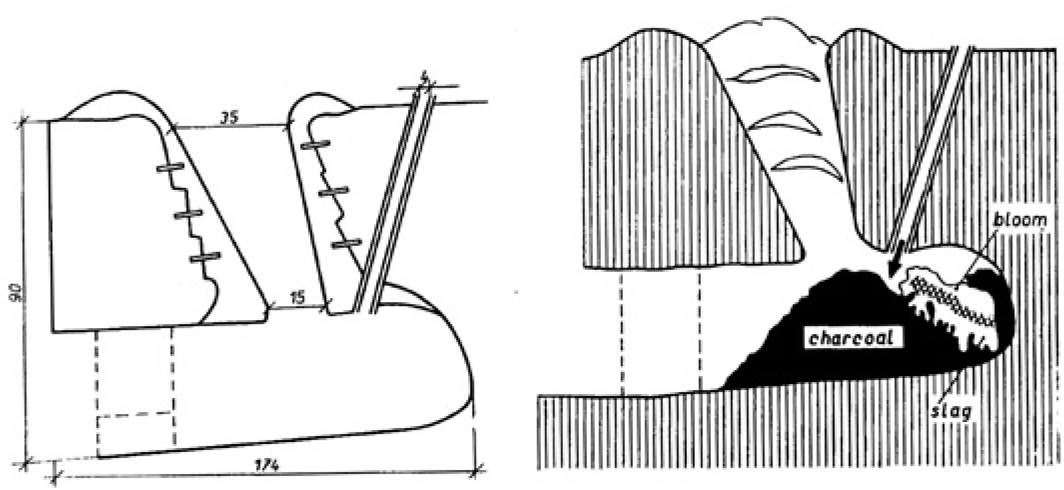


Fig. 3. Profile of the Slavic furnace of the type Želechovice prepared for the smelt II.2. On the right hand: the position of the metallic bloom in the cavity during the process.

Figure 5 (Pleiner 1969, 461)

The Pleiner text contains no discussion of whether the ironmongers of north Moravia had access to any of the manganese laced ores that were available to the south in the Carinthian and Styrian sections of Austria, but this type of bloomery was certainly used specifically to produce a steely iron, not low carbon wrought iron. There is, as yet, no documentation that this particular bloomery design was used in the Roman period, but the Scharmbeck type bowl furnaces, which were also used in Pleiner's investigations, are a typical form of bowl furnace used during that time. The Pleiner team was not completely successful in smelting natural steel in the furnace they built, but some steel was detected within the compact center of the bloom of smelted iron, but not in the thin sheets of sponge iron surrounding the charcoal. Pleiner sliced one of the blooms produced in the experiment into two parts using a diamond cutoff wheel, then etched the bloom surfaces with nital; macroscopic examination then revealed that most of the surface of the bloom was steel. Pleiner notes that there was some inhomogeneity but it was "not quite as bad as in many original fragments of prehistoric blooms" (Pleiner 1969, 475). While all the smelts in the experiment were not successful, at least one smelt yielded a bloom that contained about 25% of the iron in the ore charge, though only part of it was of a quality that could be forged. Pleiner indicates that the necessity of taking frequent measurements of the process occurring in the relatively small furnace, in the form of partial opening of a control hole every five minutes, may have influenced the stability of the smelt. The iron mongers of Moravian prehistory would have had no such intrusions, and apparently were able to produce blooms of raw steel on a regular basis. Pleiner comments that while steel artifacts in the area he has surveyed are not ubiquitous, the objects found suggest the steel was:

> …produced in metallurgical furnaces and not by secondary cementation… [He also observes that during] excavation of the Zelechovice bloomery an unusual structural aspect of the furnace drew our attention; they were all equipped with a cavity just behind the tuyère. This arrangement was hypothetically interpreted as a reheating and cementation chamber for the bloom, which would have been put there immediately after the smelt. The production of steel in such a type of furnace was therefore taken for granted. (Pleiner 1969, 484)

Pleiner further notes that his smelting experiments were done with "haematite" ore without manganese and with a low phosphorus content; the bloom thus produced:

> …consisted of pearlite and a minimum of ferrite fibers or cementite grains: we had produced high carbon steel. Only small parts and tips were decarburized by the airflow. The hypothesis that the furnaces of Zelechovice steel thus found a splendid confirmation. (Pleiner 1969, 485)

Pleiner also comments on the many observations of carburization within medieval bloomery furnaces as illustrated by samples of pig iron and artifacts recovered from archaeological sites. He notes the presence of manganese was positive for carburization, whereas the presence of phosphorus had a negative influence, and also that the blooms from most furnaces had to pass through a very dangerous zone of reoxidation near the tuyère mouth. It was this reoxidation process that reduced the carbon content of the bloom from raw steel to malleable or wrought iron. Pleiner then makes this final comment that, in contrast, in the Zelechovice type furnace:

> …the reduced red-hot bloom passed relatively quickly through the oxidizing zone and slipped into the back cavity where the reheating process took place, under very good reducing conditions. The bloom, surrounded by charcoal, was protected against blowing, and the properties of the carbon steel were retained. This result… offers important evidence about the

> technical ingenuity of the early medieval smelters among the Moravian Slavs. (Pleiner 1969, 487)

No similar bloomery furnaces with recessed cavities have yet been documented in southern Europe, England, or the United States. The existence of this unique style of bloomery furnace again illustrates the wide diversity of steel smelting options, which characterize polymetalic societies in the centuries before the development of modern steel producing technologies.

Iron Tools, the Vikings, and Scandinavian Ore

Of most interest to students of the history of metallurgy, the advent of the Dark Ages failed to squelch the ability of northern Europeans to forge iron and steel tools. The memory of most smelting techniques survived the advent of the Dark Ages in Europe. Charlemagne, Carolingian King of the French (768 - 816), and emperor of the Roman Holy Empire under Leo III (800 - 814), had access to steel swords and iron tools of equal quality to those used by his Roman predecessors. The florescence of Frankish culture at this time helped ensure the transition between the robust tradition of wrought ironwork in the medieval period and the development of steel producing economies as the result of the construction of the enlarged blast furnaces of the 14th century.

The art of the Merovingian sword smith was eclipsed only by the "Damask" patterns of Islamic sword blades and the famed Japanese swords, both of which are described in detail by Smith. But the Vikings soon followed the Franks with their own version of a steel sword that was also often also pattern welded but may have utilized more steel strips and less wrought iron that Merovingian examples. Cyril Smith (1960) suggests the pattern welded swords of the Merovingians were not derived from Roman prototypes, but have their own unique style based on a sophisticated pattern welding technique, which utilized strips of steel and wrought iron. Treatment with a reagent discloses the unique microstructures of Merovingian swords, which Smith illustrates in the opening chapter of his text. The later development of a heavier all welded steel Viking sword was probably influenced by Merovingian prototypes. Also influencing the design and forging of Viking swords was their knowledge of and contact with the sophisticated Muslim Wootz steel producing communities to the east of the Danube – Black Sea trading routes the Vikings utilized for over a century.

Of particular interest is the wide ranging trading routes of the Vikings, one of which followed the ancient amber route from the Baltic to the Danube and through alpine passes to Venice. The Danube River also provides easy access to the Black Sea, Constantinople, and Levant. Controversy exists as to whether the Vikings used a distinctive all steel sword that possibly derived from their contact and trade with Wootz steel producing Muslim cultures in the east. To what extent were their sword production techniques influenced by those used by the Merovingians in the lower Rhine Valley during the time of Charlemagne?

The only evidence for a Viking settlement in North America is at L'Anse aux Meadows, Newfoundland, where excavation revealed distinct evidence of a primitive iron forge (1000 AD). However, no tools survive from this site. The London Museum and British Museum, however, contain excellent examples of Viking era edge tools and weapons. Their shapes and designs reflect a long tradition of northern European metalwork differing only slightly from Roman and Celtic Iron Age prototypes. One of the distinctive forms of Viking tools is a three-in-one tool: adz, ax, and mattock, for convenient use by raiding Vikings. To repair a ship, hack off the head of an enemy, or prepare a campsite, for marauding Vikings, an all-in-one portable tool kit, where steeled edge tools also served as weapons, was most essential. The sources of steel utilized by Viking blacksmiths, who were active traders throughout the Mediterranean region, remains a subject of controversy.

Scandinavia remained an important source of iron ore as well as of steel tools well after the end of the Viking age. The relationship of Scandinavian metallurgists with artisans who built the cathedrals of England and France in the 11th and 12th centuries, or with the resurgent steel production centers in western France, southern Germany, and central Europe remains unclear. Scandinavia, and especially Sweden, continued to be an important source of high quality bar iron, and possibly some direct process forged natural steel after 1400. Imported Swedish bar iron was especially important to English steel producers once the cementation furnace arrived in England and began producing blister steel from wrought iron bar stock in the late 17th century. First appearing in the northeastern region of England near Newcastle, the blister steel furnace required high quality low phosphorus low sulfur charcoal fired iron. Only Swedish iron would fit this need. English iron ores were high in both contaminants, making them unsuitable for edge tool production. After 1760, when the substitution of coke for charcoal as fuel occurred, general purpose steel production increased due to higher blast furnace temperatures and the more efficient removal of contaminants as slag. English forests were already so depleted as to limit the ability of English iron masters to smelt iron from charcoal; the high quality charcoal iron from Sweden became a most valued import. The same Swedish iron so highly valued by English steelmakers was also probably the main form of iron bar stock utilized by the American colonists for making edge tools when they began constructing their clandestine cementation furnaces after the end of the Queen Anne's War and the Treaty of Utrecht. Numerous references are contained in American colonial history texts referencing the importation of Swedish and to a lesser extent, Russian and Spanish bar iron to North America. The impost records of the New Bedford custom district, made available to this author by the New Bedford Whaling Museum, are filled with the record of multiple yearly arrivals of ships (1816-1831) laden with Swedish bar iron, which were loaded in Gottenberg and unloaded in New Bedford for use by its many whalecrafters and edge toolmakers.

