Introduction

A Glossary of Ferrous Metallurgy Terms: A Voyage through the Labyrinth of Steel and Toolmaking Strategies and Techniques 2000 BC to 1950 is published by The Davistown Museum as part of its Hand Tools in History publication series. This Glossary, formerly an appendix of Volume 7 of the series, *The Ferrous Metallurgy of the New England Shipsmith*, is now published as Davistown Museum special publication #42 due to its growing size and numerous requests for copies. The preface to the entire publication series is included in this glossary to explain its context. This glossary, as well as the publication series as a whole, is updated on a weekly basis. Please contact the author with corrections, suggested revisions, or additional definitions at curator@davistownmuseum.org.

Also included as an introduction to this Glossary is the Appendix of Volume 10, A Registry of Maine Toolmakers, titled, *A Guide to the Metallurgy of the Edge Tools in the Davistown Museum: Art of the Edge Tool*. This guide has two components: I. *Steelmaking Strategies 1900 BC - 1930 AD* and II. *Edge Toolmaking Techniques 1900 BC - 1930 AD*.

Readers of this glossary who would like more information about the steel and tool making strategies and techniques that form the context of this glossary please refer to the museum publication series listed below.

- 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

Preface to the Hand Tools in History Publication Series

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 Tool Making 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 Tool Making Strategies and Techniques 2000 BC to 1950

A Guide to the Metallurgy of the Edge Tools at the Davistown Museum: Art of the Edge Tool

An Exhibition Opening in June 2007

The following steel and tool making strategies and techniques were used for the forging of the edge tools included in The Davistown Museum's Exhibition *Art of the Edge Tool*.

I. Steelmaking Strategies 1900 BC – 1930 AD

1. **Natural Steel: 1900 BC – 1930 AD**

   Natural steel was made in direct process bloomeries as occasional nodules of steel (+/- 0.5% carbon content (cc)) entrained in wrought iron loups, by altering the fuel to ore ratio in the smelting process, producing heterogeneous blooms of malleable iron (0.08 to 0.2% cc) and/or natural steel (0.2 to 0.5 cc and higher) or by carburizing bar or sheet iron submerged in a charcoal fire. Manganese laced rock ores (e.g. from Styria in Austria or from the Weald in Sussex, England) facilitated natural steel production; as a slag constituent, manganese lowered the melting temperature of slag, facilitating the more uniform uptake of carbon in the smelted iron. The first documented production of natural steel occurred at the height of the Bronze Age, 1900 BC, by the Chalybeans, using the self-fluxing iron sands from the south shores of the Black Sea. Occasional production of bloomery derived natural steel edge tools continued in isolated rural areas of Europe and North America into the early 20th century.

2. **German Steel: 1350 - 1900**

   German steel was produced by decarburizing blast furnace derived cast iron in a finery furnace, and after 1835, in a puddling furnace. German steel tools are often molded, forged, or cast entirely of steel as exemplified by trade and felling axes without an inserted (welded) steel bit. Such tools were a precursor of modern cast steel axes and rolled cast steel timber framing tools; German steel shared the world market for steel with English blister and crucible steel until the mid-19th century.

3. **Blister Steel: 1650 - 1900**

   Blister steel was produced by carburizing wrought iron bar stock in a sandstone cementation furnace that protected the ore from contact with burning fuel. It was often refined by piling, hammering, and reforging, into higher quality shear or double shear steel or broken up and remelted in crucibles to make cast steel. Blister steel was often used for "steeling" (welding on a steel cutting edge or bit) on axes and other edge tools.

4. **Shear Steel: 1700 - 1900**

   Shear steel was made from refined, reforged blister steel and was used for "steeling" high quality edge tools such as broad axes, adzes, and chisels, especially by American edge toolmakers who did not have access to, or did not want to purchase, expensive imported English cast steel. The use of shear steel was an alternative to imported English cast steel for making edge tools in America from the late 18th century to the mid-19th century.

5. **Crucible Cast Steel: 1750 - 1930**

   Crucible cast steel is made from broken up pieced of blister steel bar stock, which is inserted into clay crucibles along with small quantities of carboniferous materials (e.g. charcoal powder). After melting at high temperatures, crucible cast steel was produced in 5 to 25 kg. batches and was considered the best steel available for edge tool, knife, razor, and watch spring production. Due to lack of heat resistant clay crucibles, extensive production of high quality crucible cast steel didn't begin in the United States until after the Civil War.

6. **Brescian Steel: 1350 - 1900?**

   Brescian Steel was a common Renaissance era strategy for making steel in southern Europe, for example, for the condottiers of the Italian city states. Wrought or malleable iron bar stock was submerged and thus carburized in a bath of molten pig iron. Brescian steel cannot be visually differentiated from German steel or puddled steel, both of which were produced from decarburizing pig iron.

7. **Bulk Processed Steel: 1870 f.**

   After the American Civil War, a number of new strategies were invented for producing large quantities of steel, especially low carbon steel, required by the rapid growth of the industrial age and its factory system of mass production. The first important innovation was Henry Bessemer's single step hot air blast process, followed by several variations of the Siemens-Martin open hearth furnace and electric arc furnaces. For edge tool production, the electric arc furnace supplanted, then replaced, crucible cast steel in the early decades of the 20th century. A few modern drop-forged edge tools are included in this exhibition as examples of modern bulk process steel producing strategies.

For more information on these later techniques, including the drop-forging of the all cast steel ax, see:

Davistown Museum special publication 42: A Glossary of Ferrous Metallurgy Terms: A Voyage through the Labyrinth of Steel and Tool Making Strategies and Techniques 2000 BC to 1950

This publication is available for hands-on perusal by museum visitors.

Also see the exhibition handout: **Edge Toolmaking Techniques**

Art of the Edge Tool

II. Edge Toolmaking Techniques 1900 BC – 1930 AD

Shaped and forged by Hand

A. Forge-welded: edge carburization by heating followed by hammering and additional heat treatment

B. Steeled: the welding on of a steel bit to an iron shaft or body

C. Pattern welded: the welding together of alternating layers of sheet iron and steel, used by knife and sword makers; seldom used by edge toolmakers

D. Molded: the shaping of short lengths of hot malleable iron or German steel bar stock in an iron pattern; sometimes the iron pattern was water cooled. Not used after blister steel became widely available (1700)

Shaped and forged by Machine

E. Rolled: cast steel hot rolled into bar stock, then socketed and ground or forged

F. Casting: cast steel hot rolled into bar stock and then shaped by drop-forging entirely by machines

G. Drop-forging: the hydraulic pressing of low carbon steel and malleable iron into tool forms by using dies as patterns

Most hand tools made in the 20^{th} century show no evidence of hand work, but in a minority of cases (e.g. the ax) there is no clear distinction between the hand-forged and the machine made tool until the late 20^{th} century. Most edge tools made before 1930 are "hand-forged" or "forge-welded" to some extent, no matter the technique used to "steel" their edges. The trip hammer and the water wheel are examples of machines that assisted edge toolmakers in the forging of their tools. The advent of the modern rolling mill (Henry Cort, 1784) for hot rolling cast steel bar stock did not end the long tradition of hand-forging an edge tool. When the Collins Axe Factory began drop-forging all steel axes sometime after 1837, many smaller ax companies continued hand-forging and hand hammering axes they produced, often with the aid of other machinery, well into the 20^{th} century. The evolution from hand-forging to machine forging (drop-forging) hand tools was thus a gradual process. One goal of the creative economy of the post-industrial era is the revival of handmade hand toolmaking strategies and techniques.

A Glossary of Ferrous Metallurgy Terms

These definitions derive from a wide variety of contemporary and antiquarian sources pertaining to the art of the smelter, forge master, blacksmith, edge toolmaker, shipsmith, founder, and other artisans of ferrous metallurgy. A brief listing of principal bibliographic sources is listed after the glossary, followed by a detailed bibliography of writings and research on ferrous metallurgy.

Acicular: The needle-like crystals that characterize the crystalline structure of slowly cooled pearlite during the production of blister steel.

Acid process: Production of steel using furnaces lined by a siliceous refractory such as sand or clay, suitable for low phosphorous ores only. Until 1877, the acid process was the primary means of bulk process steel production. Introduction of the basic process after 1877 allowed smelting of ores with a high phosphorous content. See basic process and ganister.

Acid steel: Steel melted under a slag that has an acid reaction, and in a furnace with an acid bottom or lining (Shrager 1949).

Acier forge: The French term for fined pig iron.

Adz: The most ancient and important of all forms of woodworking tool, primitive forms of stone adzes were used as early as the beginning of the Stone Age. Cold hammered bronze adzes were the most important shipbuilding tool in the Bronze Age; the oldest known "steeled" adze is a malleable cast iron adze with a heat treated steeled cutting edge made in China, c. 950 BC. (Barraclough 1984a) Iron, natural steel, and steeled iron adzes are commonplace throughout the Iron Age and are well documented in Roman archeological sites (Manning 1985). Goodman, in his *History of Woodworking Tools*, has excellent illustrations of both the socket and shaft hole adze forms. The most famous of all adzes is the unique New England "Yankee Pattern" ship carpenter's lipped adz, which originated sometime in the 18th century and was probably designed by some Gulf of Maine shipsmith whose identity has been lost.

Age hardening: Changes in the physical properties of low carbon steels at or slightly above room temperatures over a period of time where unstable crystalline structures gradually return to more stable forms.

Air furnace: A furnace used to melt cast iron and refine other metals. The fuel, usually coal or coke, as well as the flame, which passes over the bath holding the melted metal, does not come in contact with the metal and thus the carbon content of iron can be carefully controlled. The term air furnace is synonymous with reverbatory furnace.

Allotropic/Allotropy: The property of having changing physical characteristics, e.g. crystalline structure, while retaining elemental chemical identity, i.e. an iron carbon alloy. Allotropy is expressed as the multiple forms of a space lattice in an element. See allotropic forms of iron and space lattice.

Allotropic forms of iron: Iron has three allotropic forms: **alpha iron**, the low temperature form of iron up to 910° C (1670° F), has a body-centered cubic structure (BCC) and is soft, ductile, and magnetic; **gamma iron**, with a face centered cubic form (FCC), is non magnetic in a temperature range from 1670° F to 2552° F; **delta iron**, with a body-centered lattice structure between 2252° F and 2795° F, exhibits magnetism above its threshold temperature of 2252°F. The space lattice structure of iron breaks down above 2795° F as iron enters the liquid state. Temperature determines the crystalline structure of iron; carbon content adds further variations to the crystalline structure of iron, steel and cast iron. See the iron carbon diagrams in the Appendices.

Alloy: A metallic substance fused with either another metal or a non-metallic element, e.g. steel is an alloy of iron and carbon. The metals most commonly alloyed with iron are nickel, manganese, tungsten, chromium, cobalt, vanadium, and silicon. Alloys usually possess properties that differ from those of their constituents. See brass and bronze.

Alloy steels and alloy cast irons: Steel and iron containing other elements in addition to carbon; strength, durability, corrosion resistance, fracture, and carbon distribution are among the many properties determined by metals alloyed with iron and steel. Some alloying elements serve to increase the formation of martensite at slower rates of cooling or at lower temperatures, therefore increasing hardenability.

Aluminum steel: A smooth, high tensile strength, modern alloy tool steel produced by the electric arc furnace.

American felling ax: A distinctive form of American ax developed in the 18th century in response to the need for a felling ax with a heavier pole than those on traditional English felling axes. Such felling axes were usually forged out of two slabs of iron, which were steeled with an inserted bit after being folded and welded. (Kaufmann 1972)

American system of manufacturing: Developed after 1830, the American system is characterized by the power-driven production of tools and firearms with machine-made, interchangeable parts. The lower Connecticut River Valley was America's first center of manufacturing utilizing interchangeable parts, e.g. Eli Terry (clockmaker); Elisha Root (axes); Eli Whitney (firearms manufacturing); also John Hall, Harper's Ferry, VA. See the Chronologies of Manufacturing History Appendix in Volume 8, *The Florescence of American Toolmakers 1730 – 1930*.

Amisenian: Synonymous with Chalybean, the Anatolian community that produced high nickel steel from Black sea sands using chloanthite as a flux in the high Bronze Age (1900 BC). See Chalybean steel.

Ancony: The short thick wrought or malleable iron bar stock produced in a finery from shingled iron prior to being sent to the chafery for shaping into special sizes suitable for colonial era production of iron tools and artifacts. Anconies were two to three feet long with knobbed or square ends (Gordon 1996).

Anisotropic: Materials having different properties determined by variations in the directional arrangement of their crystallographic patterns. See grain, isotropic.

Annealed eutectoid steel: When slowly annealed, the transformation product of austenite, a eutectoid steel containing 0.83% cc, is pearlite.

Annealed hypereutectoid steel: When slowly annealed, the transformation product of austenite containing more than 0.83% carbon is pearlite and cementite.

Annealed hypoeutectoid steel: When slowly annealed, the transformation product of austenite containing less than 0.83% carbon is pearlite and ferrite.

Annealing: Annealing is the heating of steel above its critical temperature followed by its slow cooling to toughen it by altering its microstructure, allowing the uniform distribution of particles of cementite within the crystalline structure of the annealed steel. The variants of time, temperature, carbon, and alloy content allow an immense variety of annealing techniques. "...to relieve internal strains and improve strength, elasticity and ductility to meet the stresses to which it is subjected in service. It is usually done by heating and holding at a certain temperature followed by slow cooling." (Salaman, 1975, 246). Annealing changes the diffraction patterns of the crystalline structure of the metal being annealed. During the annealing of cast iron, which typically takes 60 hours or longer, all the chemically combined carbon is reduced to free carbon or graphitic carbon surrounded by pure iron. Iron oxide or millscale packed with the white cast iron facilitates malleable cast iron production by assisting in the freeing of the carbon from its chemical bond within the iron. Many variations of the annealing process produce a wide variety of forms of malleable cast iron; partially decarburized, annealed cast iron can be reheated and suddenly cooled, giving a steely fracture. Decarburized malleable cast iron can be re-carburized in the cementation furnace, allowing production of an even wider variety of iron tools and other products. In many cases, the specific procedures and techniques used to produce items such as the Griswold cast iron cooking ware were highly guarded trade secrets. See martensite, malleable cast iron, white cast iron, tempering.

Annealing methods: Shrager has these comments on annealing steel, "Annealing may be performed by one of several methods, depending upon the results desired. The purpose of annealing may be: (1) to remove stresses that have occurred during casting or as a result of work done on steel; (2) to soften steel for greater ease in machining, or to meet stated specifications; (3) to increase ductility in order to make steel suitable for drawing operations; (4) to refine the grain structure and make the steel homogenous; (5) to produce a desired microstructure." (Shrager 1949, 154). All of Shrager's comments also pertain to the annealing of white and/or gray cast iron to produce the many forms of malleable cast iron.

Annealing pots: Cast iron pots utilized to enclose and protect steel being annealed from the formation of iron oxide scale; used especially for annealing wire.

Anvil: "A heavy iron block with a hardened or applied steel topped face suitable for use by a blacksmith in working hot metal." (Sellens 1990, 5), defining the blacksmiths' anvil. Anvils were made from both wrought iron and cast iron and generally had a steel plate welded to the top. In the late 19th century all cast steel anvils were produced by some makers. In his *Dictionary of American Hand Tools*, Sellens lists 36 different types of anvils, many of which, such as dengel stocks (scythe anvil), had a wide variety of forms. Most anvils had a flat work surface in contrast to mandrels and other tools with curved work surfaces.