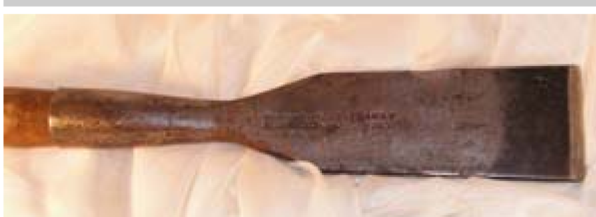


Figure 6 Slick made by B. D. Hathaway of New Bedford. Photo courtesy of Dave Brown.

In contrast to forest depleted England, the vast forest resources of Scandinavia provided the lucky combination of low sulfur iron deposits and forest resources, which allowed Sweden, in particular, to be the most important source of high quality refined bar iron for both Sheffield cutlers and its growing edge tool industry. During the late 17th century the cementation oven for producing blister steel was put into use in England, supplementing German steel and bloomery produced natural, forged, and case-hardened steel after 1700. The rapid increase in wooden shipbuilding in Europe after 1550 may be directly correlated with the increased availability of edge tools made possible by the increased efficiency of the blast furnace and the continuing production of German steel. After the mid to late-17th century, the development of the cementation furnace, especially in England, further increased steel production. After a ten day firing the typical cementation steel furnace could produce 3 – 5 tons of blister steel.

The production of blister steel was accompanied by the growing knowledge of case-hardening utilizing cementation furnaces, the size of which allowed steel production in much greater quantities and with better quality control than either steel produced by the continental method of decarburized cast iron (German steel) or natural steel produced in primitive charcoal-fired bloomery furnaces. Case hardened iron, with a steely outer surface but a softer wrought iron interior, was produced by the cementation furnace operating for a few days. Higher quality, more homogeneous blister steel required furnace firings as long as ten or twelve days to complete carburization of the interior portions of the several tons of bar iron in a conversion furnace. Rather than fully converting wrought iron to blister steel, the case hardening technique allowed production of tools and knives from heterogeneous blends of blister steel, which had not been fully carburized into tool steel. After further forging and heat treatment, i.e. case hardening, which would occur in a separate furnace, tools made from this partially carburized heterogeneous steel were characterized by both a hardened steel outer surface and a softer, flexible inner more carbon-free subsurface, providing both a durable outer casing and a fracture resistant interior.

Scandinavian (Swedish) iron, low in sulfur, was the key resource for Sheffield cutlers, beginning at least as early as the 15th century. With the development of the cementation furnace for steel production in England after 1686, Sweden remained the main source of charcoal iron for English toolmakers until the late-19th century despite the importation of significant quantities of colonial iron from Maryland, Virginia, and Pennsylvania after 1740. But the most important developments in early modern European iron and steel production occurred to the south of Scandinavia and England in southern Germany.

Steel Production in Europe 1300 - 1740

The shaft furnace of late medieval Europe had something in common with those used in Europe in the early Iron Age in the days of the Roman Empire: they were difficult to control. Pure wrought iron, or malleable iron for horticultural tools, might have been the objective of the smelter, but as a matter of normal operations most shaft furnaces produced a certain amount of liquid cast iron as a bloom of iron absorbed carbon and melted. In between the melting of iron with a 3% carbon content at 1200° C and the solidifying bloom of wrought iron (with a lower carbon content 0.02 – 0.8% but with a much higher melting temperature, 1500° C) would be the heterogeneous bloom of raw steel (0.5 – 0.8% carbon content). As shaft furnace height increased so did the difficulties of controlling the smelt.

This is an early example of a Dutch maker-signed edge tool, circa 1575. The maker's mark was probably placed on this ax as a way to advertise the products of the maker, either as a member of the blacksmith's guild or as an individual vendor -- a tell-tale sign of an emerging market economy where toolmakers would produce and sell their tools on the open market rather than being controlled by a King, Lord, etc. This ax lacks any obvious signs of a weld steel edge. It almost certainly predates the wide-spread use of the cementation furnace to produce steel. More likely this ax typifies the direct process production of edge tools from small shaft furnaces in the early modern period.

Figure 7 From the collection Amsterdam Archaeological Depot. Wiard Krook of the bureau Monumenten & Archeologie states this ax was "...excavated in the 1970's in the City of Amsterdam, by our Archaeological Department, during the construction of the Amsterdam subway. As the metro-trace did cross the former 15th and 16th century ship wharf's area (called the Lastage), many excavated tools could be related to these shipbuilding activities and maritime history." "material: iron; length: 14,2 cm; archaeological dating: 1575-1650; marking: Chotic A in circle; excavation date: 1973; location: Weesperstraat 55-71, Amsterdam; inventory number: MWE5-112"

Of notable importance was the development of the high shaft Stuckofen furnace in southern Germany. Isolated bloomeries produced natural steel of varying quality throughout the medieval period. Individual blacksmiths transmitted their knowledge of how to make steel tools from generation to generation based on the color, texture, fracture and feel of the tool steel and their intuitive knowledge of the importance of rapid quenching, then tempering of edge tools, armor, knives and weapons.

Producing natural raw steel wasn't anything new; it had been done either deliberately or accidentally since the beginning of the Iron Age. Natural steel was first produced from relatively low shaft furnaces in the form of raw steel, which was then removed for further processing. As shaft heights increased during the late medieval period so too would have the inadvertent or deliberate production of cast iron, which would have accompanied any attempt to produce raw steel. As the high shaft furnace grew a little taller and ran a little hotter the manganese laced cast iron it produced (Spiegeleisen) had to be decarburized to produce "German steel". No documentation exists to tell us when some clever iron monger noticed that he could produce natural steel not only from the bloom of a direct process shaft furnace, but also by reheating, refining, and decarburizing the salamanders of cast iron that the larger shaft furnaces were creating as an unwanted waste product.

While some steel tools could be made using the time consuming technique of carburizing wrought iron or that part of a wrought iron implement to be steeled, Stuckofen produced natural steel, however impure and imperfect, could be made in relatively large quantities, e.g. 25 - 75 kg blooms. It was this natural steel that could be hammered into thin sheets and further carburized by case-hardening techniques. The most important steps in making quality steel tools were repeated hammering (piling) to expel slag and other impurities, homogenizing the naturally heterogeneous iron and steel bloom into an iron alloy with evenly distributed carbon. The final essential step in making durable steel edge tools, weapons, knives, or wood chisels was rapid quenching after heating followed by tempering (reheating) followed by slow cooling to relieve brittleness. Endless variations in hammering and heat treatment techniques replicated the complexity and variability of the microstructures of the iron being forged into steel. Every iron bloom differed according to carbon, slag, alloy (e.g. manganese), and contaminant (sulfur, phosphorus) content.

The development of the Stuckofen furnace provides a unique opportunity for a major advance in steel making technology after 1350. Iron mongers in the Nuremberg area of Germany, and possibly in northern Italy and Spain, had access to the superior Styrian and Carinthian iron ore from the region of what is now Austria. Its unique characteristic was having manganese content of +/- 2%; when smelted in the larger, high shaft direct process Stuckofen furnace, which burned hotter but also allowed better quality control, these spathic ores neutralized the deleterious effects of sulfur in iron ore, facilitating more homogeneous carbon distribution.

As the Stuckofen furnace evolved into the fully developed blast furnace, natural steel production was replaced by the smelting of cast iron with a high manganese content that has to be reprocessed (fined) into steel by decarburization. German metallurgists perfected this technique after 1400 or 1450, making Germany the European center of steel production during the Renaissance, until the War of the Roses decimated the German steel industry in the 4th decade of the 17th century.

As the high shaft furnace evolved into the blast furnace, the refining of decarburized cast iron or the further fining and forging of natural steel resulted in the perfection of a continental "German" steel manufacturing strategy that was transferred to England at least as early as the 16th century by immigrating French iron mongers (Cleere, 1985). They also brought their (relatively) new blast furnace technology to the forest of Dean and the Sussex Weald, where direct process bloomeries had reigned for centuries. For two centuries, German steel was England's primary steel producing strategy. The cementation furnace came to England by 1686 (or possibly earlier); totally pure steel was not produced until Benjamin Huntsman rediscovered the art of crucible steel production in England in 1742.

Ancient Origins of Cast Iron

There is a broad consensus among writers on the history of metallurgy that the blast furnace made its first appearance in Europe in the late medieval period. Tylecote notes the first carbon dated specimens of cast iron in Europe as originating in Sweden between 1200 and 1300 (Tylecote 1987, 327). Tylecote speculates knowledge of the operation of the blast furnace may have been a result of the trading activity of the Swedes (Varangians) who had contact with Asian sources using Baltic, Black Sea, and Caspian River trading routes as early as the 7th century. But production of cast iron in blast furnaces was not limited to the European florescence of industrial activity in the late medieval and early Renaissance. Numerous writers, including Wertime (1980) and Tylecote (1987), note the widespread production of cast iron in China during the Warring States period 475 - 221 BC, and later during the Han dynasty 206 BC - 220 AD. The intriguing question arises: did the Chinese first produce cast iron using some variation of a furnace design specifically to produce cast iron? Further consideration of the puzzle of Chinese furnace design leads to the fact that the earliest central European bloomery furnaces consistently had the ability to produce not only blooms of wrought iron, but both natural steel and cast iron, depending on the fuel to ore ratio, the location of the tuyere, and the resultant temperature of the furnace during the smelt. One of the traditional problems bedeviling the direct process smelting of wrought iron from the point of view of the blacksmith was the occasional nodules of natural steel that appeared in a wrought iron bloom as a matter of course. These nodules made the working of the wrought iron much more difficult for the smith; wrought iron blooms laced with these nodules of natural steel was considered an inferior product. The problem faced by the furnace master attempting to produce either high quality wrought iron or that most difficult to achieve but highly desirable product, natural steel, was that as the furnace temperature was increased, carbon uptake by the bloom of wrought iron or natural steel increased rapidly. As the carbon content of the iron bloom increased, it passed from a transitional stage of being natural steel with a somewhat lower melting temperature than wrought iron to that of being liquid cast iron with a significantly higher carbon content than natural steel. The rapid uptake of carbon resulted in the rapid decrease in the melting temperature of the iron being smelted producing liquid cast iron that ran out of the bottom of the furnace.

In the context of our understanding of the modern blast furnace, some modern commentators have commented that this liquid cast iron was always considered an unwanted waste product of the smelting process in ancient times. This technohistoric bias now requires re-evaluation. Wertime and other writers note that early direct process furnaces produced wrought iron, natural steel, and cast iron almost as a matter of course; that is, early forge masters were not able to control direct process bloomery operations in furnaces of many designs to the extent that they would only produce high quality wrought iron. Occasional production of cast iron as well as natural steel seems to characterize all pre-modern iron smelting. This may help explain why fragments of cast iron consistently appear in Roman as well as pre-Roman sites. Tylecote notes cauldron fragments dating to the 4th century BC from Ukraine, as well as Roman era fragments from north Wales. Tylecote speculates these may have been imports from far eastern sources reflecting the extensive trade routes of both Hellenistic and Roman times. The question naturally arises, however, for both Oriental and European forge masters: since cast iron was relatively easy to produce in small direct process furnaces in small quantities, why wouldn't ancient founders deliberately produce cast iron for the everyday utilitarian cooking pots and other uses? Remnants of such vessels would be extremely difficult to date unless located within carefully surveyed and dated archaeological sites. The assumption that cast iron vessel fragments found in Europe have Oriental origins with respect to their production sources is extremely questionable in view of the wide range of steel and iron producing strategies and techniques that now can be documented and which characterize all Iron Age societies. The great age of Chalybean natural steel occurred at the height of the Bronze Age, circa 2000 BC. This clearly illustrates the inadequacy of the diffusion model of technological adaptation and innovation. So too does Renfrew's (1973) observation of a flourishing Bronze Age culture in the steppes of southwestern Russia (Ukraine) two millennium before the Bronze Age became well established in the Mediterranean region. In this context, the appropriate metaphor for technological change may not be diffusion in waves, or in the case of the Industrial Revolution, diffusion by a tsunami of technological innovations, but independent eruptions of new techniques, which send out wave patterns in a non-uniform manner in both time and space. Another analogy might be the image of not quite random explosions of fireworks in a darkened landscape. At first a few explosions, then more fireworks; with the coming of the blast furnace the landscape would have a glowing quality that would extend for months, a prelude to the all encompassing incandescent light of 20th century warfare.

Wertime (1980) suggests their never was a bloomery era in the evolution of Chinese cast iron, nor do we know the exact date of the appearance of cast iron in China, which was its principle iron smelting strategy for centuries, if not longer. Nor may we ever know when the first cast iron vessels were deliberately produced in the Mediterranean region in Italy or in central Europe. A reasonable conclusion may be drawn that blast furnaces designed specifically to produce cast iron first arose as the practical response to the demand for large quantities of cast iron tools and implements. In the case of China, the need for agricultural tools seems to be the most important factor. In pre-Roman (Hellenistic) and Roman sites cast iron cooking vessels seemed to dominate the surviving examples of cast iron. In Mongolia, cast iron cart hubs were being used as early as the 13th century (Tylecote 1987, 327). The florescence of blast furnace construction in northern Europe and southern Germany, which followed the first Swedish blast furnaces, had many precedents. The most important observation to be made is that cast iron production – for cooking vessels, wagon hubs, or agricultural tools – predates the design and construction of the larger and more efficient blast furnaces that appeared in Europe after 1300. The first production of cast iron may, in fact, date to the first blooms of wrought iron and is not necessarily connected to the design of the modern blast furnace.

The Wreck of the Mary Rose

Henry VIII was in a shoreline castle near Portsmouth, England, in 1545, when the newly constructed Mary Rose, over-burdened with troops and equipment designed to intimidate French patrols lurking off the southern English coast, suddenly capsized. The loss of the Mary Rose signifies the end of a medieval era in Europe and the beginning of intensive exploration of the North American coast by English merchant adventurers and French and Dutch trappers and traders. At this time, English, Breton, Norman, Basque and Portuguese fishermen were already well acquainted with the rich cod fishing offshore of the new - found - lands. St. Johns, Newfoundland, was already a well established late winter port of destination for European fishermen who knew the best cod fishing was in March and April.

The Mary Rose fiasco marked the beginning of a renewed effort of naval shipbuilding in England, which, with the help of the weather, led to the defeat of the Spanish Armada in 1588, and ensured that the competition for North America would be a French - English affair for the next 171 years. Of special interest in helping to fill the gap between our knowledge of late medieval tool forms and early modern tool forms is the ship carpenter's tool chest that the Mary Rose carried to the bottom of Portsmouth Harbor when she sank. This chest, along with the Mary Rose herself, has been recovered and restored at Portsmouth, England. The carpenter's tools from the Mary Rose are now available for study. They fill in an important gap between medieval tool design and technology, which they reflect, and the appearance of modern style planes in England after the great fire of London in 1666. The technology of ship construction with broad ax, adz, pit saw, pod auger, drawknife and chisel remained unchanged from the sinking of the Mary Rose until the appearance of the circular saw mill and steam powered machinery (1840 - 1860) in England and America almost 300 years later. The metallurgy of edge tool production also remained unchanged, but for a lesser period of time, about 200 years. The form and style of hand planes in England between 1545 and 1690 is not well documented. The great fire of London destroyed most of the woodworking shops of the time. But by 1690, new forms and styles of hand tools had appeared. The Robert Wooding plane in the Davistown Museum collection signals a new era in the production of woodworking tools: the advent of a market based economy where individuals such as Wooding produced their signed tools not for their own use or for the use of the King's shipwright but for a newly emerging market economy that was the essential stimulant for the merchant adventurers whose explorations would soon prompt settlement of south then north Virginia. The merchant adventurers and explorers of the Elizabethan era and their need for wooden ships armed with cast iron cannon provided the economic stimulus for the rapid growth of English and continental shipbuilding and iron foundry industries. The hundreds of American toolmakers who would begin their task of making the tools that built America in the years after 1640 had their roots in this milieu.

The wreck of the Mary Rose marks a point in time where early modern iron and steel making techniques – the blast furnace, and production of steel by the partial decarburization of cast iron – were well established throughout Europe and England. After 1545, the rapidly expanding economies of Spain, the Netherlands, then England and France, were responsible for this proliferation of blast furnace technology, which included the rise of “integrated ironworks”: blast furnaces, finery and chafery forges, slitting and rolling mills, and blacksmith shops for making tools. It would be another 150 years before the next innovation in steel production strategies – the cementation furnace – became widely available the late 17th century.

The Blast Furnace: The First Industrial Revolution

At the same time that southern Germany was producing a natural low carbon steel with the help of its manganese-laced iron ores, larger and larger shaft furnaces were being constructed not only in southern Germany, but also in northern Europe. At some point in the 14th century the high shaft Stuckofen furnace evolved into a true blast furnace. One of the risks of any direct process bloomery shaft furnace was that if it ran too hot, high carbon cast iron would run out of the furnace as a useless waste product. This ironic phenomenon occurred because the higher temperatures in a blast furnace promoted the rapid uptake of carbon in iron. This then resulted in a proportionately lower melting temperature. To become useful wrought iron, the cast iron wastes from medieval furnaces would have to be remelted again and decarburized into the spongy blooms of wrought and malleable iron that were the primary products of most bloomeries. Natural steel blooms were a secondary and difficult to produce product of most bloomery furnaces. The steel content usually consisted of higher carbon globules of natural steel entrained with the slag in the heterogeneous iron bloom. Unless present in large quantities or at least as individual removable globules, steel inclusions were often the bane of blacksmiths needing pure wrought iron from the forge master. True blast furnaces, which, because they ran hotter and more efficiently than shaft and bowl furnaces, produced high carbon pig iron, not as waste, but as their primary product.

To produce either iron or steel from cast iron, refinery furnaces were built to decarburize the cast iron into nearly carbon free wrought iron, low carbon malleable iron, or raw steel with a heterogeneous carbon content. One of the advantages of the blast furnace was that it more efficiently removed slag contaminants than direct process bloomeries, while lowering the high loss of iron, which occurred in the more inefficient direct process bloomery. This two step blast furnace - iron refinery process is known as the indirect process of producing wrought iron.

Natural and forged steel were difficult and time consuming to produce, and very irregular in quality, unless extensively reforged by additional hammering and heat treatments. In the Renaissance, the demand for steel for weapons and tools was greater than the supply. The Italian Renaissance in southern Europe and widespread warfare in northern Europe in the 15th century increased the demands for cannon, hand guns, steel weapons, and armor and to a lesser extent for steel edge tools and other implements for construction, woodworking, and shipbuilding. The blast furnace supplied the larger quantities of cast iron for the production of wrought and malleable iron, and would be the later basis of steel production in England using the cementation process after 1685, which required large quantities of refined cast iron, i.e. wrought and malleable iron. In Germany and Austria and to a lesser extent in France, blast furnace cast iron, especially spiegeleisen, was partially decarburized into steel, producing in one step a raw steel, which could be further refined into the famous German steel, which was such a superior alternative to the traditional tedious method of natural steel production. The robust German steel industry of southern Germany and Austria, utilized this strategy of steel production, now known as the continental method (Barraclough 1984a) to meet the growing need for steel tools in the age of exploration.