Arc furnace: A furnace in which the heat needed to smelt metals is produced by an electric arc between carbon or graphite electrodes and the furnace charge.

Archimedean screw: A hollow, inclined screw, usually in the form of a spiral pipe with an inclined axis; when used as a water pump, the lower end of the screw gathers in water, which is then discharged at the upper end. It was named after its Egyptian inventor, Archimedes (260 BC).

Arquebus: The most common form of firearms at the time of Native American – European contact, the arquebus, always made of wrought iron, was brought to North America by French traders in exchange for furs, forever changing the lifestyles of the indigenous communities impacted by its availability. See matchlock.

Arms Race: Use of the blast furnace became widespread in northern Europe sometime during the late 14th and early 15th centuries. Its principle function was the production of cast iron cannon, which along with bronze cannon, were used to arm the growing fleets of England, France, Spain and The Netherlands. Both France and Spain were 16th century adversaries of the English; the defeat of the Spanish Armada in 1588 marks a point in time when the English gained control of North Atlantic trading routes; the attempt of Sir Raleigh Gilbert to sponsor a settlement in the Maritime Provinces was soon followed by the ill-fated Popham expedition and the settlement of the north and south Virginia plantations. The East India Company was organized in Britain in the first decade of the 17th century. The growth of English merchant shipping and the Royal Navy were accompanied by the expansion of cannon and ordnance casting, as well as the proliferation of wrought iron hand guns such as the matchlock and then the flintlock. The arms race that began with the construction of the first blast furnace has continued unabated into the 21st century. All advances in metallurgy have as their primary social function the objective of improvements in ferrous metallurgy for weapons production.

Atomic planes: The planes within a crystal along which the atoms of a particular lattice structure are arranged.

Austempering: The production of bainite by the interrupted quenching of austenite in a bath of molten salt held at a temperature of 450º F – 900º F until bainite formation is completed.

Austenite: An iron carbon alloy (steel), in which carbon is dissolved in iron as a stable solid solution in a temperature range from 723º C to 1400º C. Unstable at room temperature, austenite has a face-centered cubic (fcc) lattice structure, creating more space for a higher proportion of carbon to be held in interstitial solution than in the body-centered cubic (bcc) lattice structure, as in ferrite, for example. If cooled slowly, granules of pearlite will appear in the austenite matrix, creating steel of inferior quality. If cooled rapidly, hard and brittle martensite will be produced, which if then tempered (slowly heated and cooled) will be slightly softened and made less brittle by the homogenous redistribution of tiny particles of cementite, creating steel with a uniform carbon content (cc).

Austenitic steels: Alloy steels containing chromium, nickel, or manganese that retains austenite at atmospheric temperatures.

Austenizing: To create steel by heating iron above 723º C (1670º F) (the austenizing temperature), and holding that temperature to allow the microstructural formation of Austenite. The rate of cooling which follows determines the microstructural qualities of steel. (Wayman 2000). See austenite, quenching, and tempering.

Ax: A common woodworking tool, in which the cutting edge, and thus the cutting angle, is in the same plane as the sweep of the implement, in contrast to the adz, in which the cutting edge is perpendicular to the plane of the sweep.

Axe-Adze: The earliest metal form (copper) of a woodworking tool, dating to c. 4000 BC, 2100 years before the age of Chalybean steel; the cold hammered copper axe-adze was only slightly less dull than a stone ax. The cutting edges of the ax and the adz were perpendicular to each other as in a modern variation of this tool, one form of the fireman's ax.

Axe bar: A standard commodity of the 19th century, axe bar stock was 1" x 3" and was often provided in 12' lengths. Axe bar stock ranged from malleable bar iron suitable for steeling to German or blister steel, suitable for additional steeling or forging. In the 1830s, cast steel became available for drop forging axes. See Collins & Co., ax, ax making, eyepin, and overcoat method.

Ax making: Before the era of the one piece cast steel ax, two strategies for steeling an ax were used in most ax making factories. The oldest method of steeling an ax, used since the early Iron Age, was to insert a piece of carbon steel between a folded slab of iron, and then weld them together. A more modern form of steeling is the overcoat method, in which a piece of high carbon steel is wrapped over the (folded) iron or low carbon steel ax body prior to welding. The modern method of drop forging an ax involves cutting steel billets, typically into three pieces, and then heating them to a temperature of 2350° F prior to drop-forging and quenching in brine. (Kaufman 1972, Klenman 1998). See ax, cast steel, steeling, and eyepin.

Babbitt: An alloy used to make bearings; in its original form, Babbitt is 89% tin, 3.5% copper, 7.5% antimony; also made with varying quantities of lead.

Bainite: A mixture of ferrite and cementite with a microstructure that forms during the rapid cooling of austenite to a temperature of 800° F, after which it is held for a long period of time at a temperature above 400° F, but less than 800° F. Bainite is an intermediary between ferrite/pearlite (slow cooling) and martensite (fast cooling, as with quenching) and is more ductile than Pearlite, but less brittle than martensite. Bainite is often shown as ledeburite on some iron carbon diagrams.

Balkan Copper Age: The earliest pyrotechnic society, c. 6000 BC, the Balkan Copper Age culture evolved from the Neolithic Vinča culture, which was located along the shores of the Danube and flourished prior to the Copper Age in the Aegean. Early Iron Age smelting techniques and furnace designs can be traced back to this culture. Its most famous archeological site is Catul Huyuk. See Renfrew (1973).

Ball vise: The principal vise used to hold die blanks for shaping drop-forged dies; also used by silversmiths and pewter spinners for securing die sinking patterns for flatware, Britannia ware, and pewter.

Bar mill: A mill in which billets of iron or steel are reduced in thickness and width by grooved rollers.

Basic oxygen process: One of the two most widely used steelmaking processes in the 20th century; the basic oxygen process is an offshoot of the Bessemer process, utilizing pure oxygen for the rapid decarburization of cast iron, with significantly less pollution produced as an unwanted byproduct.

Basic steelmaking process: Invented by Sidney Gilchrist Thomas in the 1870s and patented in 1879, steel furnaces utilizing linings of limestone and other basic elements revolutionized bulk steel production processes by allowing smelting of ores high in phosphorous, which previously had not been able to be smelted in furnaces with acid linings such as sand and clay. This process was particularly useful for the open-hearth and Bessemer process and furnaces in continental Europe, especially Germany, located near high phosphorous ore deposits. The basic process supplemented the acid process after 1880. Sir Wescott Abell, in *The Shipwright's Trade* (1948), notes 1877, two years prior to the patent, as the landmark year when the basic process became widely used, thus marking the beginning of the reign of the bulk process steel industry.

BDTT: Brittle-ductile transition temperature.

Beak iron: Tools with various designs of horns, points, or beaks, which could be inserted into swage blocks and anvil hardy holes for the purpose of shaping iron and steel, especially sheet iron. Historically important variations of the beak iron, all derived from European prototypes, include the blowhorn, ball-top, flat-top, etc. stakes, which were first produced in the U.S. by the North Brothers in CT. Collected in Europe and brought to America by Kenneth Lynch, most of these forms are illustrated in the publication *The Kenneth Lynch Tool Collection*.

Bears: Also called salamanders, bears were the ferruginous furnace bottoms produced by the smelting of copper during the Copper and Bronze Ages, when iron oxide (Fe_2O_3) was used as a flux. During the Iron Age, many of these bears, rich in iron oxide, were re-smelted to produce iron tools and weapons.

Beating out: The shaping of the curved futtocks and other components of the ship's frame with the use of the broad ax, either in woods at the timber harvesting site, or at the shipyard. The Yankee pattern broad ax is the generic ax used by New England shipwrights. See shipsmith and broad ax.

Bed charge: In a cupola furnace, the pig iron placed on its coke bed prior to firing is the bed charge.

Belgian iron: The soft wrought iron preferred by gun makers in Europe and Britain during the Renaissance (1450-1650); more easily forged and welded than other irons and steels used in gun barrel forging. (Greener 1910)

Bell metal bronze: 75-80% carbon, 20-25% tin; tin serves as a hardener.

Bessemer process: First described by Henry Bessemer in 1856, the Bessemer process converts pig iron to steel in one step. A hot air blast produces Bessemer steel in a closed converter by rapid oxidation of the impurities in the pig iron, including silicon and most carbon. "When Bessemer and open-hearth steels made their appearance in the market an attempt was made to use them instead of wrought iron as the base for high-grade crucible steels. Though seemingly pure enough, apparently purer even than wrought iron, these metals were not able to compete with wrought iron for this purpose. For some reason, not yet satisfactorily explained, these new materials which are made in 15, 35 and 50-ton batches, when used a as a base, do not give as high quality tool steel as puddled wrought iron, which is slowly and laboriously made in 500-pound lots." (Spring 1917, 121-122). "The Bessemer process, which gave a brilliant fireworks display, was a rapid one, taking less than half an hour. For this reason, it was not easy to control the process, so the steel varied more than was thought proper." (Abell, 1948, 148). Until the addition of spiegeleisen to strengthen it, Bessemer steel was unsuitable for many of its later uses. See silicon, spiegeleisen, open-hearth process, and manganese.

Billets: Wrought iron bars forged by a blacksmith from an iron bloom; in the early Iron Age, billets were made from the smelter's currency bars after removal of slag and consolidation of the iron. After the development of bulk process steel, billets are defined as semi-finished squares of iron and steel made from red hot ingots prior to further mechanical (rolling and forging) and thermal treatment. Roman billets were typically 5 – 10 kg. (Tylecote 1987)

Bi-metalism: In early polymetalic societies, the production of tools and weapons using more than one metal, e.g. pattern welded bronze and iron knives (rare), or the use of bronze rivets in iron shafts for sword production.

Biscayne axe: The Biscayne area in Spain (Catalonia) was the principle location of the manufacture of trade axes in the 15th and 16th centuries. These axes were brought to the Carolinas and Florida by the Spanish, and transported over the Pyrenees and sold to the French, who also brought them to North America (e.g. St. Lawrence River) and sold them to indigenous communities, hence the name "trade axe." See Russell (1967) and Kaufmann (1972).

Bit: The steel cutting edge of an ax. See ax making and overcoating.

Black-heart: A form of malleable iron annealed only for a short time, with the result that its fracture has a white rim with a black center; most American made malleable iron takes this form. See white-heart, malleable cast iron, free graphite.

Blast: The machine that pumps air to the tuyeres of the blast furnace. See blowing tubs.

Blast furnace: A high shaft furnace developed in Europe after 1350 to smelt iron ore in the reducing atmosphere of the partial oxidation of charcoal (and after 1750, of coke). The liquid iron produced was cast into cannons, other utensils, or "pigs" for further refinement (decarburization) into wrought iron as well as steel. In modern smelting processes, a flux of limestone is used to combine with and remove silicate and other contaminants as slag. The blast furnace was a significant improvement over the smaller direct process bloomery furnace because it more efficiently reduced the ore to its metallic state with a higher carbon content and lower melting temperature than bloomery iron; larger quantities of iron were produced with significantly less iron oxide lost as slag, therefore allowing smelting of lower quality ores. A series of improvements, including the use of the steam engine for air blast (1775), furnace design changes (1784), and the adoption of the hot air blast (1828) increased operating temperatures, furnace capacity and efficiency, and the control of carbon content. The blast furnaces used to smelt bog iron in southeastern Massachusetts (1653 – 1820), much smaller than modern blast furnaces, had three fundamental designs: square, cone, and pyramid. (Murdock 1937). See bloomery, arms race, cupola furnace, foundry, molding, slag, and carbon content of iron.

Blister steel: Steel produced in the cementation furnace, which protected the wrought iron from the oxidizing fire of the burning fuel. Bars of wrought iron were stacked in the sandstone furnace with layers of charcoal dust (etc.) and fired for a period of five to 12 days. The resulting steel bar stock had a heterogeneous carbon content, with less carbon in the inner layers and a higher carbon content (cc) in the outer layers and blisters on the steel surface, which were due to gas formation from the chemical reaction between the carbon and impurities in the slag. After 1750, blister steel bar stock was broken into pieces and re-melted in crucibles with the addition of carboniferous material (e. g. powdered charcoal) to produce small quantities of cast steel (5-50 kg). Prior to the introduction of crucible steel, blister steel was used as a "weld" steel in the manufacturing of edge tools, and was the principal form of steel produced in England between 1686-1850. A knowledgeable blacksmith or metallurgist could judge the quality of the steel by its fracture, which expressed the changing forms of its crystalline structure, ranging from 80% sap (low carbon steel 0.6% cc) to a fine crystalline structure (tool steel 1.2% - 1.35% cc). Higher carbon content (above 1.4% cc) is denoted in fracture as an increasingly coarse crystalline structure. Bars of blister steel were frequently piled (bundled) and reforged into higher quality special purpose steel tools such as spring steel, shear steel, and double shear steel. Benjamin Huntsman's innovative introduction of easily hot rolled cast steel (1742) revolutionized edge tool manufacturing by producing steel with uniform carbon content. After 1750, blister steel, along with German steel, continued to dominate the world steel market until the development of bulk process steel (1870). See German steel, Sheffield classification of blister steel, Bessemer steel, shear steel, cast steel, and cementation furnace.

Bloom: The partially melted, pasty mass of iron and slag resulting from the smelting of iron ore. Some bloomery-produced iron was nearly pure ferrite with a very low carbon content, less than 0.08 %, but slight changes in the fuel-ore ratio, tuyere location and smelting temperature could produce iron with a variable carbon content ranging from that of malleable iron (0.08 - 0.2 %) to low carbon steel (0.2 to 0.5% cc) and occasionally to raw tool steel (0.5 to 1.5% cc). Pins and globules of steel, which would reduce the malleability and ductility of wrought iron as unwanted inclusions, often characterized blooms with higher carbon content. These steel inclusions in the iron bloom may have also assisted blacksmiths in forging natural steel tools in early direct process open-hearth furnaces by encouraging experiments with furnace design and smelting processes, otherwise steel nodules were considered to lower the quality and workability of wrought and malleable iron. See loop, direct process, wrought iron, and carbon content of iron.

Bloom, modern definition: Hot-rolled, semi-finished billets, bars and slabs of iron and steel.

Bloom size: Early Iron Age blooms (Halstadt, La Téne, Noricum) were two to ten kilograms in size; medieval and late medieval bloomeries with water-powered trip hammers made larger blooms, 25 – 50 kg. (Tylecote 1987)

Bloom smithing: Direct process production of wrought iron by the hammering of the bloom at red heat to remove slag; an inefficient process due to the loss of +/- 50% of the iron content in the slag. In the early Iron Age, the first iron furnaces were run by bloom smiths who also functioned as blacksmiths, forge welding the first iron and steel tools. Historically, the bloomery process was the only practical way to obtain wrought and malleable iron until the widespread production of cast iron required strategies for decarburizing the cast iron. In the colonial period, bog iron, widely available along the coastal plains of the colonies, was widely utilized by the first bloomeries for the production of wrought and malleable iron. See carbon content of iron, bloomery, direct process, and natural steel.

Bloomery: A charcoal fired shaft furnace used for the direct reduction of iron ore to produce wrought iron and natural steel; widely used in the United States until the Civil War.