Brescian steel

For 200 years after the use of the blast furnace became widespread, a third steel producing strategy, the Brescian method of making steel, was used for producing steel for edge tools, armor, and weapons, especially in southern Europe (Italy, Spain, and southern France). Bars of refined wrought iron were dipped into molten cast iron, carburizing the wrought iron, which was piled and reforged into steel bar stock, some of which was used for weapons production, especially in the city states of the Italian Renaissance. These bars were thinned into sheets of steel, which then could be cut and welded on to or inside of iron stock to produce pattern welded knives and edge tools. Variations of pattern-welding, which combined thin sheets of steel with wrought iron, were the basis of most sword production. Nonetheless, edge tool production by traditional techniques continued. Hand tools were made by the tedious forging of one tool at a time by a smith recarburizing a piece of wrought iron, case-hardening of the outer surface of an iron tool, and most commonly, since ancient times, inserting a piece of homogeneous steel into a folded piece of wrought iron and forge welding them together to make an ax, or onto the edge of a socketed piece of iron to make a chisel. Brescian steel, along with German steel, were probable sources of most steel used for making weld steel edge tools and weapons until the widespread use of the cementation furnace in England and northern Europe after 1685. A clever forge master could produce small quantities of natural steel from a bloomery furnace; artful hammering and heat treatment by a knowledgeable blacksmith could produce a high quality natural steel edge tool, but only one tool at a time could be produced. The Brescian and German methods lent themselves to the widespread production of larger quantities of steel of equal quality to the blister steel made in England after 1685. In either case, it was the task of the blacksmith and especially the armorer to take unrefined natural steel, Brescian steel or raw German steel with wide variations in carbon and slag content and manufacture higher quality steel by time consuming mechanical (hammering) and heat (quenching and tempering) treatments. The widespread fame of German steel before the age of crucible steel (1750f). was due, in fact, to the ability of German forge masters to refine the raw steel produced from decarburized spiegeleisen into the sophisticated steel artifacts as exemplified by the displays of the Victoria and Albert Museum in London.

Was there a more reliable way to produce a more uniform quality steel in the 15th and 16th centuries, where ever larger armies were battling each other throughout Europe? The Renaissance was characterized by the search for improvements in the design and efficiency of firearms ranging from cannon for the growing English, Spanish, French, and Dutch fleets of warships and merchant vessels to the need for better hand guns, the result of the increased warfare among competing nation states and nations. Also playing a role in increasing the demand for steel was the discovery of the New World, the rise of competitive market and trading economies, and the rapid increase in shipbuilding, especially in and after the Elizabethan era. The demand for much larger quantities of swords and armor soon included the need for tools of all kinds, including steel tipped edge tools for shipbuilding. The need for wrought and malleable iron also increased rapidly after 1600. The blast furnace and associated refineries produced large quantities of relatively pure wrought iron, the essential ingredient needed by the new cementation furnaces to make steel, which began appearing in Europe and especially England after 1600, as a result of the demand for larger quantities of higher quality steel. To produce steel from the refined pig iron made in blast furnaces from these furnaces, new centers of industrial activity based on the cementation process for producing "blister" steel arose. The cementation furnace provided the most efficient method for making large quantities of steel, especially in England, which had depleted its resources of siderite and low phosphorus ores in the Sussex Weald and the forest of Dean. The first documented cementation furnace in England was operating by 1686 (and possibly earlier in some locations) and quickly superceded the continental method of making steel by decarburizing cast iron. In England, it remained the principal means of making steel until the late 19th century, supplying the raw steel refined in the crucible steel casting process, which came into use in 1742. The cementation furnace had first appeared in Nuremburg in 1601 (Barraclough, 1984a); the exact time of its first arrival in England is unknown, but the continental method of producing steel from cast iron was so well established that it remained the principal steel producing strategy in Germany, Austria, and France until the advent of bulk process steel making after 1870.

German Steel

One of the ironies of our ethnocentric understanding of the sources and methods of steel production is our assumption that first, cementation steel, and then after 1750, crucible steel from Sheffield, England, were the primary sources of American steel, most of which was imported, supposedly until the Civil War. The story of steel production prior to the modern bulk practices (Bessemer, Siemens - Martins) is more complicated. The Sweden (iron) - Newcastle - Sheffield (England) steel producing network is well documented. The story of German steel is much less well documented and is now a nearly forgotten chapter in the history of steel production. The spathic ores of Erzberg, Austria, near the border of southern Germany, both of which were part of the Hapsburg Empire, had facilitated the production of natural steel tools since the early Iron Age. Halstadt, the earliest center of central European ferrous metallurgy, and Erzberg, the Iron Mountain with its siderite (manganese containing iron ore), were both located in the ancient Roman province of Noricum in Austria, and testify to the long history of steel production in this area. The manganese content of the spathic iron ores of this region facilitated a more uniform carbon distribution in the smelted bloom of iron by selectively combining with sulfur at a lower temperature as slag, which was then expelled during the smelting process. The resulting bloom of iron had a more uniformly distributed carbon content facilitating natural steel production, which had been taking place in this area since the early Iron Age.

With the introduction of the blast furnace, which evolved from the high shaft Stuckofen furnace, the production of cast iron utilizing manganese containing iron ore from the Erzberg deposits resulted in the production of Spiegeleisen - a cast iron with 5 - 10% manganese content. It was the partial refining of this type of cast iron that produced “German steel” rather than “natural steel”, both of which required extensive additional forging to be used to make high quality edge tools. The cementation furnace always produced steel by the carburization (adding carbon) of wrought iron. German steel, in contrast, was produced by the partial decarburizing of Spiegeleisen (cast iron high in carbon content). The decarburizing process was halted before carbon free wrought iron was produced, leaving an iron alloy with a variable carbon content, often between 0.2 – 0.8% carbon content, i.e. steel. It was the combination of a Celtic tradition of producing natural steel, well designed finery or smaller shaft furnaces, knowledgeable forge masters, and cast iron high in manganese (Spiegeleisen) that resulted in the production of large quantities of German steel. During the high Renaissance, the availability of German steel via the Rhine, Rhone, and Danube rivers must have supplanted the use of Brescian steel in the years before the widespread use of the cementation furnace in England and northern Europe became a third source of steel. German steel produced by decarburizing cast iron is frequently called natural steel in the older literature; this is incorrect, as natural steel is a direct process product produced only from the bloomery. In the south German-Austrian region, with its manganese containing iron ores, it was inevitable that the robust and ancient tradition of producing direct process natural steel would evolve into the continental method of decarburizing cast iron. Though the first documented cementation furnace appeared in Nuremberg in 1601 (Barraclough 1984a), most steel produced in the southern German-Austria region in the next 250 years was produced by the continental method of decarburizing pig iron (German steel), not by the use of the cementation or conversion furnace.

The high manganese content of the iron ores being used in the production of German steel, unique to the ores of the nearby Erzberg formation, played a role in both promoting homogenous carbon distribution and also in strengthening the steel being produced. Almost 400 years after the first appearance of blast furnace derived German steel, Spiegeleisen again makes an appearance in the 19th century as an essential ingredient in bulk processed Bessemer steel. With modern knowledge of the chemistry of steelmaking, manganese is routinely added as a constituent not only of Bessemer steel, but in many types of alloy steels, which have been invented during and after the era of Bessemer steel.

German steel was also a likely cargo in coasting traders from America visiting Europe in the centuries before bulk steel production. In the 1840s, the tonnage of German steel production was approximately equal to the English production of cementation steel (see Barraclough 1984a, Figure 5). Its use remained widespread in Europe despite the appearance of the cementation process in the 17th century. It is important to note that German steel is still misnamed natural steel. But by 1840 all "natural steel" was derived from decarburized cast iron, now more appropriately named German steel. German steel is one possible source of the many edge tools not marked cast steel that frequently appear in the tool chests of American shipwrights prior to the Civil War and the era of mass production of crucible steel edge tools. Sheffield, England, was not the only source of steel for the American shipwright.

Producing Country	Natural Steel	Cementation Steel	Total Product
Great Britain	nil	20,200	20,200
Austrian Monarchy	12,600	nil	12,600
German Customs Union	7,000	100	7,100
France	3,320	3,710	7,030
Russia	520	2,640	3,160
Sweden and Norway	1,970	890	2,860
Spain	200	100	300
Italian Peninsula	100	100	200
TOTAL	25,710	27,740	53,450

300

Figure 8 (Day 1991, 300). European steelmaking in 1840, the measurements are stated in tons.

Occasional reference still occurs in the 19th century texts to "German steel". One of the interesting footnotes pertaining to English strategies for producing high quality steel is that German steelmakers were brought to Shotley Bridge, on the Derwent River, southwest of England’s principal 17th century steel producing center at Newcastle in 1686, and quickly utilized cementation steel produced in England from Swedish iron ores to tediously fold and pile sheets of cementation steel into a more highly refined product known as sheaf (shear) steel. Any tool labeled "German steel" in English was produced in England by this technique, hence the misunderstanding that German steel was actually English sheaf steel. Steel production in the 18th and 19th century was much more complicated than what would have been the case had all steel been produced in Sheffield by a uniform series of processes: cementation - shear - crucible. The reality was that multiple strategies of steel production were being used at the same time. Some were centuries old and only produced small quantities of steel, as with natural steel production, which was still made in both Catalan bloomeries in southern Spain and American bloomeries until the late 19th century. The extent and termination of the production of Brescian steel is nearly undocumented; even the beginnings of the use of the cementation furnace are only vaguely known. The appearance of German steel made in fining furnaces from cast iron pre-dated the appearance of the cementation furnace. The variety of steel production techniques that had evolved by the early 19th century was further complicated by Henry Cort’s improvements to the refractory furnace, which provided yet another method for decarburizing cast iron to produce puddled steel (see below). German steel produced by decarburizing blast furnace derived Spiegeleisen was greater in tonnage than the production of the cementation furnaces that carburized wrought iron in the period from 1600 - 1750. In fact, in the 15th and 16th centuries, natural and German steel produced from decarburized pig iron in centers such as Aachen, Augsburg, Nuremberg and elsewhere in southern Germany may have been the single most important source of steel in the Renaissance.

Cyril S. Smith (1968) in *Sources for the History of the Science of Steel (1532 - 1786),* explores the growing knowledge of the chemistry of iron and steel production up to the discovery of the role of carbon in "steeling" in 1786 by French and Dutch scientists. The literature Smith quotes reflects the growing sophistication in steel production technologies, including advances in hardening, tempering, soldering, quenching, and the development of spring or shear steel and the cementation process. Perhaps the most startling aspect of Smith's survey is the wide variety of continental European sources for production of pure "weld" steel. Though of widely varying quality, steel, at least in small quantities, was being produced everywhere, it seems, in Europe after 1600. It was this "weld" steel from German fineries and continental cementation furnaces, available in small as well as large quantities, that may have been exported to the American colonies where colonial blacksmiths could combine direct process open hearth produced wrought iron with the small piece of expensive but absolutely essential imported "weld" steel to produce axes, adzes, drawknives, scythes, and other tools so essential for the colonization of a new frontier, the harvesting of its rich forest resources or the construction of its ships. Blister steel from England’s converting furnaces would not have been available before 1700 in the American colonies. Shortly after that date, illegal steel furnaces, often undocumented because of their violation of English restrictions on steel production in the colonies, became widespread (Bining, 1933). The myth of the hegemony of blister steel imported from England cementation furnaces during the 17th and 18th centuries to supply colonial and early American blacksmiths, ax makers, and other toolmakers is an ethnocentric conceit. The mystery surrounding the flowering of a vigorous New England shipbuilding industry beginning in 1645 is the extent to which knowledgeable shipsmiths might have fined and decarburized readily available cast iron, often derived from bog iron, to make steel tools before the widespread appearance of blister steel after 1710. Savvy New Englanders in their coasting vessels knew that there were multiple international sources for the weld steel needed in the rapidly expanding American frontier. Blister steel made in England's cementation furnaces still had plenty of competition even after it became available in the early 18th century.

The long tradition of wrought and malleable iron and natural and spathic steel production in continental Europe is especially highlighted by the excellent and gorgeous display of ornamental iron and steel at the Victoria and Albert Museum in London. The exhibit fills the entire front of the main hall on the second floor and includes many specimens of wrought iron from the medieval period through the Renaissance. Particularly noteworthy are some of the elaborate ornamental iron and steel safes, locks and architectural elements, the most outstanding of which are the malleable steel locks made in Nuremberg, Germany. The armada chest on display, probably dating from the 16th or 17th centuries, is similar in design and, in fact, a prototype for Captain Tew's pirate chest currently on display at The Davistown Museum. This Victoria and Albert display provides evidence of the growing variety of iron and steel manufacturing techniques in late medieval and early Renaissance Europe. The Victoria and Albert collection does not include weapons or even edge tools; it does, however, illustrate the wide application of sophisticated ferrous metallurgy technologies in such trades as locksmith, clockmaker, architect, iron and steel ornamentation, and for numerous consumer products made by German blacksmiths. While the focus of The Davistown Museum is on the history of edge tool manufacturing, the broad array of iron and steel products produced in continental Europe before the availability of English blister and crucible steels foreshadows the florescence of American toolmakers in the mid-19th century and the unequaled production of the malleable cast iron planes of Chaney, Phillips, the Baileys, and the Stanley Tool Co. during the classic period of America's Industrial Revolution.

The Cementation Furnace and Blister Steel Production

Barraclough (1984) notes the first mention of the cementation furnace at Nuremberg in 1601. Access to the manganese rich ores of Styria, which facilitated direct process natural steel production in small quantities from the early Iron Age to the appearance of the blast furnace, was supplemented then replaced after 1400 by the widespread use of the continental method of producing German steel from partially decarburized cast iron, postponing the need for alternative methods of steel production. The blast furnace greatly improved the efficiency of smelting iron; in England it took over two centuries before the efficient production of iron from the blast furnace was equaled by the efficient production of steel from the cementation furnace.

The German "Stuckofen" was a high shaft bloomery furnace producing iron by the direct process; its capacity was +/- 500 kilograms of iron production per day. First appearing around 1300 AD, the Stuckofen furnace was gradually superseded by larger true blast furnaces, the flobofen (circa 1500) and the bloen (circa 1750) with capacities of 600 - 700 kilograms per day, and 1500 kilograms of iron per day, respectively. The development of these larger furnaces after 1500 reflect the transition to the indirect process of iron production, where the larger quantities of cast iron produced by blast furnaces had to be refined by partial decarburization to produce the large quantities of German steel, which was the predominant steel producing strategy until after 1650 when blister steel production in England and northern Europe began to challenge the dominance of German steel, and to a lesser extent Brescian steel. Southern Germany remained in the forefront of iron and steel production because their manganese rich ore facilitated production of iron which had steel-like qualities, if produced by the direct process Stuckofen furnace. With the larger blast furnaces, where the resultant pig iron had a 5.0 - 10.0% manganese content, the iron refined from this pig iron contained the manganese so helpful in neutralizing sulfur, facilitating the difficult process of partially decarburizing pig iron into steel by enhancing uniform carbon distribution in the smelted iron.

In England, lack of access to the spathic ores of Styria (Austria) made natural and German steel production more difficult. The cementation process for producing blister steel was patented in England between 1613 and 1617 (Barraclough 1984) and quickly became the primary strategy for steel production in a country already dependent on high quality low sulfur Swedish iron. Much of England’s iron ores were lower quality high sulfur ores suitable for cast iron, but not fine steel production. For 300 years England relied on Swedish iron for blister steel production despite extensive use of domestic deposits for cast and wrought iron for other uses. The development of the cementation furnace allowed more control of the carburization process necessary for producing steel through the refining of cast iron produced by the blast furnace. Layers of wrought iron were interspersed with layers of carboniferous materials and the mixture was heated for periods as long as 10 to 12 days. The carboniferous materials used in the early days of the cementation process varied from wood and bone to a wide variety of strange combinations, all of which produced carbon monoxide. The cementation furnace, essentially a closed box, kept the fuel, charcoal, isolated from the ore and carburizing additives in an environment that could be checked and regulated, producing larger quantities of steel of a much more uniform quality than could be produced by the direct process as natural steel. After 1700, use of the cementation furnace became widespread throughout England, and to a lesser extent in northern Europe, but was infrequently used in Austria and southern Germany due to the popularity of the continental method producing steel by the partial decarburization of Spiegeleisen. Both steel producing strategies combined to supply a key resource for the rapidly expanding empires of Spain, the Netherlands, Portugal, England, and France in the age of exploration and settlement of the New World.

Sheaf Steel and the Search for Quality

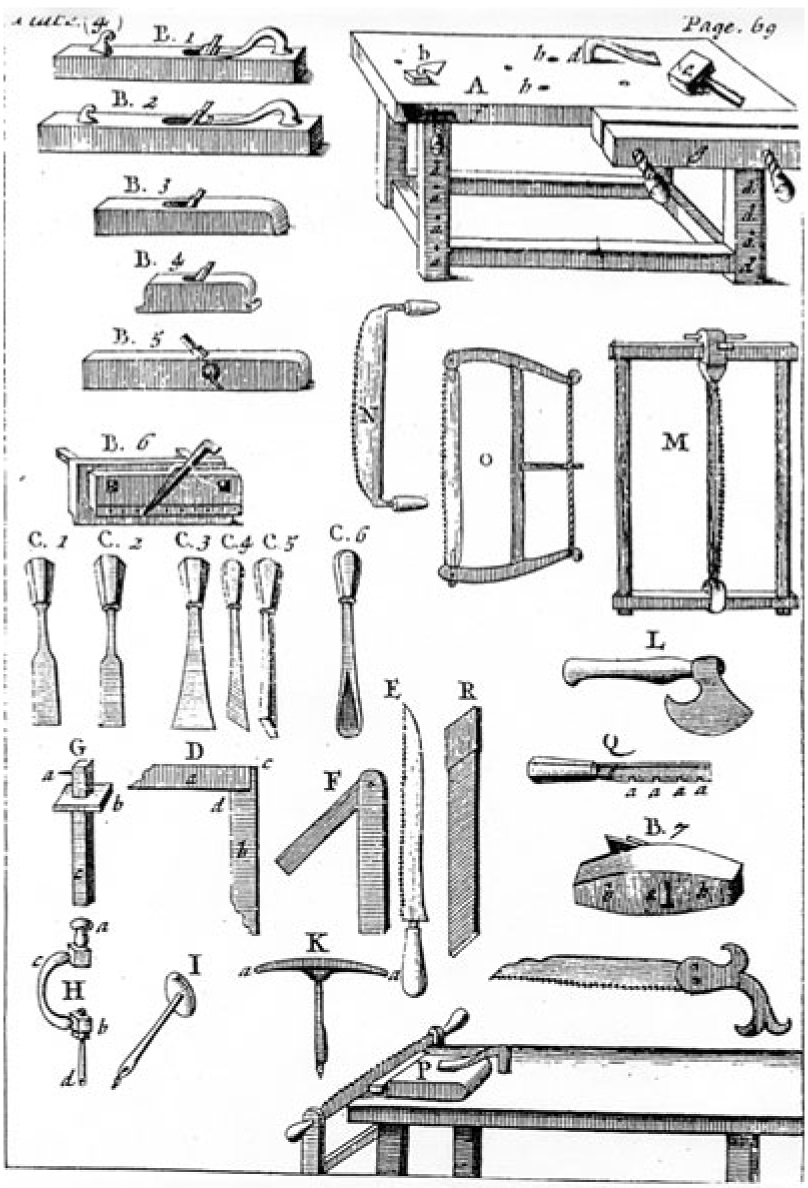
Blister steel, the product of the cementation furnace, was of a higher quality and with a more uniform microstructure than the natural steel produced by the direct process in smaller shaft furnace bloomeries, where pounding out a tool with steely characteristics from a bloom of iron was often a "hit or miss" situation. However, blister steel was not of a uniform quality; gaseous inclusions and other contaminants in the smelting process created blisters and air pockets in the steel. Though much of the slag inherent in the production of blister steel had been removed in the fining of cast iron to produce wrought iron used in the cementation furnace, the cementation process often failed to produce steel with the uniformity of carbon distribution that characterized fully martinized steel produced by the crucible process in the late 18th century. Edge toolmakers, not to mention armorers and watchmakers, were aware of the wide range of the quality of blister steel, which was still sufficient for many applications. The best woodworking edge tools, armor, watch springs and swords required a uniformity of carbon distribution for maximum effectiveness, which most batches of blister steel could not provide.