Bloomery iron: "'Bloomery iron' was essentially similar to 'wrought iron' in being virtually carbon free, but with entrained slag." (Barraclough 1984, 11) Implicit in Barraclough's definition is a difference between the relatively slag fee wrought iron produced in the puddling furnace and the high slag content iron produced in the bloomery furnace. In New England, implements made from direct process bloomery-smelted bog iron ores have an obviously higher slag content than the wrought or malleable iron produced by decarburizing cast iron in the puddling furnace. A lingering question remains: Was direct process bloomery iron always reduced to nearly carbon-free wrought iron, or did the bloomers often halt the process to produce a "wrought iron" with a slightly higher carbon content (malleable iron) since this form of iron was more useful for forging horticultural tools, such as hoes, rakes, and other implements? See malleable iron, bloom smithing, and natural steel.

Blow hole: The defect caused by trapped gas within molten metal; an ongoing problem in crucible steel production until the invention of the dozzle.

Blowing devices: The instruments used to provide the air flow or blast in bloomery and blast furnaces. The earliest blowing devices were leather bag bellows and fan bellows used in Asia. These later evolved into piston bellows. The trompe is a form of hydraulic bellows commonly used in Europe. The steam powered blower was the universal blowing device used after 1775 to provide the air blast for modern blast furnaces before the advent of gas and electric motors. See blast furnace and trompe.

Blowing engine: The steam powered rotary blowing engine, which was first introduced by Joseph Nasmyth in England in 1837, greatly increased the operating temperature and efficiency of the blast furnace. One of a series of important innovations in blast furnace operation, it was quickly adopted by American ironmongers. See blast furnace and tuyere.

Blowing tubs: Blowing tubs replaced bellows in the late 18th century, creating a stronger air blast in both bloomeries and blast furnaces. Of various and gradually improved designs based on piston-valve-cylinder combinations, blowing tubs were wooden cylinders containing leather edged wooden pistons driven by water-powered piston rods. (Gordon, 1996) See blast, blast furnace, bloomery.

Bluing: The color of surface oxide on steel resulting from low temperature heat treatment (+/- 300º C).

Body centered cubic structure: One of the three most common forms of crystalline structures in most metals, body centered cubic (bcc) space lattice is the low temperature (< 910° C/1670° F) crystalline form of (alpha) iron in which atomic centers are located at the corners and center of sets of cubic cells. After heating beyond the eutectoid temperature (723° C), the lattice structure of iron deforms into a face centered cubic structure (fcc) (gamma iron); at a temperature of (2552° F/1400° C), gamma iron reverts to a bcc structure. The third form of cubic space lattice is the close-packed hexagonal (CPH), characteristic of such non-ferrous metals as cobalt, magnesium, and titanium. Metals in this latter group lack plasticity. (Shrager 1949, 5-6)

Bog iron: Iron precipitated in upwelling waters by contact with oxygen; in bogs and swamps, the constant process of bog iron formation can be seen by the characteristic brown scum on the top of the water formed by bacteria precipitating the iron from the water, which then falls to the bottom of the pond or swamp forming bog iron deposits. Limonite and goethite are the most commonly encountered hydrated iron ores in the North American coastal plain. Because both are combined with water, they are called hydrated iron ores. In the colonial era, bog iron was the most important local source of iron until the exploitation of mined terrestrial ores occurred around Salisbury, CT in the mid-eighteenth century, as well as in PA, NY, MD and elsewhere. Pennsylvania soon became colonial America's most important source of terrestrial ore. High in phosphorous, bog iron, unless extensively refined, was smelted and forged into tools with highly visible slag inclusions. See bloom smithing, bloomery, wrought iron, and hydrated.

Bombard: The earliest form of firearms utilizing gunpowder, the production of bombards in Europe after 1350 greatly increased the demands for wrought iron, which in turn, facilitated the development of the blast furnace, which could produce large quantities of pig iron easily refined into wrought iron. See arms race and gunsmithing.

Bosh: The tapered combustion zone of a blast furnace, located just above the hearth.

Botting: The plugging of the tap hole in a cupola furnace after removal of molten iron prior to the accumulation of the next batch of melted cast iron.

Bottom swage: The lower die placed into the hardy hole of an anvil for the purpose of shaping iron bar stock.

Bowl furnace: The most ancient form of an open hearth furnace; the first bowl furnace was probably a campfire in which copper ore was accidentally melted. See furnace types.

Brass: A copper-zinc alloy with +/- 2.0% zinc content and lead as a micro-constituent.

Brazing: The joining of an alloy and a metal with two different melting points.

Brescian steel: An ancient North Italian process for producing steel from carburized wrought iron soaked in molten cast iron. One of several steel producing technologies of the Italian city states during the Renaissance; later used in Europe and possibly in the United States before the introduction of crucible steel. The cast iron was broken into pieces and mixed with saline marble as a flux and then melted; billets of wrought iron were then placed in the molten cast iron for +/- 5 hours, removed, forged, and quenched, producing a high slag content steel with a variable carbon content. A similar procedure was also used to make steel in China, at least as early as 700 BC and probably earlier. (Needham, 1958; Barraclough, 1984a). See Chinese steel.

Brine quenching: Brine quenching expedites uniform cooling by the chemical action of its salt crystals, and was the most preferred quenching medium of many early edge toolmakers.

Brinell hardness: An older method of determining hardness by measuring the diameter of an impression made by a ball of a given diameter under a specific load.

Britannia metal: The combination of tin, copper, and antimony to imitate pewter; invented in Sheffield, England, by James Vickers in the late 18th century (Tweedale 1986). Also called Britanniaware.

British thermal unit: The amount of heat necessary to raise the temperature of one pound of pure water by one degree Fahrenheit starting at its maximum density temperature – 39.1° F.

Brittle cleavage: The nearly instantaneous slip of the crystalline lattice structure of a metal.

Brittle-ductile transition temperature (BDTT): "...temperature at which iron upon cooling; suddenly becomes brittle. The transition temperature is sensitive to the purity of the metal." (Gordon 1996). Also the temperature at which iron and steel undergo a loss of toughness, usually below room temperature. Phosphorous raises BDTT above room temperature in the presence of carbon. (Kaufman 1972). The most notable example of brittle-ductile transition temperature is the rapid cooling of austenite to form martensite. See cold short.

Brittleness: The tendency of a metal to suddenly fracture under low stress without deforming.

Broad ax: A form of ax with a wide blade (in excess of five inches); made in numerous styles ranging from the bearded broad ax of German origin to the wide Pennsylvania style broad ax. The "New England" style broad ax and the English pattern mast ax are the two most common forms of broad ax found in New England shipyards. The former was particularly important for use in the woods to "beat out" the white oak futtocks and keel components for New England shipwrights.

Bronze: A copper-tin alloy; +/- 10% tin.

Bronze edge tools: The most common form of woodworking tools before the Iron Age, hammering flattened the cutting edge of a bronze tool while at the same time hardening it. Bronze celts were often secured in knee bent hafts and later followed by enclosed hafts and socket cores. Bronze axes were often cast in molds with the aid of eyepins. (Tylecote, 1976). See cold hardened, celts, eyepin, and shaft hole vs. socket hole.

Bulk carburization: The production of steel in the order of magnitude of tons, first made possible by the design and use of the cementation furnace >1600. See converting furnace, blister steel, Bessemer process, Siemens-Martins process, basic process.

Butt riveting: The riveting of two plates of low carbon steel or iron together by the use of a covering plate that overlaps the two plates. One of two methods for building iron and steel ships. See lap riveting.

Calcining: The roasting of ore to remove impurities and moisture; the resultant product was called ironstone, which was then smelted and reduced to loops (blooms) in a bloomery furnace. See bloomery.

Calking (caulking): In ship building or ship repair, the process of inserting oakum between planking by the use of calking irons and calking mallets, followed by further compression by a horse-iron, to prevent leakage. During ship repair, the seam would first be opened by a reaming iron prior to removal of old oakum. In colonial era shipyards, hemp was sometimes used instead of oakum. (Story, 1995)

Cannon metal: An alloy of copper and tin, also called gun metal.

Carbon: The most important element in the creation of steel or cast iron from pure iron. The amount of carbon added to iron and its pattern of distribution as an alloy determines the microstructure and mechanical properties of steel or cast iron. With respect to the ferrous metallurgy of woodworker's edge tools, carbon is the key element differentiating iron from steel; various forms of steel contain an intermediate level of carbon. Carbon was first identified as a component of steel in 1786 by Vandermonde, Berthollet, and Monge (Partington 1961). Before the knowledge of the chemistry of steelmaking became well known (1865), the role of carbon in converting iron to steel was unrecognized. The alchemy of converting iron to steel involved adding or subtracting carbon as the major critical ingredient; blacksmiths knew this intuitively but were not aware of the science of metallurgy.

Carbon content of ferrous metals: Sources vary widely in defining the carbon content of wrought iron and steel. The Davistown Museum uses the criteria that follow to differentiate wrought iron, malleable iron and low carbon steel from tool steel; please note the caveats that follow the definitions.

Wrought iron: 0.0 – 0.08% carbon content (cc); soft, malleable, ductile, corrosion resistant and containing a significant amounts of siliceous slag in bloomery produced wrought iron, with less slag in blast furnace derived, puddled wrought iron.

Malleable iron definition 1: 0.08 – 0.2% carbon content (cc); malleable and ductile, but harder and more durable than wrought iron; also containing significant amounts of siliceous slag in bloomery produced malleable iron, with less slag in blast furnace derived, puddled malleable iron.

Malleable iron definition 2: > 0.2 – 0.5% carbon content (cc); prior to the advent of bulk processed low carbon steel (1870), iron containing the same amount of carbon as today's "low carbon steel" was also called malleable iron. Its siliceous slag content gave it a malleable quality not present in modern low carbon steel, hence its name. Before 1870, a wide variety of common hand and garden tools and hardware were made from malleable iron with a significantly higher carbon content than wrought iron.

Low carbon steel: 0.2 – 0.5% carbon content (cc); less malleable and ductile than wrought and malleable iron, low carbon steel is harder and more durable than either and can be only slightly hardened by quenching. Produced after 1870 as bulk process steel (e.g. Bessemer process), low carbon steel has all its siliceous slag content removed by oxidation. Before the advent of bulk process steel production, there was no such term as "low carbon steel." All iron that could not be hardened by quenching (< 0.5cc) was known as "malleable" iron, more recently often referred to as “wrought” iron.

Tool steel: 0.5 – 2.0% carbon content (cc); tool steel has the unique characteristic that it can be hardened by quenching, which then requires tempering to alleviate its brittleness. Increasing carbon content decreases the malleability of steel; if containing >1.5% carbon content, steel is not malleable, and thus not forgeable, at any temperature; also called high carbon steel. Palmer, in *Tool Steel Simplified*, provides this generic description of tool steel: “Any steel that is used for the working parts of tools.” (Palmer 1937, 10)

Cast iron: 2.0 – 4.5% carbon content (cc); hard and brittle, not machinable unless annealed to produce malleable cast iron.

Caveats

Both modern and antiquarian sources vary widely in their definitions of wrought iron, malleable iron, and steel. Modern sources variously define steel and/or low carbon steel as iron having greater than 0.08%, 0.1%, 0.2%, and 0.3% cc.

Before the advent of bulk process steel (1870), which produced huge quantities of low carbon steel that could have a carbon content in the range of 0.08 – 0.5%, iron having a carbon content of < 0.5% cc was called malleable iron; other generic terms for iron that could not be hardened by quenching (> 0.5% cc) were "bar iron" and wrought iron.

The 1911 edition of the Encyclopedia Britannica defines wrought iron as containing less than 0.3% carbon, cast iron as having 2.2% or more carbon content and steel as having an intermediate carbon content > 0.3% and < 2.2%.

Gordon, in *American Iron*, defines steel as having a carbon content > 0.2%. This cutoff point is probably the most appropriate to use in defining steel, but also poses a problem since most sources define wrought iron as having < 0.08% cc; therefore, leading to the confusion of iron with a carbon content > 0.08% but < 0.2% as being either wrought iron or low carbon steel.

In view of the long tradition of the use of the term malleable iron, this glossary resurrects the use of that term to cover this gray area of the carbon content of ferrous metals.

Carbon diffusion: Carbon diffusion occurs mechanically as a result of hammering or from thermal treatments such as annealing, but is more efficiently initiated as a chemical reaction during crucible steel production. The gaseous diffusion of carbon into wrought iron, malleable iron, and low carbon steel cannot occur at a temperature less than 850° C. See carburizing, case hardening.

Carbon gradation: The pattern of carbon distribution that results from the cementation or case hardening processes; the heating of the iron bar stock in the cementation furnace, or of tools packed for case hardening, gradually moves carbon atoms from the surface to the interior, resulting in gradation patterns expressed as changes in the crystalline structure. Bloomery steel (natural steel) lacks carbon gradations due to the erratic and heterogeneous distribution of carbon during the smelting process. See cementation furnace, blister steel, natural steel, case hardening.

Carboniferous materials: Charcoal dust, charred bone, bone meal, wood, charcoal, coal, pigskin, hides, and other carbon-bearing materials used in a cementation furnace to make steel, or as fuel or as a source of carbon for case hardening of low carbon steel tools.

Carbon monoxide: The gas (CO) formed from the combustion of oxygen and carbon in the reduction of iron ore in the direct process bloomery. Hot carbon monoxide serves as the reducing agent in the three-stage removal of oxygen from ferric oxide, first creating Fe_3O_4 then FeO. In the final stage, carbon monoxide removes the last oxygen molecule from the ferric oxide (FeO), creating pure iron (ferrite). The slag created by the reduction process served as a protective covering for the iron bloom, allowing transfer of oxygen from the furnace gas to the bloom to burn out the carbon.

Carbon movement: "The average carbon atom moves 0.06 inches in about eight hours during carburizing" (Shrager 1949, 176) hence the tedious nature of carburizing edge tools by forge welding. All blacksmiths know it is much easier to make a tool out of low carbon steel bar stock than to carburize wrought iron into a low carbon steel tool.

Carbon steel: Also called "low carbon steel" (0.08 - 0.5% carbon); a form of malleable iron with no slag impurities, the mass production of which was made possible by the implementation of the Bessemer process and other bulk steel production methods that oxidized all slag constituents. Due to its lack of siliceous slag, carbon steel is not corrosion resistant, nor is it as malleable or ductile as wrought iron, but more malleable than steel. Very useful for manufacturing drop-forged tools, especially if mixed with alloys, but not appropriate for the manufacture of edge tools. The low carbon steel produced by the Bessemer process had limited useful applications until Spiegeleisen was added in the smelting process. See Bessemer process, Spiegeleisen, manganese, carbon content of iron.

Carburizing: The gaseous diffusion of carbon into wrought iron or steel at temperatures above 850º C – 910º C, but below its melting point, in a carbon rich environment of charcoal, coke, or coal. Carburizing sheet iron into sheet steel by submergence in a charcoal fire (case hardening) was an ancient steelmaking tradition of desert sword smiths and medina-dwelling cutlers. Partially enclosing an iron tool within a charcoal fire for a period of 12 to 36 hours was another variation of the carburization process for making an edge tool; however, the iron shaft of the tool being carburized had to be enclosed in clay or some other covering to protect it from the oxidizing effect of the fire.

Case carburization: An ancient as well as modern tool making technique of carburizing tools in charcoal pits; ideally at a temperature at or above 850º C -- 910° C, where the increased solubility of carbon results in the production of layers of ferrite and iron carbide (cementite). The various crystalline patterns of pearlite that result are dependent on the relative abundance of ferrite and cementite created during the carburizing process. See carburizing and case hardening.