European edge tool makers soon learned to pile, bundle and reforge blister steel into a higher quality product called "sheaf" steel in England; this steel was also known as "shear", "spring", and "double sheaf" steel. In 1693, a German steelmaker – William Bertram, was shipwrecked on the east coast of England and settled near Newcastle, later operating steelmaking facilities there as well as at Blackhall Mill, also in the Derwent valley, which initially utilized the continental method of steel production due to small deposits of manganese rich brown hematite in the Derwent valley. Barraclough provides this account of Bertram's role:

> William Bertram is quoted as having pioneered the production of 'German steel' by forging blister steel. He produced five kinds, the hardest being 'Double Spur and Double Star'. Progressively getting softer, the other grades were 'Double Spur and Single Star', 'Double Spur', 'Double Shear', and 'Single Shear'. Angerstein is quite definite that the 'Shear Steel' mark – a stamp showing crossed shear blades – was Bertram's own mark; thus it comes as no surprise to learn that the making of shear steel was introduced into Sheffield by a workman from Blackhall Mill in 1767. The process was developed by building up a knowledge of how to segregate the blister steel into batches of similar hardness, presumably by examination of the fracture, using selected grades of iron. Suitable bars would then be faggotted and forge-welded. Bertram had built up a reputation for quality in this way; since he was a German, it seems to have been accepted that he had produced the true German steel – this presumably is where the later confusion between German steel and shear steel arose. (Barraclough 1984a, 65-66).

That confusion continues today, facilitated by the mark (in English only) "German steel" on many an English backsaw. This high quality saw steel was, as noted by Barraclough, shear steel made from reforged blister steel and entirely different in its strategy of production from German steel. Blister steel production was tedious, time consuming, expensive and accelerated the destruction of European forests. Sheaf and spring steel production - reprocessed cementation steel - represented a fourth stage in the indirect process of manufacturing edge tools from iron ore. The labor intensive nature of piling, folding and reforging strips of steel for special applications such as razors, knives, saw blades, watch springs, pins and woodworking edge tools doubled the costs of blister steel but only partially solved the need for absolutely pure steel for these products. It was the combination of the complexity and expense of production and lack of uniformity of sheaf steel that prompted Benjamin Huntsman to search for a simpler method to produce pure steel in small quantities.

As for blister steel, its wide availability as steel bar stock after 1700 continued and enhanced the long tradition of "weld steel" (steeling) tool production, which was only gradually, and then only partially, superseded by crucible steel as a weld steel alternative, and only then after 1800. Blister steel became known as "weld steel" because it was exported from iron and steel making centers, first in Europe, and later in the American colonies, to be used by blacksmiths making tools from wrought iron. The steel components of edge tools could be welded onto the wrought iron tool, using the higher quality blister steel and avoiding the uncertainties inherent in forging steel from a bloom of slag contaminated natural steel or from the tedious process of carburizing the edge of a



Moxon, Joseph. (1989, reprinted from the 1703 edition). *Mechanick Exercises or the The Doctrine of Handy-Works.* Morristown, New Jersey: The Astragal Press.

Figure 9 (Moxon 1975, 69).

This illustration shows the typical tools and their designs in the 17th century. With the exception of the loop handled hand planes, most of these tools are characteristic of those brought to the colonies by the earliest English settlers. The loop handled hand planes were an obsolete medieval design already supplanted by modern Dutch-derived forms at the time of Moxon's 1703 edition.

wrought iron implement.

The tool forms illustrated in Moxon's *Mechanick Exercises* (1703) show the transition from late-medieval tool styles (e.g. the planes with the looped handles and the hatchet) to early modern forms (chisels, saws, planes with wedges, bevels and try squares). While we cannot be sure from the Moxon text, the edge tools are almost certainly forge-welded combinations of iron and German steel. The tools recovered from the wreck of the Mary Rose illustrate the widespread availability of German steel as a source of weld steel before the advent of blister steel production after 1650. The popular conception is that the steel in the tools of American explorers and colonists was English in origin. In forest depleted England, coppice rather than oak fueled English blast furnaces after 1550. Steel was produced by the continental method until the 17th century, when the cementation furnace replaced the older strategy. The transition was complete by 1686 when ironclad proof of its use is noted by Barraclough (1984a). It was during this transitional period that Newcastle, in northeast England, became England's primary steel producing center (1675 – 1750). After 1750, Sheffield equaled then surpassed Newcastle and Birmingham as the center of English steel production.

Early Modern Metallurgy

Crucible Steel: The Second Industrial Revolution: Part I

The most important event in the evolution of the production of modern tool forms is the demand for ever larger quantities of steel of uniform quality, which led to the development of crucible steel. Benjamin Huntsman, English inventor and watch maker, had a urgent need for higher quality steel for his watch springs. Blister and shear steels, though containing less slag inclusions than natural steel, still had tiny particles of slag that, as constituents of watch springs, limited the ability to manufacture ever more accurate and ever smaller watches. Huntsman may or may not have been aware of the tradition of crucible steel production in China or India or its presence as a Viking trade item or in Viking swords, a development only recently recognized by historians of metallurgy (Tylecote 1986, Wayman 2000). Huntsman single-handedly reintroduced crucible steel making techniques in England in 1742. Breaking up small quantities of blister steel, adding flux and using crucibles made of special heat resistant (Stourbridge) clay, Huntsman reheated and remelted the steel in ovens with no fuel contact. After a period of hours, rather than days, most remaining slag impurities were skimmed off the surface of the melted steel, resulting in the production of steel with homogenized carbon distribution. This resulted in a uniformity of the grain size throughout the steel. Called martensite by modern metallurgists, the uniform microstructure of crucible steel marked a significant advance over both cementation furnace produced blister steel and bundled and reforged shear steel. The patchy and irregular microstructures resulting from the more heterogeneous distribution of carbon in the blister and shear steel was avoided. The high quality of crucible steel, with its uniform carbon distribution remains unsurpassed for edge tool production by any modern alloy steel. It was particularly useful for toolmaking because it was easily shaped by hot-rolling.

Crucible cast steel plays a critical role in the second stage of the Industrial Revolution. Initially kept a secret by Huntsman, crucible steel production for edge tools, which did not reach significant quantities before 1785, constitutes a recognizable landmark in the modern era due to the ubiquitous marking of almost all edge tools produced with crucible steel, with the notation "cast steel" or "warranted cast steel". For a century after 1785, this insignia advertised cast steel edge tools as superior to the weld steel edge tools using steel made by the older technologies.

Exquisite English-made chisels, gouges, carving tools, shaves, knives and other edge tools are the most obvious legacy of Huntsman's reinvention of crucible steel production. His need for high quality watch springs played a major role in providing the cast steel hand tools that built the ships, the wood patterns for casting machinery, and much of the wooden infrastructure of the coming Industrial Revolution. But crucible steel provided only a tiny percentage of the growing need for steel and iron in the early 19th century. Three other industrial developments occurred in the late 18th century that were essential components of the second Industrial Revolution. The use of coke instead of charcoal as blast furnace fuel, the development of the steam engine and the redesigned reverbatory furnace all combined with crucible steel production to provide the basis of a massive expansion of industrial production first in England and Europe, and then, after 1830, in America. Between 1785 and 1860, English made crucible steel, though produced in small quantities, dominated the small but essential market for high quality steel edge tools and machine components. The continuing use of and improvements in the older steelmaking strategies and technologies, especially in the decades before America perfected the art of crucible steel production in the early 1860s, remains a nearly undocumented chapter of American industrial history.

The Steam Engine: The Second Industrial Revolution: Part II

The most important event in the second stage of the Industrial Revolution was the invention of the steam engine. First utilized effectively to pump water from mines, the steam engine, initially made of cast iron, was soon applied to manufacturing applications where water power, especially in England, was an insufficient energy source. But the steam engine was invented, not because of the lack of water power in England, but because of the lack of wood. The shortage of wood for heating fuel resulted in part because of the widespread use of charcoal for fueling blast furnaces. Coal was widely available as a substitute for blast furnace charcoal and as a home heating fuel but unfortunately was often located in mines below the water table. The need for coal soon necessitated deeper and deeper coal mines, which in turn required the invention of pumping equipment. Thomas Savery's water raising pump was soon followed by Newcomb's steam pump; these two proto-steam engines, initially designed to pump water from coal mines, provided James Watt with the basic principles needed to produce the first fully functional steam engine in 1763.

The steam engine is the symbol of the modern age, the mother of all machines in a rhetorical if not in a practical sense. It is a machine which, using water vapor as a power source, converts heat into mechanical work. Along with the transformation of water power into work, the invention of a tool to transfer heat into work are the two keystones of the Industrial Revolution. The mass production of cast iron by the blast furnace - that first essential stage of the Industrial Revolution - provided the raw materials to build the machines of the Industrial Revolution. The steam engine (in lieu of water power, which was in short supply in England, but not in America) provided the link between an energy source (coal, as coke) and the thermodynamic application of this energy - heat - to the rhythmic changing of the atmospheric pressure of a volume of air, the key to the operation of the steam engine.

The steam engine could not have wide application until a substitute for charcoal fuel for blast furnace operations was developed; coal could not be used in blast furnaces because it so thoroughly contaminated the iron being produced with sulfur. In 1709, Abraham Darby discovered how to use coke instead of coal in a blast furnace; the large scale production of coke to fuel steam engines did not occur until later in the 18th century. The period from 1742 - 1784, starting with Huntsman's reintroduction of crucible steel and ending with Cort's redesign of the reverbatory furnace and his invention of the rolling mill in 1784, represents the calm before the storm of an English Industrial Revolution that resulted in a cascade of new inventions, or the practical implementation of recent innovations. In England, the factory system of mass production began emerging once coke was produced in sufficient quantities to power steam engines, especially those used in the textile industries.