Case hardening: The process of creating a hardened and long wearing thin outer edge of steel, on forge-welded tools; the inner component of the tool remained soft and ductile. During case hardening, selected tools were placed in a protective enclosure with carboniferous material and heated to harden the outside surface. The development of the converting furnace (after 1650), which protected the enclosed wrought iron from the oxidizing effects of the fire, was simply case hardening on a grand scale; the interior bundles of wrought iron in the cementation furnace always had a lower carbon content than the case hardened exterior bundles. In the 19th Century, case hardening became widely utilized on malleable cast iron and drop-forged carbon steel tools after they had been shaped and machined, by annealing or slowly reheating and cooling the tool. The notation "case hardened" is often found on L. S. Starrett and other precision tools such as combination squares. See carburizing and case carburization.

Cassiterite: Alluvial tin, found in Cornwall, Thailand, Malaysia, and desert areas of Egypt. It was essential for the production of tin-bronze tools, which replaced arsenic-bronze tools in the early Bronze Age. Interruption of tin trade routes may have played a role in the rapid substitution of iron for bronze in the late second millennium BC (+/- 1200 BC), first in Cyprus, then in Crete, and the Peloponnesus region of Greece.

Casting: The pouring of liquid metals into molds to achieve a particular shape or form; also, a casting is the shape thus obtained.

Cast iron: A carbide of iron, i.e. iron with such a high carbon content (2.0% -- 5.0%) that it is not malleable at any temperature. Cast iron was originally a waste product of early shaft furnaces that ran too hot; later the principal product of blast furnaces. If not cast into cannon or hollowware, it must be reheated and refined to further remove impurities and excess carbon before being reworked as wrought or malleable iron, carbon steel, or crucible steel. According to Edward Knight, "The new production, instead of remaining a spongy mass in the midst of the coal and slag, to be hauled thence by tongs and be subjected to the hammer to clear it of foreign matter and condense it, ran down like a fluid to the bottom hearth, and found its way out of a hole, running into a form according to the shape of the hollow in the ground which received it. By this means the smelter found he could withdraw the iron, without tearing out the front of his furnace for each bloom." (Knight 1877, 1378). Also see malleable cast iron, white cast iron, and gray cast iron.

Cast irons: Cast iron comes in many forms, the following of which are the most important:

	Silicon %	Graphite % (Free Carbon)	Combined Carbon %	Total Carbon %	Properties
White cast iron	0.70	0.10	2.65	2.75	Very hard
Annealed malleable iron	0.70	2.70	0.05	2.75	Machinable
Cast iron for chilled castings	1.00	1.00	2.00	3.00	Very hard
Semi-steel	1.75	2.80	0.40	3.20	Machinable
Gray cast iron	2.00	3.10	0.30	3.40	Machinable
Soft gray cast iron	2.50	3.50	0.15	3.45	Machinable

(Spring 1917, 180)

Cast steel definition 1: A term specifically referring to the steel used in the late 18th and 19th century for the forging of edge tools for shipwrights, woodworkers, and other trades (e.g. scythe blades, watch springs). Listed by Moxon in 1677 as one of the principle forms of steel available to blacksmiths at that time, Cyril Smith (1960, 24) notes that Robert Hooke's 1675 diary also references cast steel, suggesting that "cast steel was commonly known in England long before the time of Robert (sic Benjamin) Huntsman." Cast steel became more well known after Benjamin Huntsman reestablished the crucible steel process (1742) to make pure steel for his watch spring business. Edge toolmakers soon recognized the higher quality of crucible steel and marked their edge tools "cast steel" to advertise the superiority of the products over the less homogenous blister steel, and its derivatives shear and spring steel, previously used for edge tool production, especially as weld steel. Not to be confused with the more modern use of the term with respect to Bessemer's single process steel production (1865). The words "cast steel" continued to be stamped on English and American made edge tools into the early years of the 20th century. The use of the electric furnace and the introduction of a wide variety of high speed and special purpose alloy tool steels beginning in the early 20th century coincided with the decline and end of crucible steel production. After 1930, the one piece cast steel edge tools produced by Collins and other companies were not made from crucible cast steel, but from steel produced in the electric arc furnace. Also see crucible steel and cast steel definition 2.

Cast steel definition 2 (the modern definition): Casting molten steel from modern bulk process furnaces directly to molds, which create the shape of the final product being manufactured. Cast steel made in crucibles for the production of edge tools (definition 1) was made in batches of 10 to 50 kg; modern "cast steel" is made in batches that can range up to 25 tons, usually in the form of "low carbon steel" (0.2 – 0.5% carbon content). All bulk process modern steel is cast into one form or another. See Bessemer process and Siemens-Martin process.

Catalan furnace: A bowl type "low bloomery" direct process furnace common in southern Europe after 1200 A.D., and still utilized as recently as the early 20th century for the production of wrought and malleable iron; a precursor of the more efficient American bloomery furnace. Depending on the fuel to ore ratio, open-hearth Catalan furnaces operated by knowledgeable forge masters could be and were used to produce small quantities of raw steel, which could be reforged into edge tools and weapons. See natural steel.

Celtic metallurgy: Knowledge of ferrous metallurgy, including a wide variety of steel and tool making strategies and techniques, was brought to central Europe by migrating Celtic communities moving westward through Europe from the western steppes of Russia. Celtic metallurgists were responsible for the flowering of the early Iron Age at Halstadt and La Téne, respectively, beginning about 800 BC. The source of their knowledge of ferrous metallurgy is unknown, but they were responsible for forging the swords, knives, and edge tools in ancient Noricum that first led to the success of the Roman republic and the Roman Empire, and then led to the defeat of the Roman Empire at the battle of Adrianople (400 AD) by Goths supplied with Celtic made doubled edged pattern welded broad swords. Celtic metallurgists were already occupying and working in Britain when Caesar invaded in 54 AD. See Halstadt, La Téne, Noricum, gladius, spathas, natural steel, and manganese.

Celts: The earliest form of stone tools that were attached to handles of antler or wood, often secured by leather thongs.

Cementation furnace: The use of the cementation furnace to make blister steel was the principle means of producing steel in Britain (1700-1850); less widely adopted in continental Europe, the cementation furnace is essentially an enclosed stone or firebrick box containing alternate layers of a carboniferous material such as charcoal dust and the iron bar stock to be converted into blister steel. The air-tight furnace, with the fire located in an open-hearth below the box, is fired for periods ranging from 8 to 12 days, and has a capacity up to 10 tons. First noted in 1574 (Wayman 2000), its first documented use was in Nuremberg in 1607; its first documented use in England was in 1686. Common after 1690 AD, it was supplemented by the crucible steel process after 1750 and was gradually replaced by modern steel making technologies after 1865. Blister steel is used for both shear (sheaf) steel and crucible steel production. The cementation steel furnace represents an industrial scale application of the case hardening principle. Steel bar stock with a widely varying carbon content could be produced depending on exposure time to carboniferous materials, such as charcoal dust, in the cementation furnace. Steel with a more uniform carbon content could be produced with lengthy firings (8-14 days). Blister steel was often piled and welded into special steels such as shear steel for cutlers and edge tools before cast steel became widely available (1750-1775). See blister steel, shear steel, cast steel, and converting furnace.

Cementation steel: Also called "blister steel," it is created by heating wrought iron in powdered charcoal. "Sheffield, England steel makers have been very successful in the manufacture of cementation steel. Their usual method is to pack flat strips of the best Swedish Walloon iron in charcoal inside rectangular stone boxes about four feet wide, three feet high and fourteen feet long. Alternate layers of small-sized charcoal and thin iron bars are piled in these boxes until they are filled, the bars not being allowed to touch one another. When full, top slabs are luted on to the boxes to make them airtight. Fire is kindled in the fire-box below and the heat gradually raised until furnace and boxes are cherry-red in color. This heat is maintained for seven to eleven or more days, depending upon the hardness desired, i.e., the amount of carbon they desired absorbed. The furnace is closed and allowed to cool slowly, which requires another seven or more days. Upon unpacking the furnace the bars are found to be brittle and of a steely fracture instead of the soft malleable material which was put in. They have become high carbon steel. Expert workmen are able to judge very closely the hardness of the steel by looking at the fracture and they sort the bars in this way, piling bars of similar hardness together. Bars thus made show many blisters on the surface and the steel became known as 'blister steel' on this account." (Spring 1917, 116-117). See blister steel and cementation furnace.

Cementite: The most common iron carbide, Fe^3C; hard and brittle; the carbon content of cementite is all in the chemically combined form, with no free graphite flakes. The carbon content of pure cementite usually is 3.25%. (Spring 1917) Often fully dissolved in austenite with proper heat treatment, otherwise partially dissolved in steel and iron in various particle sizes and patterns, giving mechanical properties to steel and iron products (strength, hardness, brittleness, etc). "Iron carbide (Fe^3C) in the microstructure of steel and cast iron." (Gordon 1996, 308) As carbon steel, cementite forms directly from the melt in the case of white cast iron. As a component of carbon steel, it either forms from austenite during cooling or from martensite during tempering. It mixes with ferrite, the other product of austenite, to form lamellar structures called pearlite and bainite. Uniformly dispersed particles of cementite are an essential component of martensite; the uniform homogeneous distribution of cementite differentiates cast steel from other forms of steel, such as blister and natural steel, which are characterized by a more heterogeneous distribution of cementite. See austenite, white cast iron and pearlite.

Chafery: A forge for the further reworking of anconies of wrought or malleable iron by re-tempering, reshaping, or slitting the metal into forms compatible with the production of specific tools and iron products, e.g. nails, rolled sheet iron, wrought iron hardware, and malleable iron agricultural tools. See bloomery, muck bar, direct process and indirect process.

Chalybean steel or **Chalibean steel**: High nickel steel smelted from the self-fluxing iron sands of the Black Sea c. 1900 BC, at the height of the Bronze Age; often mistaken for meteorite-derived steel (Piaskowski 1982); described in Greek literature by Aeschylus and Strabo.

Charcoal: The principal fuel used to make wrought iron and cast iron from the early Iron Age until the mid 18th century when coke became available as a blast furnace fuel in England. Charcoal continued as the main source of fuel in heavily wooded environments, such as the US and Sweden, for a century or longer than in forest-depleted England. The very low sulfur content of charcoal iron made it ideal for edge tool production, in contrast to coke and coal fired blast furnace iron, which was high in sulfur and ash. Swedish charcoal iron, also low in phosphorous, was the key ingredient for blister steel production used in converting furnaces by Sheffield crucible steel manufacturers prior to the final smelting of cast steel, Swedish charcoal iron was also imported in large quantities to New Bedford (and many other U.S. ports) from 1816-1830 and later, presumably for use by New Bedford whale crafters and edge tool makers (Lytle, 1984). Charcoal wrought iron was produced by American direct process bloomeries for the Pittsburgh crucible steel industry from its inception in 1860 until the end of the 19th century.

Charcoal hearth iron: Iron produced using charcoal as a fuel; also called charcoaled wrought iron.

Charcoal iron: A highly refined variation of iron made by alternating layers of pig iron and charcoal in a reverbatory furnace. After being partially melted, most of the silicon and part of the phosphorus was eliminated, and, after solidification the mass of iron was broken up and reheated in a second furnace with alternate layers of charcoal, which removed most of the remaining carbon, but some slag remained entrained within the bloom. Charcoal iron produced by this method contained a higher carbon content than wrought iron but contained less slag, most of which was in the form of iron oxide. Charcoal iron is thus a form of malleable iron containing 1% or less of silicon slag content and is more ductile than wrought iron, especially in the direction opposite to its fibrous slag layers. It is not known whether high quality Swedish bar iron produced in the late 18^{th} and 19^{th} centuries may have been refined by this alternative method of iron production. (Aston 1939)

Chasing: The sinking of ornamental designs onto the surface of malleable sheet metals by the use of the jewelers' hammer and cast steel chasing tools, resulting in the formation of grooves, indentations and furrows in the metal surface; used especially in jewelry design and manufacture. See repoussé.

Chemistry of carburization: The absorption of carbon by steel from carbon monoxide, which is formed by the reaction of the oxygen in the enclosed environment of, for example, the cementation furnace, with the carbonaceous material inserted with the iron bar stock. Iron carbide (cementite) and carbon dioxide are the resultant products. The carbon dioxide is reconverted to carbon monoxide by reacting with more carbon to extend the cycle of carbide formation.

$3Fe + 2CO = Fe_2C + CO_2$

$CO_2 + C = 2CO$

Chill: The use of metal within mold cavities to facilitate rapid cooling, producing castings with hard surfaces but soft interiors.

Chilled cast iron: Cast iron that retains carbon in its chemically combined form if insufficient cooling time is allowed for the precipitation of graphite flakes, as occurs when the iron is cooled rapidly in iron molds rather than slowly in sand molds. "Cast iron with a low silicon content cooled rapidly enough to form cementite rather than graphite in its microstructure. Molders placed chills in molds to get white iron at places in a casting where extra hardness was desired, as on the rim of a railroad-car wheel." (Gordon 1996, 308). The characteristics of chilled cast iron are a function of the thickness of the chill (iron mold) and the carbon, silicon, sulfur, and other alloy content of the molten cast iron. See white cast iron, free graphite, and combined carbon.

Chinese steel: The Chinese had multiple methods of making steel, including: immersing bars of wrought iron in a crucible containing melted cast iron (similar to Brescian steel production); making steel from ". . . charcoal refining of pig iron, probably a process not dissimilar to the Styrian process 1500 years later," (Barraclough 1984A, 29-33); and malleableizing white cast iron and steeling the edges of woodworking tools made from the cast. Barraclough (1984A) describes an adze c. 500 BC, "The fascinating feature of this implement is that the cutting edge has been sufficiently decarburized to produce a steel-like structure; this is quite uniform and would appear to be intentional . . . The methods of "malleableizing" cast iron castings were obviously well understood at this period since agricultural implements cast to shape and then fully malleableized were fairly widespread during the Menchius era of the 4th century BC . . . this was the process rediscovered by Réaumur some 2000 years later; in China it had gone out of use in about the 7th century AD, after 1000 years of use." Barraclough also notes several modifications to the Brescian style co-fusion process, including a solid diffusion method whereby coils of wrought iron were entwined with insertions of cast iron to produce lump or raw steel. See Needham (1958), malleable cast iron, white cast iron, and Brescian steel.

Chloanthite: A nickel arsenide compound composed of iron, nickel, cobalt, arsenic, and sulfur added to the iron sand smelting process to produce the famed nickel steel made by the Chalybean's of northern Anatolia, c. 1900 BC, a process noted by Aeschylus and Strabo. See Amisenian, Chalybean, Iron sand smelting processes. (Wertime 1980, Piaskowski 1982)

Chrome steel: A high grade alloy tool steel produced by the electric arc process and used for applications requiring great hardness such as ball bearings. Variations include chrome vanadium steel used in automobile frame production and nickel chromium steel used for automobile gears, axles, armor plates, projectiles, and airplane parts. See alloy steels and alloy.

Cire Perdu: The lost wax method of making castings by using wax to make a pattern of the object being cast. After being set in plaster, the wax is melted out of the mold; the resulting mold often has great detail. This method was used for casting bronze objects in antiquity and has been recently revived by contemporary artists. See pattern, core, and drag.