The roots of the steam engine can be traced back to Hero of Alexander's Pneumatica (circa 130 BC) a primitive steam reaction turbine, which was invented to open and close temple doors. After a gap of 17 centuries, Renaissance Treatises on Pneumatics began appearing (Della Porta, 1601, Giovanni Branca, 1629). In England the first prototypical steam engines were designed by the Marquis of Worcester, 1663, and Thomas Savery, who obtained a patent for a water raising engine. This engine was initially used in Britain for pumping mines, operating water wheels and supplying public water systems. Thomas Newcomb (1705) separated the boiler from the cylinder, designing a piston engine with potential for wide practical applications. In 1763, James Watt, while repairing a Newcomb atmospheric engine, noticed how the alternative cooling and heating of the piston cylinder wasted heat. Watt added a cylinder to hold the hot steam, an air pump, and an insulating steam jacket around the cylinder. Watts patented his improvements in 1769. A most important and now almost forgotten innovation of the second Industrial Revolution was John Wilkinson's invention of a boring machine to make the engine cylinders, which were the key component in Watt's newly designed steam engine. See figure below. Other improvements followed - the double action steam and vacuum applications (Watt 1782) and the introduction of a noncondensing high pressure steam engine (Richard Trevithick, England and Oliver Evans, America, 1800). The later improvements provided the way for the development of steam driven carriages and locomotives. Compound engines followed; the first steam boat appeared in England in 1802. The later invention of the compound steam turbine (C. A. Parsons, 1884) coincides with the later third stage of the Industrial Revolution and its bulk steel production technology.

The Reverbatory Furnace: The Second Industrial Revolution: Part III

In 1784, Henry Cort, who had just invented and patented grooved rolling mills for producing bar stock and iron rod, redesigned the reverbatory puddling furnace, which had been in use in England for almost two centuries. This furnace allowed the production of much larger quantities of higher quality wrought iron utilizing coke rather than charcoal as a fuel. Older, even ancient, furnace designs were plagued with the problem of fuel - ore contact. The innovative design of the reverbatory furnace separated the cast iron being decarburized from the fuel, preventing contamination of the iron with sulfur in the furnace. Fuel-ore contact resulting in oxidation due to contact with combustion gasses, and inefficient contaminant oxidation had been ongoing problems in traditional refinery furnaces. In the reverbatory furnace, "the hearth was lined with iron ore mixed with roasted puddling cinder from a previous operation; such a combination was obviously rich in iron oxide and relatively free from salacious matter. Onto this hearth was charged some 300 to 500 pounds of pig iron, which was melted down under the action of heat from a coal fire on the adjoining fire gate." (Barraclough 1984b, 92). Wrought iron production in the reverbatory furnace went through several stages: oxidation of silicon, manganese and phosphorus and their fixation in slag, followed by rabbling (mixing with a rabbling tool). The seething mass of liquid iron would lose its carbon content as carbon monoxide was released. Decarburization of the pig iron in the furnace would eventually lead the liquid iron to become a spongy mass of wrought or malleable iron within the liquid slag as the melting point of the iron rose in proportion to the fall of its carbon content. The resultant rabbled balls of iron (+/- 35 kg) would be removed from the furnace and hammered to eliminate remaining slag. The bloom of wrought or malleable iron would be reheated before rolling, shingling or other mechanical treatment.

The reverbatory furnace was revolutionary in its impact, allowing a wide expansion in industrial production. It increased the quality of iron available for blacksmiths making tools and implements prior to the era of bulk processed carbon steel. It increased the volume of iron available for manufacturing purposes. The most important product of the reverbatory furnace was puddled iron bar stock, essential for the growing needs of a proto-industrial society, for iron and steel implements of every description and for making blister steel in cementation furnaces. The need for steel during and after the Napoleonic wars was rapidly increasing. Coal fired reverbatory furnaces provided wrought iron bar stock for every practical application where cast iron could not be used. One possible exception was its use for edge tool production. In Sheffield, the highest quality edge tools were produced from cementation steel made with charcoal fired Swedish wrought iron but this represented only a tiny fraction of the burgeoning demand for other types of steel (note the steel price list in the figure below).

An important observation about Cort's reverbatory furnace is one made by Barraclough: "Cort

24 *Sheffield steel and America*

Table 1.2 *Sheffield and Pittsburgh crucible steel prices 1863*

	Cents per lb		
	Sanderson Bros New York	Singer, Nimick Sheffield Works	Jones, Boyd Pittsburgh Works
Best cast steel	22	21	20–21
Extra cast steel	23		
Round Machinery	14	13–15	13–16
Swage cast steel	25		
Best double shear steel	22		
Best single shear steel	19		
Blister first quality	17½		
Blister second quality	15½	8–12	
Blister third quality	12½		
German steel best	15½		
German steel Eagle	12½	9–12	9–11
German steel third quality	11½		
Sheet cast steel 1st quality	22		
Sheet cast steel 2nd quality	18	15–21	15–23
Sheet cast steel 3rd quality	16		
Shovel steel best	14½		
Shovel steel common	13½		
Sheet cast steel for hoes	14½	11½	11½
Mill saw steel	15½	14	14
Billet web steel	17½		
Cross-cut saw steel	17½	18	18
Best cast steel for circulars to 46 in.	25	23	23
Toe corking best	10	9¾	9¾
Spring steel best	11		
Spring steel 2nd quality	10	9–10¾	9–10¾
Spring steel 3rd quality	8¼		

Source: SCL Marsh Bros. 249/24, 28–9.

Figure 10 Tweedale, Geoffrey. 1983. *Sheffield steel and America: Aspects of the Atlantic migration of special steelmaking technology, 1850-1930*. London: F. Cass & Co., Table 1.2, pg. 24.

originally expected he would be able to produce steel by means of this furnace." (Barraclough 1984b, 93). While it took another 50 years to perfect the production of puddled steel by the decarburization of pig iron, and this mostly in Germany, enterprising English forge masters also certainly produced significant quantities of steely cast iron to construct the machinery invented by the English industrial revolutionaries who followed Henry Cort. This steely cast iron (puddled steel? German steel?) can be seen today in the many early 19th century machines on exhibition at the Victoria and Albert Museum in London, England. German, English and American puddled steel later played a critical role in supplying steel needs between 1835, when the steel puddling process was perfected, and 1870, when bulk steel production by the Bessemer and Siemens-Martin open hearth process came to dominate steel production. Puddled steel may also have played an important but as yet undocumented role in those critical years of the Industrial Revolution between 1800 and 1835, when steel was in short supply. Puddled steel from Cort's reverbatory furnaces may have played a co-equal role with German steel in supplementing expensive crucible steel for edge tool production from 1785 to 1865, when American made crucible steel became widely available.

Charcoal Iron and Edge Tools

Reverbatory furnaces were fueled by coal or coke, especially by coal. Edge tool makers had always known that iron made from refined pig iron produced in coke fired blast furnaces was very inferior to high grade Swedish charcoal fired iron for making edge tools from cementation and sheaf steel. The reverbatory furnace partially solved this problem by isolating the sulfur producing fuel from the iron being puddled, therefore, increasing the quality of wrought iron, which then could be used to make steel for many other uses. Nonetheless, the Swedish charcoal iron traditionally used in the first stage of crucible steel production via the cementation process maintained the cachet, the reputation for excellence in the specialized production of crucible steel for gouges, chisels, drawknives, carving tools and other edge tools for woodworking. Even after reverbatory furnace puddled iron dominated the market, most edge tool manufacturers wanted cementation steel made from Swedish charcoal fired wrought iron for their crucibles. Tweedale (1987) notes the continuing robust market for Swedish charcoal iron for crucible steel production long after the introduction of Cort's reverbatory furnace.

In America, Swedish iron was a major cargo on colonial merchant ships returning to Boston and Salem. Since the cementation furnace had made its appearance in the American colonies by 1713 (Bining, 1933) it is likely indigenous if clandestine colonial steel production was already well underway well before the American Revolution. Early U. S. Custom’s impost records for New Bedford show continuing shipments of Swedish iron to New Bedford from Gottenberg, Sweden, between 1816 and 1831. Individual steelmakers in Sheffield loved that Swedish iron - it was used for special applications long after better quality cementation steel was also available for edge tool production. Crucible steel made from Swedish low sulfur charcoal iron was the most expensive of all steels. It was also the highest quality steel available before the era of R. K. Mushet and alloy steels.

Two observations about charcoal fired wrought iron are important for considering future edge tool and / or steel production. Charcoal iron always contains some traces of silicon, which play an important but obscure role in the production of edge tools made with crucible steel. Tiny amounts of silicon remained when the relatively pure Swedish made charcoal fired wrought iron was made into cementation steel. The traces of silicon still remaining in cementation steel were enhanced by additional traces of silicon shed by the clay crucibles during crucible steel production. These silicon traces apparently played a key role in the metallurgy of crucible steel derived edge tool production for woodworkers. There appears to be a connection between silicon traces in crucible steel and the use of charcoal fired rather than coke fired wrought iron to produce cementation steel. Edge tool makers traditionally used charcoal fired wrought iron to make special batches of cementation steel for crucible steel for their edge tools. Malleability, ductility, tensile strength and lack of brittleness are characteristics associated with crucible steel for edge tools made from high quality charcoal iron. Traces of silicon in steel made specifically for edge tools (other than knives) may have played a central role in enhancing the quality of the best edge tools.

Most of the iron fined in a reverbatory furnace was coke fired pig iron. Documentation is lacking as to the extent that crucible steel producers specifically made edge tools with iron that was originally made with charcoal, but the literature (Tylecote, Barraclough, Tweedale) indicates so many sub genres of crucible steel categories that cementation steel destined for edge tool production in crucibles may have been specifically made out of charcoaled iron. When crucible steel production for edge tool manufacturing ended in the 1920s and 1930s the era of high quality edge tools - chisels, slicks, adzes, carving tools, etc. also ended. The end of the crucible steel era also coincides with the end of the era of wrought iron production. New modern bulk steel making processes were responsible for the demise of both as well as for the end of the era of wooden shipbuilding, which had lingered into the first two decades of the 20th century. When the internal combustion engine replaced the unwieldy steam engine on large ships it became practical to use it on smaller fishing vessels. The wooden age, already in its twilight since before the Civil War, unequivocally ended.