Clay ironstone: A common form of iron ore, and the principal form of iron ore in the Weald (Sussex), England's most important iron producing region of the 16th century. It occurred in the form of siderite as a hard gray rock within the clays, silts, and sandstones of the Wealdean beds. This ironstone contained magnesium carbonate ($MgCO^3$) and manganese carbonate ($MnCO^3$), which, as with the manganese in the Austrian ores of Noricum, played an important role as a flux, enhancing carbon uptake in the production of raw steel (Cleere 1985). See natural steel, Weald, and manganese.

Cleavage plane: The smooth fracture occurring parallel to one or more crystallographic planes. See deformation and lattice structure.

Close-packed hexagonal structure: The lattice structure characteristic of metals that lack plasticity or lose plasticity during cold forming, including antimony, beryllium, cadmium, cobalt, magnesium, titanium, and zinc. (Shrager, 1949). See body centered cubic unit, and face centered cubic unit.

Coal: Coal is a mineral fuel with two common forms: bituminous - with a long flame and containing 70 - 90% carbon; or anthracite - with a short flame, but containing 90-95% carbon. Coal was used as fuel in blast and reverbatory (puddling) furnaces, but was unsuitable for bloomery and finery furnaces due to high sulfur content (+/- 2.0%).

Coalbrookdale: An important 17th and 18th century iron producing center located on the headwaters of the Severn River, in the Midlands of England, just west of Birmingham, Coalbrookdale was the location of Abraham Darby's first coke-fired blast furnace and also the location of the famous Ironbridge. It may also have been the site of one of England's first cementation furnaces, constructed by Sir Basil Brooke, 1636(?). (Barraclough 1984a)

Co-fusion: A variation of the Brescian process for producing steel whereby wrought iron was dissolved in molten cast iron. One of the most ancient steel producing technologies; a variant of crucible steel production of Merv (Turkmenistan +/- 500 AD) in India and Asia. Later patented in England by Vickers (1839), with thousands of tons produced annually (Barraclough 1984). Similar combinations of ore were fired in the first Siemens-Martin open-hearth furnace (+/- 1870). See Brescian steel and Chinese steel.

Cogging: Hammering, rolling, or pressing a red hot tool steel ingot to convert it to a billet.

Coke: "Porous, cohesive carbon made by expelling the volatile constituents from bituminous coal." (Gordon 1996, 308). A product of the partial combustion of coal, usually in large brick ovens; coke was invented by Abraham Darby in England in 1709, and first produced commercially in 1735. Its use in blast furnaces resulted in the production of iron with a high sulfur content, requiring a calcium bearing flux (lime) for slag removal and well as higher firing temperatures. The availability of coke as a fuel stimulated the invention of the steam driven piston bellows, which was needed to provide a more powerful air blast for the smelting process. After 1785, the efficient use of coke stimulated production of larger quantities of higher quality cast iron for reprocessing as wrought and malleable iron in the newly invented reverbatory puddling furnaces. See reverbatory furnace and puddling furnace.

Cold blast/hot blast: The switch from using a cold air blast to a hot air blast after Nielson's 1828 innovation of using waste gases to preheat the blast greatly increased the efficiency of 19th century English, American, and European blast furnaces.

Cold drawing: The reshaping of iron or steel bar stock by drawing it through dies, resulting in its permanent deformation.

Cold forging: The ancient tradition of hammering cold, malleable iron into tools and armor. Bloomery smelted charcoal iron with slag impurities, especially silicon, lent itself to toolmaking because it welds easily, does not split, and is malleable to mold with a hammer and anvil even at low temperatures. Modern low carbon steel made in blast furnaces with mineral fuel, gas, or electricity lacks the silicon inclusions that facilitated the creative cold hand forging of Swedish and American charcoal irons. (Bealer 1976a, 36)

Cold short: Wrought iron containing phosphorous, thus brittle if worked or hammered at room temperature.

Cold working: Rolling or forging steel at temperatures below 400° C to avoid re-crystallization; it increases strength and decreases ductility and toughness of steel. If high in phosphorus, cold worked wrought iron can reach a hardness as great as 300 HV, above that of non-heat treated carburized steel. (Shrager 1961). See phosphorous and carburizing.

Collier: The producer of charcoal for bloomeries, fineries, and charcoal-fired blast furnaces was the collier. (Also defined as a coal miner and a ship transporting coal.)

Combined carbon: Carbon chemically combined in iron and steel alloys and therefore not existing as free graphite flakes. As contained in rapidly cooled white cast iron, the transformation of combined carbon into free carbon is the key step in the successful production of malleable cast iron. See white cast iron and malleable cast iron.

Combustion gasses: Gasses produced in smelting and fining furnaces and forges that oxidize carbon and prevent carburization.

Compressive strength: The relative ability of a metal to avoid failure when pressed or squeezed.

Converting furnace: An airtight furnace, usually of a rectangular design, used to convert iron bar stock to blister steel after being packed in charcoal. The first converting furnace to make steel appeared in Nuremburg in 1607 (Barraclough 1984), in England in 1686, and in the United States by 1713. The converting furnace prevented contact between the fuel and the bar stock, allowing production of steel in larger quantities and of a more uniform quality than that made by fining cast iron lacking the manganese content of the ores used to make German steel. Synonymous with cementation furnace. See blister steel, cementation furnace, and cementation steel.

Cope: The top half of a foundry mold. See drag and pattern.

Copper alloys: The two most important copper alloys are brass (an alloy of copper and zinc) and bronze (an alloy of copper and tin); usually both contain small amounts of lead.

Coppice: The wood harvested from a wide variety of trees used to make charcoal. In England, small sized wood including branch tops with a diameter of 6 cm. or less (2.26 in.) were used to make charcoal; larger wood sizes produced friable charcoal that transport, or weight of the charge in the bloomery or blast furnace, would reduce to dust. The small diameter of the wood used to make charcoal meant that regenerative coppicing was able to renew charcoal sources on the estates of the landed gentry who supplied much of the furnace fuel in England before the age of coke (1709). See Weald and charcoal.

Core box: Wooden molds used to form sand cores, which replicate holes, cavities, and pockets in foundry castings. See pattern molding and foundry.

Core maker: Along with a patternmaker, the core maker designed and constructed the wooden molds used for foundry work. Sometimes, the core maker and the patternmaker were the same person; at larger foundries, these functions were often two separate trades.

Coring: The procedure for cutting the opening or the middle of an ax or adz for hafting.

Creep: A slow, impermanent deformation of material under steady force that is below the elastic limit of the material being deformed, occurring over a long period of time.

Critical cooling rate: The lowest rate of the cooling of austenite at which martensite will form; the critical cooling rate is dependant on the carbon content. If the cooling rate is lower than the critical cooling rate, pearlite will be formed instead of martensite. See austenite, martensite, and pearlite.

Critical point: The lowest temperature at which tool steel will harden when quenched, or at which changes in the crystalline structure of a metal will take place. See quenching and quenching threshold.

Crucible: A high temperature resistant earthenware vessel used for melting, fusing, or casting metals. Clay crucibles have been used since the early Iron Age for the smelting of small quantities of steel. The earliest documented use of crucibles for steel production would have been those used in Muslim communities to smelt Wootz steel; Sheffield cast steel was produced in small clay crucibles by Benjamin Huntsman beginning in 1742. During the height of Sheffield crucible cast steel production in the 19th century, cast steel was produced in rows of crucibles with a +/-50 kg capacity. The lack of high temperature resistant clays postponed cast steel production in the United States until the mid-19th century, when Joseph Dixon's invention of the graphite crucible provided an alternative to Stourbridge clays for crucible production. See crucible steel, Wootz steel, and Stourbridge clay.

Crucible furnace: A furnace composed of two firebrick boxes: the fire was in the lower box and the upper box held the crucibles. Used to manufacture cast steel for specialized purposes such as watch springs and edge tools. Other forms of crucible furnaces had only a single firebox (see crucible steel). Wasteful of heat and expensive to operate, they were made obsolete by the invention of the electric furnace. See cast steel.

Crucible steel: Steel created by melting together of pieces of blister or shear steel in a clay crucible containing carboniferous material. The resulting chemical reaction equalized the uniformity of carbon distribution. In the mid 19th century, crucible steel was also produced from a combination of puddled wrought iron and steel scrap. Easily rolled crucible steel was used for the manufacture of high quality edge tools, often advertised by edge toolmakers as "warranted cast steel." Made in and imported from England after 1742 (Benjamin Huntsman); not manufactured in the United States until about 1860. Spring (1917) makes the following observation: "For a century crucibles were made from clay molded to form, slowly dried and very carefully burned. Usually each steel maker made his own crucibles. They could be used but three times, becoming so thin and tender after use for three batches of steel that they were not safe for a fourth. Graphite crucibles are now very largely used. They withstand the severe heat much better and can be used five or six times. The expense item for either clay or graphite crucibles is a large one. After filling with small pieces of blister or shear steel the crucibles are entirely surrounded by coal or coke in the furnace pit. The fire is so regulated that the steel is not too quickly melted. Fresh coal or coke must be put in around the crucibles two or even three times. When he thinks the steel should be molten, the expert attendant known as the 'melter' quickly removes the tight fitting cover of the crucible and with an iron rod determines whether any un-melted pieces remain. After complete melting the steel must be 'killed,' else it will boil up in the mold upon pouring and leave a spongy or insufficiently solid 'ingot' or block of steel. This 'killing' of steel is a rather peculiar phenomenon. It is accomplished by allowing the steel to remain quiet in the furnace for another half hour or so. Undoubtedly the quieting is the result of the escape of the gases or impurities which are contained in the charge, and absorption of the chemical element, silicon, from the walls of the crucible. ...When the steel has been properly melted and killed it is ready to pour. An assistant lifts the cover from the melting hole, the 'puller out' seizes the crucible just below the bulge with circular tongs and pulls it from the coke which surrounds it. The slag is skimmed off the top and the steel poured into iron molds forming small 'ingots,' usually from 2 to 4 inches square and two feet or more long. Every part of the process, even the pouring, must be done with extreme skill and care or the product suffers. After liberation from their molds, the ingots are heated and either rolled or hammered down to the sizes desired for tools, etc." (Spring 1917, 118-120). Not to be confused with the "cast steel" ingots of the Bessemer process. See cast steel definitions 1 and 2.

Crystal: A geometric structure with a homogeneous distribution of atoms in patterns characteristic of the specific elements or compounds in that structure.

Crystallography of ferrous metals: The study of the variations in the space lattice formations (cubic structure) of iron, which result after various thermal and mechanical treatments. See lattice structure and space lattice.

Cubic structure: The space lattice forms of unit cells within the crystalline structure of metals. In ferrous metallurgy, two forms of cubic structure characterize iron, the FCC (face centered cubic) and the BCC (body centered cubic). A third form of cubic space lattice is the close-packed hexagonal (CPH), characteristic of such non-ferrous metals as cobalt, magnesium, and titanium. Metals in this latter group lack plasticity. (Shrager 1949, 5-6). See space lattice and unit cell.

Cupola furnace: A 19th century form of a blast furnace used for re-melting cast iron in foundries; a simple, fuel efficient shaft furnace usually using coke as a fuel and, along with the air furnace, one of the principal means for melting cast iron for foundries. The iron is melted in contact with the fuel; only gray cast iron is produced in the Cupola furnace. Instead of the stone pyramid form of the traditional blast furnace, cupola furnaces are constructed of sheet iron shells culminating in a narrow top with adjacent elevators and a bridge to bring fuel and ore to the top of the furnace. See blast furnace, blast, cast iron, and foundry.

Currency bar: The primary form of iron as a trade item in the early Iron Age, later replaced by iron bar stock after the invention of rolling equipment in the 17th Century. A currency bar is a bloom of wrought iron, malleable iron, low carbon steel, or raw steel derived from a direct-process smelting furnace. A blacksmith would take this bloom, often of heterogeneous carbon content, hammer it to expel the slag, and form bars of iron or raw steel of various shapes and sizes, usually with handled ends, for easy transport from smelting sites such as those in Austria to iron working and sword making centers such as those on the lower Rhine. Metallographic analysis indicates these bars had a widely varying carbon content ranging from wrought iron to raw steel. Currency bars were traded throughout Europe beginning in the early Iron Age. See bloomery and natural steel.

Damask: An etched pattern; when present on the surface of Merovingian pattern welded swords, the damask expresses the crystalline structure of the pattern welded iron and steel in the sword. See damascened steel.

Damascus Blade: Persian, Indian, and Indo-Persian swords, daggers, and scimitars, examples of which survive from the 16th to the 19th century and are characterized by a diversity of patterns based on alternating layers of high and low carbon steel, but dissimilar to the traditional pattern-welded Merovingian sword. Damascus blades were made out of Wootz steel; Cyril Smith (1960) has the following comment, "Attempts to duplicate Wootz and watered steels generally led to James Stodart's work in France early in the nineteenth century, most of which was based on the erroneous belief that the texture arose from forging. Many workers described the production of fancy surface patterns by welding, twisting, and forging together variously shaped pieces of iron and steel. The results were both decoratively and mechanically inferior to the Oriental product and, in fact, were merely a return to sword-making of a technique descendent from that of the Merovingian smiths which had meanwhile been extensively used in the Near East and India for making so-called ‘Damascus’ gun barrels, which had nothing but name in common with the sword." See Wootz steel.

Damascened steel: The treatment of a pattern-welded iron and steel sword by a reagent for the purpose of disclosing the crystalline pattern of the microstructure of the sword, which results from the forge-welding of the iron and steel and is dependent upon the unique combination of iron and steel constituents and the lattice structure of the material being forged. In the case of Japanese swords, makers can often be identified by their characteristic patterns, which appear after treatment with the acid reagent and express their forge-welding techniques. In the 18th and 19th centuries, Englishmen collected damascened gun barrels, the patterns of which illustrated the artful forging technique of the gunsmith. Damascened steel is not the same as Damascus steel; see Cyril Smith (1960) for his commentary on damascened versus Damascus steel.

Damascus steel: A specialized form of crucible steel made for producing pattern-welded wrought iron and steel sword blades. Made in India (Wootz steel), Asia (Asian crucible steel), and probably in Damascus, usually in very small batches of 2-3 kilograms per firing. Possibly one of the earliest forms of steel; as Wootz steel, it was known in Europe after 1500, but was not widely utilized due to the difficulty of reaching a temperature sufficient to relieve its hard, brittle crystalline structure by reforging. See Wootz steel, Stourbridge clay, Moxon, Damascus blade, and cast steel definition 1.

Decarburization: The removal of carbon from cast iron during fining or puddling by oxidation, or from steel during heat treatment, the latter of which produces surface decarburization. Decarburization occurs either directly in an oxidizing atmosphere or indirectly with iron oxide as an intermediary, producing carbon monoxide or carbon dioxide gas. "Loss of carbon from the surface of heated steel. Decarburization prevents steel from being properly hardened." (Gordon 1996). The decarburization of cast iron to produce steel was the principle steel making strategy of the Renaissance and was not replaced by the alternative method of carburizing wrought iron to make blister steel until after 1690, and then primarily in England. See German steel, blister steel, and puddling furnace.

Decalescence point: The lowest temperature at which a change of structure occurs in steel (1330° F), at which time the body-centered cubic unit cell changes to a face-centered cubic unit cell, accompanied by the absorption of heat.

Deformation bands: The creation of new grain boundaries that result from the rotation of the lattice structure of metals during slip events, as with cold worked metals. See creep and lattice structure.

Dendrites: The branching forms characteristic of crystal growth patterns in metallurgy. See crystallography of ferrous metal.

Deoxidizing: The removal of oxygen by the addition of elements with a high oxygen affinity, e.g. carbonaceous materials, as in crucible steel production, to suppress formation of gas porosity during the solidification of the liquid steel.

Deoxidizing alloys: Alloys used to remove oxygen or oxides from metals being smelted.

Depth of case: The depth of hardness penetration sought or achieved during the case hardening of steel tools. See case hardening and case carburization.

Diderot's encyclopedia: ([1751-75] 1959). A widely circulated multi-volume encyclopedia illustrating important French trades such as carriage making. The Diderot encyclopedia is particularly detailed in its depiction of the blast furnace, anchor and cannon forging, the casting of statutes, the mining and smelting of metals, and the manufacture of ornamental iron work, which was a specialty of the French. The encyclopedia provides vivid pictorial evidence of the longevity as well as the continental European origins of many of the tools that reappear in New England workshops from the colonial period to the mid-19th century including the leg vise, anvil, and other related tools that would have been used by toolmakers making their own hand tools. First published in the 18th century, the encyclopedia is currently available in multiple reprinted versions. See leg vise and pattern books.

Die casting: The shaping of molten metal by the use of external pressure, as in drop-forging.

Die driving: The hammering, heating, and tempering of dies prior to final casting, drop forging, or embossing of die-struck patterns or models. During hardening and tempering, all dies must be shielded from the oxidizing effects of the fire by charcoal or a sheet iron cover.

Die sinking: The creation of a drop-forged die by taking a pair of forged crucible blanks, annealing them for softening, and shaping them by filing, chipping, and machining (boring, slotting, and milling). The machining of the exactly matched die patterns provides a surface that can be finished by polishing and further machining of the edges. The matched dies are re-dropped (reheated for tempering), pickled to remove scale, and annealed again at low temperatures before being surface hardened for the fluid die-casting of drop-forged tools and other artifacts. During the die sinking or shaping phase, dies are often inserted into cast iron die holders. The best die steel alloy, superior to carbon steel, was vanadium steel (Woodworth 1911). Occasionally, especially in the 19th century, cast iron dies were used for some forgings. Die sinking is the art of creating the patterns for drop-forged tools, which are hammered or hydraulically forged out of hot carbon steel, tempered, annealed, and sometimes subjected to additional mechanical and thermal treatments, including re-tempering to restore hardness. See die driving, drop-forging, and drop press.

Die sinking machine: The machine that replaced the hand work of the die sinker and enhanced production uniformity of interchangeable dies.

Direct conversion method: Invented by William Vickers in Sheffield in 1839, this method allowed the direct conversion of Swedish charcoaled bar and pig iron, in combination with quantities of scrap iron, into crucible steel without the use of the converting furnace. See blister steel. By 1880, most use of converting furnaces to produce blister steel had ended.

Direct process: The single stage production of wrought and malleable iron from iron ore in bowl and low shaft bloomery furnaces; also an appropriate description for the single stage production of hot forged natural steel edge tools by a blacksmith directly from the bloom, rather than from iron bar stock. Direct process iron is often high in slag. See bloomery, wrought iron, malleable iron, and blast furnace.

Displacement: Displacement is the slip or creep of the crystal lattice structure of metals during their plastic deformation. See slip, creep, plastic deformation, and lattice structure.

Double-acting steam engines: Designed and produced in and after 1783, Isaac Watts double-acting steam engines represented a major improvement in the efficiency of his first steam engines, which became widely used in the English textile industry after 1775.

Double-process quenching and tempering: A modern, more complicated form of heat treatment associated with relatively easy to melt high carbon steels.

Dozzle: The clay cone invented by R.F. Mushet in 1861, to contain a reserve of liquid steel to alleviate the pipe in crucible steel ingots; the dozzle was inserted into the top of the ingot near the end of the pour (Gordon 1996). See pipe, crucible steel, and cast steel.

Drag: The bottom half of a foundry mold. See cope and pattern.

Drawing furnace: A furnace used for tempering axes after hardening; typically an ax is heated to the color "pigeon blue"; rapid cooling fixes the temper of the ax (Kaufman 1972). See tempering.

Drawing temper: The heating of hardened steel to a specific temperature followed by its quenching to obtain a lesser degree of hardness.

Draw plate: "A plate of hardened steel, furnished with a series of tapered holes of gradually diminishing diameters through which metals are drawn out into wires." (Audel 1942, 200)

Drop-forging: The use of top and bottom dies to hammer a heated bar into the shape of a die sunk pattern. Hydraulic forging performs the same function by pressing heated metal into die sunk patterns. See die sinking and die driving.

Drop press: A machine for punching, shaping or embossing metals; originally hand or foot operated utilizing a vertically guided weight; later water or steam powered; the fundamental machine used for drop-forging tools. The most modern form of the drop press is the hydraulic press. See drop-forging, die sinking, and die driving.

Dross: During the oxidation process, as in the reduction of iron ore in the blast furnace, dross is the slag-like, metallic oxides that rise to the surface of the bath.

Dry puddling: The direct production of wrought iron by the conversion of white pig iron in a Reverbatory furnace; conversion of gray cast iron to puddled wrought iron required preliminary refining due to its free carbon and low silicon content. See puddling furnace and wrought iron.

Dry sand molding: Casting with a flask and a baked sand pattern, facilitating moisture removal and providing a hard clean surface for detailed casts. See cope, drag, and pattern.

Dubbing: The shaping and smoothing of frames and timbers with an adz during the construction of a wooden ship.

Ductility: The capacity to permanently deform without fracture when cold worked.

Dunnage: Iron fragments, scrap, and faggots used as a shim, as well as ballast, in the bottom of a wooden ship to raise the cargo above the bilge water level to prevent damage.

Early steel: Typically natural steel produced in ancient and medieval times directly from the bloom; the carbon iron microstructure of early steel always contains elongated or fragmented silicon slag inclusions. See natural steel, bloomery, and Catalan forge.

Edge carburization: An alternative process for the carburization of iron, used by early steel makers; an iron tool would be enclosed by clay or another protective covering and submerged in a charcoal fire to allow diffusion of carbon to steel the cutting edge of the tool. See case hardening and enclosure.

Edge tool forging: The heating (austenizing) of iron ore into steel prior to rapid quenching, which creates martensite – iron with homogenous carbon distribution – which is then tempered to relieve brittleness and shaped by hammering into appropriate forms. Properties of edge tools can vary widely depending on carbon content, carbon distribution patterns, quenching and tempering time, thermal and mechanical treatments, alloy content (if any), and slag and other inclusions. The key to successful edge tool production is the rapid quench, which forms martensite instead of pearlite, the latter of which is formed by slow cooling. The second key is tempering of the steel tool over a longer time and at a much lower temperature (+/- 600º C) to disperse the fine particles of cementite in the martensite, which serves to soften it and increase its ductility. The silicon content and its function as a softening agent, enhancing the ductility of the steel being forged, is the third but undocumented factor in successful edge tool production. Edge tools of a more inferior quality could also be made by forge-welding unquenched, slowly cooled austenite, the traditional method of most edge tool production before 1750.

Edge tools: Hand tools used by woodworkers to cut and shape wood, especially chisels, gouges, slicks, adzes, and axes; also plane blades, knives, and swords.

Elastic deformation: Less than permanent deformation, which is remedied by the removal of the stress or load causing the initial deformation.

Elastic limit: The point at which a metal becomes permanently deformed under stress; also defined as yield strength.

Electric arc furnace: One of the two most important 20th century steel producing strategies, made possible by the electric power grid and, originally, by hydro-electric power sources. Its special advantage is that in the production of high grade tool steels, the oxidation of alloys such as chromium or nickel, are avoided. The great majority of the hundreds of varieties of useful high grade alloy tool steels produced in the 20th century were manufactured in this furnace. Its use was significant for edge toolmakers because the steel produced in the electric arc furnace gradually replaced the crucible steel production process after 1900. By 1940, the disappearance of both the puddled iron process and the crucible steel process seems to coincide with the diminishing quality of edge tools. It can be built in any size and utilize scrap iron and steel efficiently. The first electric arc furnace was constructed by Sir Charles William Siemens in 1878, but was used for melting only; the first smelting of iron ore occurred in 1898. It is also called a low frequency induction furnace; in 1927, the first high frequency electric furnace was constructed. The uniformity and the high quality of alloy steels produced in the electric furnace is illustrated in the wide variety of sophisticated products of an atomic age, which concurrently lost the ability to mass produce high quality edge tools. See Brescian process and Siemens-Martin process.

Electro fusion:

Elongation: The permanent extension of a metal by a mechanical process, such as rolling. See deformation bands.

Embossing: Ornamental designs executed by stamping or hammering on the reverse side of a metal to form a relief. See chasing.

Embossing sequence: The original pattern of the embossing sequence, e.g. a medallion, is plaster or wax cast; a model casting of the pattern, made of cast iron, is driven into the die to form a die-sunk casting and is then followed by the casting of the original pattern. See die casting and die scaling.

Enclosure: The ancient practice of protecting forged iron tools being carburized from the oxidizing influence of combustion gasses by covering the iron with a layer of organic materials (pig fat, goat skins, clay, etc.) For the production of sheet steel from sheet iron the layer of charcoal served as the enclosure; for the production of Brescian steel, the liquid cast iron provided enclosure. Various methods of case hardening necessitate strategies of closure, i.e. the production of blister steel is based on the enclosure of iron bar stock in the protective layers of the sandstone converting furnace. See case hardening, carburization, and cementation furnace.

Energizers: The carbonates of calcium, barium, and sodium in commercial carburizing compounds, which hasten case hardening and steel cementation. In early cementation furnaces, naturally occurring energizers in charcoal dust, bone, skins, and hide inserted between iron bar stock facilitated carburization. See case hardening and carburization.

Engine: A compound machine that uses any power source (water, heat, electricity) to do work. See prime mover.

Eoliths: The first tools used by humans, eoliths were un-hafted, un-knapped, found stones.

Erzberg: The name of the ore mountain in the Styrian section of Austria that was an important source of manganese laced siderite iron ores used from the early Iron Age to the early modern period. The manganese content of these ores facilitated production of natural steel in early shaft furnaces, which was then traded throughout central Europe as currency bars. See natural steel, Noricum, Styrian steel, iron road, and currency bars.

Etching: The application of a reagent to the polished surfaces of metals for the purpose of revealing their structures.

Eutectic: The minimum melting temperature of an alloy, i.e. the temperature where the crystalline becomes molten and the molten becomes crystalline, but always involving a mixture of two or more components. In ferrous metallurgy, the most important eutectic point is the melting temperature of austenite at 723º C. Steel and cast iron are mixtures of austenite and cementite, which if cooled below this temperature become mixtures of ferrite and cementite. If, however, austenite is suddenly cooled in water from a red heat, martensite, steel with uniform carbon content, is produced. Hard and brittle, martensite is softened and made more ductile by tempering, which causes the dispersion of fine particles of cementite within the austenite.

Another definition of eutectic with respect to cast iron is: "a thermodynamic equilibrium of two different solid phases with a liquid solution, e.g. an iron carbon mix with 4.3% carbon content (the eutectic composition) at 1150º C (the eutectic temperature) where liquid iron carbon is in equilibrium with austenite and cementite." (Wayman 2000). See ice cream, austenite, cementite, and carbon content.

Eutectic point: The minimum melting temperature of an alloy.

Eutectoid: The thermodynamic point equivalent to a eutectic point but with all three phases solid, i.e. one solid solution and two solid phases as in the iron/carbon system at 723º C (the eutectoid temperature) and 0.8% carbon (the eutectoid composition) where austenite is in equilibrium with ferrite and cementite (Wayman 2000). Tool steels with a carbon content of 0.6% or greater are examples of solid compositions, which have undergone a eutectoid transformation, also called the martensitic transformation. In the eutectoid transformation, austenite produces ferrite and cementite (iron carbide), which often exhibit lamellar structures, including bainite and pearlite. See lamellar and eutectic.

Eutectoid steel: Steel that contains 0.83% carbon is known as eutectoid steel, i.e. austenite (Shrager 1949). See hypereutectoid steel.

Eyepin: An insert used as the core about which two pieces of mild steel are wrapped in ax making. A high carbon steel insert is then welded into the fold to form a steel ax. In 19th century ax making factories, the eyepin was held by the hands of the grinder during finishing of the ax prior to the introduction of automatic grinding machines. "No axe grinder ever died from old age." (Kaufman, 1970). See ax making.

Face centered cubic structure (FCC): The location of atoms in a crystal structure at the corners and in the middle of a cubic cell, as in austenized steel. At a temperature of 723° C, the body lattice structure of iron (BCC) begins deforming into the face centered cubic structure; the change is completed at 910° C/1670° F, when the lattice structure of the iron becomes a face centered lattice structure. Upon further heating, the FCC structure (gamma iron) reverts to the BCC lattice structure (alpha iron) at a temperature of 2552° F/1400° C. See lattice structure, space lattice, and cubic units.

Facings: Graphite, sea coal, or other material applied to or mixed with the sand mold into which a metal is to be poured, to provide a smooth surface for the casting. For steel castings, silica flour mixed with molasses water was used c. 1910.

Faggoting: The bundling of iron rods, or the rolling of puddled iron and steel plates into bar stock, prior to further heat treatment and/or forge welding. See piling and billet.

Fatigue: The progressive loss of resistance of a metal to fracture, usually occurring at ordinary temperatures, due to the application of force on a flaw that forms a crack that spreads under repeated stress. See plastic deformation and lattice structure.

Fayalite: That component of the iron ore in a bloomery sacrificed as fluid slag before the role of lime as a flux was known. See acid process, basic steelmaking process, flux, and slag.

Feeders and risers: Fittings utilized during the solidification of cast metals in foundry work to offset shrinkage by allowing the addition of molten metals during the casting process. See shrinkage rules.

Female die: The lower die used in press working of jewelry, silverware, and toolmaking; also known as embossing dies. See die sinker.

Ferrite: The solid solution of carbon in iron up to 0.03%, stable below 910º C, as in wrought iron. "Low-temperature form of pure iron." (Gordon 1996). Ferrite contains trace amounts of iron silicide (FeSi) and iron phosphide (Fe^3P) and is strongly magnetic, soft, ductile, and has a tensile strength of between 40 and 50 psi and a Brinell hardness of +/- 80. See cementite, austenite, and wrought iron.

Ferritic cast iron: A cast iron characterized by a ferrite matrix embedded with tempered carbon particles.

Ferromanganese: An alloy of iron and manganese containing 80% manganese, 12% iron, 6.5% carbon, and 1.5% silicon, which is added to the steel during the smelting process to increase its carbon and manganese content. Ferromanganese played a key role in upgrading the strength and durability of Bessemer's bulk process low carbon steel to make it suitable for uses such as steel rails. Ferromanganese also serves as a deoxidizer. See Bessemer process, low carbon steel, and manganese.

Ferrosilicate: A siliceous (silicon bearing) flux formed from unreduced ferrous oxide and fusible silicate slag that occurs in bloomery furnaces during smelting. Ferrosilicate encourages oxidation of carbon at the end of the heat in early furnaces and thus assisted in the production of wrought iron, preventing carbon uptake that would create unwanted liquid cast iron. (Schubert 1957, Wertime 1962, 45)

Ferrous materials: Iron and iron alloy combinations within the iron carbon system.

Fettling: The millscale (iron oxide) used to line a puddling furnace.

File making: After "strings" of steel were cut and cropped into "moods," file steel was forged into triangular or half-round blanks, then softened before surface scale was removed by filing. Cutting of the file edge with hammer and chisel was followed by hardening by quenching, then cleaning and oiling. File making is thus anomalous in that softening preceded hardening (Dane 1973).