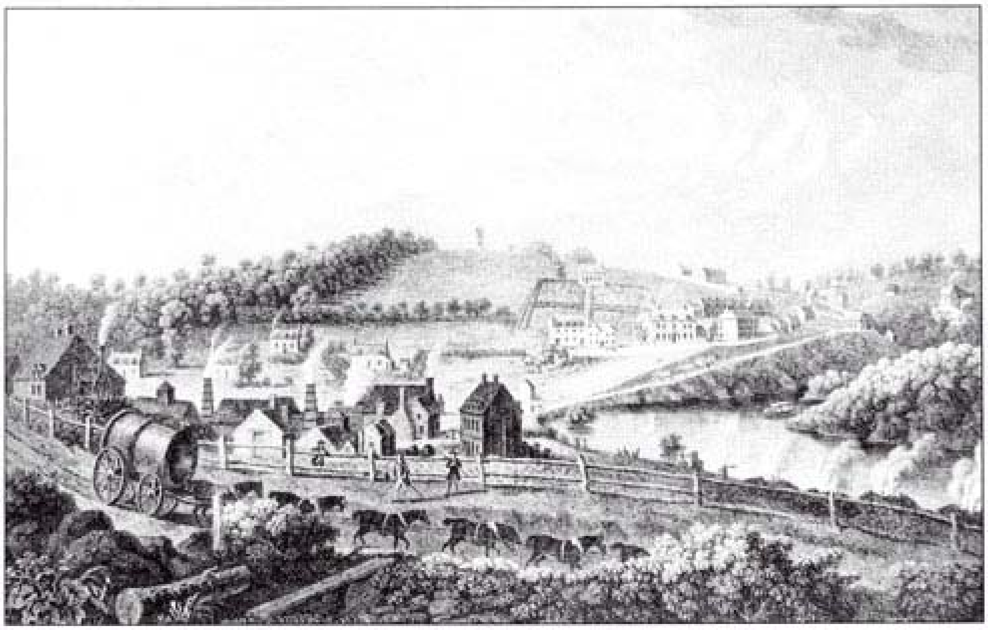
The English Industrial Revolutionaries

Thomas Savery, Thomas Newcomb, Benjamin Darby, Benjamin Huntsman, John Wilkinson, James Watt, Richard Handbury, and Henry Cort were the first generation of inventive English engineers - industrial revolutionaries who made possible the radical cultural and industrial changes of the 19th century. With the exception of Huntsman, who implemented a key innovation in ferrous metallurgy, these men designed or made improvements related to the two fundamental instruments of the second Industrial Revolution: the steam engine and the reverbatory furnace. The existence and efficient functioning of these two key tools of the Industrial Revolution opened the door to the design and production of function specific machines that insured the success of the Industrial Revolution as a symphony of engines of social and economic change. Existentially, the Industrial Revolution was not just the theoretical presentation of a crystal palace exhibition of innovative equipment; its essence was the practical application of these inventions.

While Newcomb, Watt and Cort were inventing the big ticket items of the Industrial Revolution, numerous other industrial revolutionaries were designing and inventing function specific machines that eventually, though not always obviously, brought a gradual end to the tradition of hand made hand tools. John Kay was one of the early inventors who started the revolution in the textile industry in England with the invention of a flying shuttle (1738) that doubled loom production. James Hargrave followed with his spinning Jenny for weft spinning (1764). Richard Arkwright designed his spinning frame with the help of John Kay, which extended the functions of Hargrave's Jenny, which would only weave weft, to include the weaving of the warp (1769). Arkwright opened his first water powered factory equipped with a power loom in 1771, and followed with improvements in carding and roving (1775). These developments signaled the practical beginning of an Industrial Revolution where machines supplemented, then replaced, hand work; this equipment is predicative of the later development of machinery, which would manufacture the hand tools still laboriously made by individual craftsmen and blacksmiths throughout England and America.

Equally significant as to their later impact on hand tool production is a second generation of English Industrial Revolutionaries lead by Henry Maudslay (1771 - 1831). Maudslay may have been the most innovated machine designer in the history of the Industrial Revolution. The power tools he built and the engineers he trained or influenced (James Nasmyth, Joseph Clement, Joseph Whitworth, etc.) played a key role in substituting machine-made machines for the craft based technologies that ironically lasted longer in England than America. Maudslay was preceded by John Wilkinson, who invented the boring machine necessary to hollow the cylindrical cavities of Watt's steam engine pressure vessels. John Jacob Holtzapffel began his family’s long tradition of exquisite lathe making in London in 1787. Maudslay, who first worked at the Woolwich arsenal in London at age 12 became a metal smith by the age of 15 (1786), was a well known toolmaker by 1799 (Cantrell and Cookson, 2002). During the next 30 years, he invented table engines, compound slide rests, self-tightening collars for hydraulic presses and spring winding machines, to mention only a few of the inventions, which were key elements in the industrialization of England. Maudslay designed stationary steam engines and marine engines, sawmill machinery, gun boring machinery, and hydraulic presses that insured his fame as the leading innovative design engineer of the early 19th century. His standardized screw threads were a precursor of the later work of Joseph

Whitworth. Maudslay's 1797 screw cutting lathe alone would have insured his fame. Between 1802 and 1807 he designed, along with the help of the French émigré Mark Brunel, and constructed 45 machines for the mass production of ship's blocks for the British Navy (Cooper 1984). The modern age was off to a running start.



7 A view over the Coalbrookdale Upper Works by Francois Vivares, dated 1758 and packed with interesting detail. On the left is an engine cylinder being transported from the boring mill further down the Dale. The buildings in the middle include the tall chimneys of two air furnaces and the wider top of the blast furnace belching smoke. To the right is the reservoir for the waterwheels, with the coke hearths in the foreground. In the background beyond the reservoir are Dale House and Rosehill House, with Sunniside further up on the horizon, all ironmasters' houses, and Tea Kettle Row on the side of the hill with its characteristic dormer windows

Figure 11 Richard Hayman and Wendy Horton, 2003, *Ironbridge: History & guide*, Tempus Publishing Ltd., Stroud, Gloucestershire, UK, pg. 23. Reprinted with the permission of Ironbridge Gorge Museum Trust - Elton Collection - AE185.769. Of particular importance in this view of Coalbrookdale is the depiction of John Wilkinson’s engine cylinder being transported by horse drawn wagon to some undisclosed location. This engine cylinder was one of the most important innovations of the Industrial Revolution facilitating the efficient operation of Watt’s newly redesigned steam engine.

Richard Roberts (b. 1789 d. 1864) was another of the innovators of the machine age, perhaps most famous for his design of the London Bridge. Roberts, who worked for Maudslay before the end of the Napoleonic wars in 1815, made important improvements to the power loom and the spinning mule, the slide lathe, the planning machine, and was manufacturing gear cutting engines at Manchester by 1830. Roberts also produced important slotting machines and a punching and shearing machine. These all played a role in supplementing hand work and producing the machinery that would eventually result in the rise of the factory system for all tool production after the mid-19th -century in America and then later in England.

David Napier (1788-1873) specialized in manufacturing printing presses; his inventions and innovations dominate printing press design until the advent of photo composition in the 1970's (Moss in Cantrell & Cookson, 2002). He worked for Maudslay, later designing a tracing machine, a bullet making machine, coin sorting equipment, and a registering compass. Joseph Clement, (1779-1844) who was Maudslay's chief draftsmen and chief marine engine designer, was a close friend of Napier, and invented an important ellipse machine for accurate perspective, turning lathes, the barrel tail stock, milling cutters, and produced the first taper, middle and plug taps for Maudslay in an environment where standard measurements for threads had still not been widely adopted (1830). All was soon to change under the influence of both American innovators and Joseph Whitworth, who Clement clearly influenced.

Joseph Whitworth (1803-1887) was another engineer who worked under Maudslay, and then emerged as one of England's most important machine designers. He obtained 48 British patents, and is probably best known for his standardized screw thread measuring systems and his use of decimal rather than fractional measurements in the precision tools he designed. Whitworth left Maudslay's employment in 1828, and after working with Joseph Clement, he moved to Manchester in 1832, becoming one of England's most successful industrialists. His innovations in precision measurement were quickly adapted in the United States. Occasional surviving examples of his cylindrical gauge measuring set, his hand screws, radial drilling and boring machines, and other "J. Whitworth, Manchester" signed equipment are still to be found in old workshops across the United States. His precision measuring machine was reliable to within millionths of an inch. Whitworth was part of the English Royal Commission that visited New York in 1853 to evaluate America's rapid advance in mass production techniques using standardized parts.

Joseph Nasmyth (b. 1809), was another Maudslay trained engineer and leader in machine tool technology innovation. He designed a road steam carriage, a high pressure steam engine which recycled waste steam to increase engine efficiency, and invented the flexible shaft to transmit rotary motion. Nasmyth's nut cutting machine (c. 1841) was one of the early forms of a milling machine. Nasmyth is best known for patenting his steam hammer in 1842, and manufacturing it from 1843 onwards. The efficiency of this hammer greatly facilitated industrial production of heavy equipment, especially railroad locomotives, allowing Nasmyth to establish one of the largest industrial complexes in England at Manchester, the Bridgewater Foundry.

Other engineers influenced by Maudslay and his followers included William Muir, who invented the letter press. Maudslay had first achieved significant renown working with Joseph Bramah in London, helping Bramah produce his patent lock (c. 1790-1997). Maudslay then went on to become the leader of an engineering cartel who designed the machines that forever changed the nature of manufacturing, including hand tool production, during the classic period of the industrial revolution. He was the leading innovator in the development of the factory system of production using interchangeable parts, manufactured with modern drop or die-forging techniques. The result in demand for increasing quantities of steel gave rise to the bulk steel manufacturing processes of the second half of the 19th century, the Bessemer, and the Siemens-Martin open hearth furnaces. This third stage in the Industrial Revolution foreshadowed the end of crucible steel production made from puddled blast furnace pig iron or Swedish charcoal iron, which in turn resulted in the decline in the quality edge tools made after 1930. The greatest irony in the fluorescence of the English engineering pioneers, was that while they designed and built the machinery of the Industrial Revolution, American entrepreneurs and craftsmen quickly adapted and improved their designs and incorporated them in a factory system of mass production that soon left most English hand tool manufacturers, often still using craft based technologies, unable to compete with the more efficient American factories.