Fin: The surplus iron or steel at the parting line of a two piece die from any forging, later trimmed off.

Fine grain: The uniform pattern of grain distribution in the lattice structure of iron-carbon alloys resulting from simultaneous crystallization of the lattice structure nuclei, in contrast to random crystallization, which produces more deformed and irregular crystalline structures.

Finery: A facility used for the decarburizing of pig iron to produce wrought iron using charcoal fuel; also the hearth used to further refine bloomery wrought iron. Products of the finery were often sent to a chafery for further thermal and mechanical treatment including shaping into bar stock. Finery produced iron bar stock was an important cargo in the coasting trade and was the main source of iron for blacksmiths and small foundries for the manufacturing of hand tools. Common before 1830, then gradually replaced by the puddling furnace. See bloomery, wrought iron, and malleable iron.

Fining: The process of purification by removal of contaminants, as in a fining furnace.

Fining hearth: Walloon and other open-hearth style furnaces used to decarburize cast iron into wrought and malleable iron; an increase in the fuel to ore ratio was sometimes used to produce malleable iron or raw steel instead of wrought iron, i.e. the decarburization of the cast iron was halted before all the carbon was eliminated from the pig iron being refined. In many cases the iron being produced was malleable iron 0.08 – 0.2% cc, or a malleable iron with a higher carbon content, equivalent to that in modern (1870) low carbon steel (0.2 – 0.5% cc). Finery iron differed from modern low carbon steel, however, by having a variable siliceous slag content, hence the term malleable iron. See cast steel definition 2 and malleable iron.

Fire arms: A mechanical device that ejects a missile by the explosion of gun powder. The largest firearms were cannons made from bronze and later cast iron; smaller firearms such as the Arquebus and the flintlock were usually made of soft, folded, and welded sheet wrought iron.

Flange iron: Soft, ductile wrought iron used in applications subject to heavy stress.

Flash: The waste metal that remains on drop-forged tools after steam hammering.

Flask: A foundry molding box consisting of the cope (top) and drag (bottom), often with a core as part of the pattern, into which sand is rammed and packed.

Flintlock: Originally of Spanish or Dutch origin, the flintlock, much easier to fire than the matchlock, was developed in the 1620s and was the dominant form of firearms from the reign of William III (1650) until 1840 (Greener 1910). See matchlock, Arquebus, wheellock, gun barrel iron, and gunsmithing.

Flow termination: The termination of plastic deformation in the crystalline structure of metals that results from either brittle cleavage or ductile fracture.

Flux: An additive in the smelting process, e.g. lime, which has the purpose of taking up and absorbing the melted impurities in the iron ore, creating slag. The slag is then drained off separately from the molten ore produced by the blast furnace, usually through an opening above the container of the molten iron. Clamshells were the flux of choice in the bog iron forges and blast furnaces of southeastern Massachusetts.

Forest of Dean: An area just north of Bristol and the River Severn on the west coast of England where low phosphorus brown hematite iron ore of nearly equal quality to Swedish ores was smelted in the 16th and early 17th century, before being depleted. Along with iron smelted from ores located to the east in the Weald of Sussex, iron produced in the Forest of Dean may have played an important role in the manufacturing of tools for the early colonial settlements in North America before the manufacture of blister steel became widespread (1700). The first blast furnaces in England, larger than those in the Weald, may have been located in the Forest of Dean.

Forge train: "The set of heavy rolls between which the shingle bloom of puddled iron is rolled into puddled bar (muck bar). The rolls are grooved in a diminishing series so as to reduce the bloom to a manageable bar, and are made reversing if two high, or non-reversing if three high. (Audel 1942, 246)

Forge welding: The bonding of pieces of steel or iron by hammering at high temperatures, often in the presence of flux. See steeling.

Forging: The shaping of steel and iron into various forms by hot working, including hammering, rolling, slitting, and bending. Until the early 19th century, forge welding was the primary means of shaping iron and steel tools; after 1837, the shaping or hot working of steel and iron was often done by machinery, which forced hot metal into dies. The patterns cut into the dies formed the tools being shaped. See drop forging, die sinking, steeling.

Forging mill: A facility for producing finished steel by hammering and rolling. These mills were particularly efficient when run by a water powered hammer, which had even strokes and more controllability than early steam powered hammers, i.e. before the invention of reciprocating steam engines with double acting pistons and smooth even strokes. See trip hammer.

Foundry: A workshop or factory for casting metals including gray cast iron, malleable cast iron, blister steel, crucible steel, and nonferrous metals into cannons, hollowware, tools, hardware, and other equipment. Sometimes the foundry was attached directly to a blast furnace; thus no re-melting of the metals was required. Foundries were often associated with cupola furnaces.

Fracture: Fracture is the characteristic crystalline pattern (grain) exhibited after deliberately induced cleavage exposed the internal (micro) structure of the steel being smelted. The appearance of a fracture of blister steel was the key to determining its carbon content. During the conversion of bar iron to blister steel in the converting furnace, "sap" appeared to signify ongoing changes in the crystalline structure in the bar iron ("a rim of fine crystals around an unaltered coarse central structure") (Day 1991, 270). During the converting process, the sap, indicating low carbon malleable iron, was gradually changed into a fine crystalline pattern and the percentage of the sap in the fracture became lower. According to the Sheffield classification of blister steel, the sap entirely disappeared in steel having a carbon content of 1.15% and was replaced by a pattern of fine crystals signifying fully austenized steel. At a carbon content of 1.4 and above, coarse crystals began appearing, signaling increased cementite content (Barrett 1943, 321). A fracture by brittle cleavage produces a flat, smooth surface, a shearing fracture produces a "rougher surface, usually slightly inclined to the slip plane… when this type of fracture brings ductile elongation to an end, it is found that the fracture occurs at a definite value of the resolved shear stress along the slip plane (Barrett 1943, 321). See Sheffield classification of blister steel, grain, cleavage, crystalline structure, and sap.

Free oxygen: One of the hazards for a foundry master; in a furnace, free oxygen will cause iron to burn, slag protects the molten iron from oxidation.

Freezing point of iron: The freezing (or melting) point of iron is dependent on its carbon content (cc); pure iron freezes and melts at 1535° C. As the carbon content of iron, steel, and cast iron increases, the melting and freezing point declines; cast iron with a 4.3% cc freezes and melts at a temperature of 1130° C, the eutectic temperature of this alloy composition. Below the freezing-melting temperature, the iron or steel changes from a liquid (the liquidus) to a mushy combination of liquid and solid until the temperature falls sufficiently for the alloy to pass the solidus, or temperature at which it becomes completely solid.

French iron and steel: France utilized the traditional Continental technique of making "German" steel by decarburizing cast iron, sorting the results into three categories, ferdoux (wrought iron), ferfort (malleable iron), and pure steel (quenchable steel that could be martinized). (Barraclough 1984a) See German steel.

Fuel to ore ratio: A key consideration of early direct process smelting strategies; differences in the fuel to ore ratio could result in the production of a low carbon wrought iron (< 0.08% cc), a malleable iron with a carbon content equivalent to modern (1870) low carbon steel (0.08% - 0.2% cc), low carbon steel (0.2 – 0.5%), or raw steel (> 0.5% cc). In the heterogeneous bloom of iron being smelted, increasing the fuel to ore ratio tended to increase the probability of raw steel production. See natural steel, carbon content of ferrous metals, and fining hearth.

Full annealing: The heating of iron alloys above their critical temperature for an appropriate time period, followed by slow cooling, either in a furnace or in a thermally insulated environment for the purpose of altering the crystalline structure and thus the properties of the metal being annealed.

Full welding heat: The temperature necessary to weld two pieces of iron or one piece of steel and a piece of iron together (2400° F / 1365° C). The iron will have a white color and will emit visible sparks due to the oxidation of the iron.

Furnace / Forge: While a blast furnace is only a furnace for smelting ore, a bloomery and finery can function both as a furnace for smelting and a forge for mechanical and thermal treatments of such metals after smelting. See finery, fining, bloomery, blast furnace, and ferrous metallurgy.

Furnace types (before 1870): Three basic types of furnaces characterize iron and steel production from the early Iron Age to the beginning of bulk process steel production (1870). (Tylecote 1987) (Wertime 1962)

Crucible shaped furnace: Among the earliest furnace designs was a simple crucible, especially common in northern Asia for cast iron production and also used for Wootz steel production. The crucible shaped furnace evolved into the cupola furnace commonly used in the 19th century to re-melt blast furnace derived cast iron.

Bowl furnace: The bowl furnace is the earliest form of the furnace. The charge of ore was often located in back of the fuel; reduction occurred via a current of carbon monoxide formed by the burning charcoal assisted by a directed flow of air from a tuyère. The Catalan furnace of northeastern Spain is the most well known form of the bowl furnace. Most earlier bowl furnaces were slag pit types.

Shaft furnace: The shaft furnace is the most common form of furnace throughout the Iron Age; ore and fuel are mixed together in a four sided shaft; the resultant bloom of wrought or malleable iron is extracted from a hole at the bottom of the furnace. Combustion is also aided by the use of the tuyère powered by varying types of blowing devices. Low shaft (1 to 2 meters in height) slag tapped furnaces characterized most Roman era ironworks.

Furnace types are further subdivided as being slag pit types and slag tapped types.

Slag pit furnace: In slag pit furnaces, the slag accumulates in situ at the bottom of the furnace until the furnace is moved to an adjacent slag free location.

Slag tapped furnace: More practical and efficient was the slag tapped furnace, where the slag from the smelting process was withdrawn through a tap hole to an adjacent cavity or hollow in the ground.

Stuckofen furnace: Low shaft furnaces gradually grew in height, capacity, and efficiency to become the high shaft Stuckofen of the German Renaissance, the immediate predecessor of the blast furnace.

Cementation furnace: Sandstone furnaces in which iron bar stock was enclosed to be carburized into blister steel. First noted in Nuremburg in 1601, such furnaces protected the steel being smelted from the oxidizing influence of the burning fuel; also called "**steel**

furnace”, especially in the United States in the colonial period. Not to be confused with the many modern forms of steel furnaces developed after 1860.

Reverbatory furnace: Primitive forms of the reverbatory (refractory) furnace were improved by Henry Cort into the modern form of the reverbatory furnace in 1785. Also known as the **puddling furnace**, this design allowed the decarburization of large quantities of pig iron by heat reflected from the metal roof of the reverbatory furnace, preventing fuel to ore contact.

Blast furnace: The blast furnace was a form of high shaft furnace designed specifically to operate at high temperatures, thus carburizing iron ore to produce liquid cast iron.

See shaft furnace, bowl furnace, blast furnace, blowing devices, and tuyère. For modern furnace forms see Bessemer process, Siemens-Martins, open hearth furnace, and electric arc furnace.

Futtock: The four or five separate pieces of timber comprising the ribs of a ship, usually held together by iron bolts made by a shipsmith.

Galvanizing: The coating of the surface of iron and steel with zinc, usually to prevent corrosion.

Ganister: Furnace linings made of refractory rocks such as sandstone. See acid process.

Gangue: Contaminants in iron ore removed as slag, e.g. quartz, oxides of aluminum and silicon, often found in clay-like materials associated with the iron ore. The most common component of gangue is silicon. See ferrosilicate, slag, flux, reduction.

German silver: An alloy of nickel and copper and sometimes zinc; also called nickel silver.

German steel: The predominant steel making strategy in the Renaissance, both in England and on the European continent, German steel was made by decarburizing blast furnace pig iron in a separate finery type furnace (1400-1650). The roots of German steel production lie in the manganese rich ore of Styria and Carinthia (Austria), which facilitated the first iron production at Halstadt. Used by the Romans to produce steel weapons (Noricum), the accidental (?) production of natural steel in early bloomeries became the deliberate production of German steel in Stuckofen (shaft) furnaces, which could produce pig iron, steel, malleable iron, or wrought iron, depending on the fuel to ore ratio and smelting temperatures. Production of steel from decarburized cast iron was thus an outgrowth of the appearance of blast furnaces producing large quantities of pig iron in continental Europe after 1315. "Steel made from the seventeenth century onward in Styria and Carinthia by fining manganese rich pig iron. It contained alternating bands of high- and low-carbon content and was considered a superior material for cutlery. Also, another name for shear steel." (Gordon 1996). Of great importance during the florescence of Nuremburg and Augsburg watch making and armor manufacturing, +/- 1500 AD, numerous fine examples of hand tools made between 1500 and 1750 are on display at the National Museum in Nuremburg, Germany. Having the appearance of cast steel (manganese in smelted iron ore results in a sheen, similar to that of cast steel) and probably containing some martensite, these low carbon steel tools (+/- 0.5% carbon) are labeled as "eisen" (iron) by the National Museum. Their manganese content is the probable cause of their visual similarity to the crucible steel tools produced in Sheffield after 1750. In the broader context of tool production, between 1400 and 1800, German steel can have a wide range of carbon content depending on its intended use. Many edge tools such as trade and felling axes made after the appearance of the blast furnace are composed of one piece of steel with no steel-iron interface, as in later "steeled" axes. See Spiegeleisen, spathic ore, natural steel, and Styrian steel.

Gladius: Roman short swords, made of wrought iron and low carbon steel, occasionally pattern welded. The gladius was often cold work-hardened (not -heat-treated), or surface carburized at its steeled edge. See spathas.

Glide plane: The points in the lattice structure that combine rotation on the screw axis with movement along a translation parallel, e.g. axial or diagonal length, of the lattice structure; plastic deformation of the lattice structure of iron, for example, occurs along the crystallographic glide plane, also called the slip plane. (Barrett 1943, 288)

Goethite: "Ore mineral composed of hydrated iron oxide." (Gordon 1996)

Gossans: Oxidized iron pyrite in the form of outcrops of decomposed rocks; a source of iron for early smelting furnaces.

Grain: In ferrous metallurgy, the consistent alignment of microstructural crystals, the patterns of which allow a blacksmith to judge the mechanical properties and quality of iron and steel. Grain size, in cast iron for example, is determined by the rate of cooling of the iron in molds as well as its silicon content. High silicon content (2 - 3%) produces large graphite flakes and a coarse grain structure. See fracture, free carbon, combined carbon, and microstructure.

Grain direction: The key to successful forge welding is the ability of the smith to follow the strain patterns, expressed as grain direction, of the metal and incorporate them in the design of the implement to be manufactured. “In a gun hammer, the strain is along the nose, across the finger and down the body of the cock.” (Greener 1910, 246) One of the primary objectives of the faggoting, piling, and re-forging of wrought iron into bar stock of the highest quality was the correct alignment of the grain direction of the siliceous fibers remaining in the wrought iron.

Grain growth: The increase in the grain size of crystals within the lattice structure of iron carbon alloys, which occurs when the metal is heated above the critical temperature and held at that temperature for a time sufficient for adjacent crystals to absorb each other.

Grain size: Grain size determines hardness in the crystal structure of iron and steel. Increasing grain size in polycrystalline structures decreases hardness; decreasing grain size increases hardness, as in the dispersion of fine cementite particles during the formation of martensite.

Grain structure: The microstructural arrangements of the crystals in iron carbon alloys that determine their properties, i.e. coarse grained, fine grained, stressed (slip plane dislocations). See stress fields, microstructure, lattice structure, and grain direction.

Graphitic carbon: Graphitic carbon, in cast iron for example, is that portion of its carbon content in the form of free graphite flakes, in contrast to combined carbon, as in white cast iron. The relative proportion of free graphitic carbon flakes and chemically combined carbon in cast iron determines its structure and physical properties, i.e. brittle or durable. The amount of the graphitic carbon is dependent on the cooling rate of the iron; the slower the cooling rate, as in sand molds, the higher the free graphite content. Free graphite weakens the iron, but also increases its machinability. Chemically combined carbon occurs in white cast iron, which is produced by rapid cooling, i.e. in iron molds; it is extremely durable, but difficult to machine. See malleable cast iron, white cast iron, gray cast iron, and cooling rate.

Graphite crucibles: Developed by Joseph Dixon in the 1840s, the thermal efficiency of the lead (plumbago) in American made crucibles, which allowed casting at high temperatures, played a role in the rise of American crucible steel production after 1860. See Stourbridge clay and cast steel definition 1.

Graphite flakes: Graphite flakes, as randomly occurring graphitic carbon, weakens the structure of cast iron by creating spaces in its crystalline structure. See graphitic carbon and gray cast iron.

Gray cast iron: Gray cast iron is cast iron containing free graphite in the form of graphite flakes as its principle form of carbon, and having its combined carbon content not in excess of the eutectoid percentage. Produced especially in hotter, coke fired blast furnaces, its higher silicon content inhibits cementite formation and makes the gray cast iron more difficult to decarburize. It can occur as a matrix of ferrite and pearlite, or as a mixture of both, and is the principal industrial form of cast iron; also used to make malleable cast iron by chilling and annealing. This process changes the large gray flakes of free graphite to a more finely divided pattern of graphite distribution, promoting the formation of graphite-austenite microstructures. Free graphite in gray cast iron, which occurs as loose brittle flakes, cuts through and separates grains of iron, which makes the cast iron brittle rather than malleable. The annealing of gray cast iron restores malleability; chemically combined carbon prevents malleability in white cast iron, which is also annealed to make malleable cast iron. The addition of silicon enhances the fluidity and durability of annealed cast iron. Stanley Tools in *Tool Talks* (1937, 15) describes gray cast iron for use in the manufacture of Stanley planes. This entire article on gray iron casting is reprinted as an appendix in Volume 7 of the *Hand Tools in History* series, and is available on the Davistown Museum website as a tool information file. See white cast iron.

Green sand molding: Green sand molds are used for casting gray cast iron, malleable cast iron, and other non-ferrous metals such as bronze, brass, and aluminum. Damp sand is rammed around a pattern; when the pattern is removed, the sand mold is filled with molten metal. See molder, casting, pattern.

Grindstone: The traditional tool for sharpening axes; as used in the 19^{th} century ax making industry, grindstones were 6 to 12 inches thick, 4 to 8 feet in diameter and weighed 2000 to 4000 pounds. Smaller versions of ax grindstones are still commonly encountered in rural environments; a stone thickness is typically 3 to 4 inches, with a diameter range of 18 to 36 inches, mounted in a wood or metal frame. Most grindstones were traditionally water cooled. See ax making, eyepin.

Gun barrel iron: Sheet wrought iron folded around a rod and then welded to form the gun barrel. See gunsmithing.

Gunmetal bronze: 90% copper, 10% tin.

Gunsmithing: Prior to the advent of the all cast steel gun barrel, gunsmithing usually involved the pattern welding of piled soft iron and occasionally strips of silver or shear steel (refined German or blister steel). Apparently, soft wrought iron (0.08% carbon content or less) was preferred to malleable iron (0.08 – 0.5% carbon content) due to its ductility and ease of workability. See wrought iron and pattern welding.

Gutterman: In the operation of a blast furnace, the gutterman was in charge of supervising activity in the lower region of the blast furnace, especially including the efficient drainage of liquid cast iron from the bosh through the temp to the molds. In the case of blast furnaces producing pig iron rather than hollowware, the gutterman would direct the melted iron into the rows of sows, creating cast iron ingots with the appearance of pigs, hence the name pig iron. See temp, Bosch, blast furnace, and molding.

Haft: The helve or handle of an ax or adz set up at a right angle to the major axis of the tool.

Hallstadt: The first Iron Age culture in Europe, named after the salt mining town in Austria where Celtic metallurgists switched from making bronze tools to making iron tools c. 750 BC. See *Hand Tools in History* Volume 6 and La Téne.

Hardenability: The following factors determine the ability of steel to be hardened: carbon content, grain size, lattice structure, heating temperature, heating rate, and prior thermal treatments. "The depth to which steel can be hardened to martensite under stated conditions of cooling is called its hardenability." (Shrager 1949, 145)

Hardening: During the heating and forge-welding of iron with a carbon content of 0.5% or greater (alpha iron), hardening occurs due to sudden cooling of the metal from a temperature at 910° C or above, which freezes the lattice structure of austenite (gamma iron) in a hard and brittle form, which is difficult to work unless softened by tempering or annealing. Hardness is thus a function of tempering temperature. Tempering relieves stress by allowing lattice rotation, changing the crystalline structure of the steel. "If steel contains less than four tenths of one percent of carbon it has little or no hardening power under this treatment [sudden cooling]; but steel with six tenths of one percent or more of the element, has the wonderful property of being slightly malleable in the annealed state but extremely hard and brittle after this sudden cooling." (Spring 1917, 109). See annealing, tempering, recovery, carbon content of ferrous metals

Hardness: "Resistance to plastic deformation by penetration, scratching or bending." (Shrager 1949, 367)

Hardness penetration: The depth of the hardened surface of quenched tool steel defines hardness penetration, which is often increased by the addition of alloys (Palmer 1937).

Hearth: The area in the bottom of a furnace in which the bloom of iron or molten pig iron is contained until removed by tongs or drained by tapping; often accompanied by liquid slag.

Heat treatment: The thermal processing of ferrous materials, including hot forging, quenching, tempering, annealing, and normalizing, which change their microstructure and therefore their properties. Rapid cooling of austenized steel creates martensite, a high strength easily fractured material, rather than ferrite, cementite, and pearlite. For edge tool production, martensite must be tempered in a range of 200º C to 500º C, precipitating and uniformly distributing iron carbide particles (cementite) to relieve brittleness. See annealing, tempering, martensite, and cubic structure.

Helveman: The hammer man at a puddling furnace or finery.

Hematite: Hematite is an "ore mineral (Fe_2O_3) containing 70% iron," (Gordon 1996) i.e. ferric oxide, the most commonly mined ore in the U.S. A common deposit at the bottom of marshy ponds in its hydrated form, limonite, hematite is a common component in bedrocks of all ages.

High frequency induction furnace: A modern form of the electric furnace in which a high frequency alternating current is induced via a water cooled copper core, producing the heat for smelting the charge.

High speed steel: Alloy steels formerly made by the crucible process and more recently manufactured in electric furnaces; typical high speed steel alloys include tungsten, vanadium, cobalt, chromium, manganese, and molybdenum. High speed steel cutting tools retain their hardness when heated to a red heat, whereas carbon steel cutting tools lose their temper with cutting speeds above 20 to 30 linear feet per minute. Oil hardened tungsten steel can cut up to

200 to 300 linear feet per minute on a milling machine or lathe without losing its temper. There are now hundreds of varieties of high speed steel alloys used in manufacturing processes.

History of Woodworking Tools: This definitive survey of the history of woodworking tools by W.L. Goodman was first published in 1964 and reprinted several times; this text contains information about the early tool forms (i.e. socket hole vs. shaft hole). Goodman discusses woodworking tools dating as early as Egypt 2540 BC and has important information on Roman and medieval forms, as well as illustrations from Moxon. Goodman, citing a Russian archaeometallurgist, has this comment on 11th and 12th century carpenters' tools found in a Russian late medieval horde, "of 22 axes tested, 7 had a steel tip welded over the iron base; in 7 others, the steel was inserted between the folded iron of the head. Seven others were solid steel and one of iron throughout. In most cases, there were signs of subsequent tempering, confined of course to the cutting edge." (Goodman 1964, Kolchin 1953)

Holloware: Artifacts other than ordnance made at blast furnaces or cupola furnaces by casting pig iron directly into molds e.g. anvils, hammers, kettles, fire backs, stove plates, etc. The slitting mill cylinders used by the nail makers of Wareham, MA, and elsewhere were cast in situ at the blast furnaces of Carver. (Murdock 1937). See grey cast iron and molders.

Hoop iron: Thin strips of malleable iron used to hold the staves of the cooper's cask in place; often made by the shipsmith as well as the village blacksmith in the colonial era.

Horse power: One horse power is the lifting of 33,000 lbs. to a height of one foot in one minute. The maximum horse power achieved by the editor of this Glossary in unloading hand tools from his truck after a buying trip to southern New England is approximately 1/20 horse power.

Hot blast: Developed in 1828, by Nielsen in England, cold air for the blast furnace was preheated in a separate oven already heated by the waste gasses of the furnace; the hot blast increased blast furnace temperature, slag fluidity, overall furnace efficiency, and reduced fuel consumption. In the United States, the development of the hot blast furnace encouraged the substitution of coal and coke for charcoal as a fuel, stimulating the construction of larger, more efficient blast furnaces. In England and continental Europe, the hot blast increased the efficiency of furnaces already using coke as a fuel. See blast furnace and coke.

Hot forging: Carburizing raw iron in a carbon-rich environment. See enclosure.

Hot set: A chisel with a handle used to cut iron bar stock when at a bright red orange color.

Hot short: The disintegration of hot steel during forging due to its contamination with liquid iron sulfides from ore or fuel derived sulfur. Iron sulfides are preferentially removed as slag constituents by manganese-containing flux, as occurs with the addition of Spiegeleisen to cast iron, or the natural occurrence of manganese in rock ore, eliminating brittleness in steel at high temperatures. "When [metal is] unworkable at a welding heat it is [said to be] *hot short*." (Brewington 1962, 15). See sulfur, phosphorus, and ferrosilicate.

Hot working range: The temperature at which iron maintains plasticity at or above its crystallization temperature (700 – 1250° C), allowing its reshaping into various tool forms. During hot working, including rolling or forging, the lattice structure of the metal is simultaneously deformed and reformed, but with the tendency for the formation of more uniform grain structures. See eutectic, eutectoid, lattice structure, and critical temperature.

Hydrated: To become combined with water, as in bog iron, a hydrated form of limonite. See bog iron.

Hydraulic press: Originally used for drop-forging heavier castings, e.g. railway car axles, modern hydraulic presses are now used for manufacturing most drop-forged tools. The hydraulic press squeezes instead of hammers metal into shapes, e.g.: hammer heads, ax heads, utilizing two piece dies often made of high carbon steel. See die casting, die driving, drop-forging, and die sinking.

Hypereutectoid steel: Steel with a carbon content above 0.83%, i.e. pearlite, with an excess of cementite at grain boundaries, which makes it harder and more brittle than hypoeutectoid steels.

Hypoeutectoid steel: Steel having less than 0.83% carbon content, e.g. less than the eutectoid composition, characterized by an excess of ferrite at grain boundaries, giving it the soft and ductile qualities of low carbon steel and malleable iron.

Ice cream: The eutectic point of ice cream is 32°. In a sense, it is similar to steel, an iron carbon alloy with a much higher melting temperature than ice cream. Steel, however, has a much wider range of melting temperatures due to its carbon content and also a wider range of temperature gradient between its solid and its liquid form. (See solidus and liquidus.) In between the two temperatures, steel is mushy; mushy ice cream would have a smaller temperature range between its solid and liquid forms. When frozen to 400° below zero, ice cream has something in common with martensite steel, it is hard and brittle and cannot be spooned easily; it needs to be tempered to soften it up a bit. On the other hand, ice cream does not lend itself to annealing; its re-crystallized lattice structure makes it none too pleasant for ingestion. A final observation on this unfortunate metaphor: Ben and Jerry's Chunky Monkey and Cherry Garcia are the equivalents of various tool steels to which alloys have been added, i.e. cobalt (cherries), manganese (chocolate chunks). These compare with soft serve Dairy Queen style ice cream: just the basics as with low carbon steel produced by the Bessemer process, where all the interesting contaminants, some of which help make convivial edge tools, e.g. silicon, have been burned out of the steel (Illich, 1926). See martinizing, eutectic, solidus liquidus, and critical point.

Iconography of tools: The depiction of tool forms in art throughout history. The illustration of tool forms on wall drawings in Egyptian pyramids and shaft furnaces and blacksmith tools on Greek vases are early examples of the consistent tendency to illustrate tool forms in art, and especially in printed books after 1350. See Phenomenology of tools, Diderot’s encyclopedia, Moxon, pattern books, and History of woodworking tools.

Impact strength: The measurement of the ability of a metal to withstand fracturing under shock.

Incandescent temperature colors: The key to judging the hardness of steel from the early Iron Age to the mid 19th century when instrumentation became available to measure hardness, i.e. pyrometers. The key color for the blacksmith quenching hot iron to make steel is the cherry red heat (1375° F), which is the minimum quenching temperature, or critical point of steel. See tempering, edge tools, and critical point.

Color	°F	°C
White	2200	1200
Light yellow	1975	1080
Lemon	1830	1000
Orange	1725	940
Dark orange	1680	890
Salmon	1550	840
Bright cherry	1450	790
Cherry	1375	745
Medium cherry	1275	690
Dark cherry	1175	635
Blood red	1075	580
Faint red	930	500

(Palmer 1937, 129)

Ingots: Cooled steel and iron castings derived from a cast iron mold after smelting; these castings are subsequently reheated for further mechanical and thermal treatment by forging, rolling or other forms of processing.

Internal stress: Residual stress within the lattice structure of a metal that remains after thermal and mechanical treatments; relieved by tempering.

Interrupted quenches: "An interrupted quench is one which is not carried through to the temperature at which transformation of austenite to martensite commences, but is interrupted at some higher temperature, in order to suppress transformation of austenite into pearlite and at the same time avoid formation of martensite. The quenching bath is kept at a stated temperature appropriate to the formation of the microstructure which is desired for the steel being treated." (Shrager 1949, 169)

Interstitial: Solid solutions of iron carbon alloys in which atoms (e.g. carbon) occurring within the empty spaces of the crystal lattice structure (e.g. ferrite) distort the structure.

Iron: "A heavy malleable ductile magnetic silver-white metallic element that readily rusts in moist air, occurs native in meteorites and combined in most igneous rocks, is the most used of metals, and is vital to biological processes" (Merriam-Webster Dictionary). Iron has a melting point of 2735° F and is difficult to smelt in its pure form, but when carburized (combined with carbon e.g. 3.5%) becomes the more accessible form of easily melted cast iron with a melting temperature of 2075° F. Steel is an iron carbon alloy containing 0.10 (0.20) to 2.0% carbon. See carbon content of iron and steel and associated cavets.

Iron Act: Passed in 1750, by the English Parliament, the Iron Act prohibited the manufacture of iron and steel tools, hardware, and artifacts in the American colonies. In part, this act was a response to the Swedish export tax (1750) on charcoal iron, which resulted in an increase of the import of bar iron from the colonies to England after 1750. This Act was never successfully implemented; a robust colonial iron industry had already been established at the end of Queen Anne's War and the Treaty of Utrecht 1713 (Bining 1933). The Iron Act played a key role in stimulating colonial resentment of British rule, helping to lay the foundation for the coming revolution.

Iron carbide: Alloys of strongly bonded iron and carbon atoms, with various patterns of carbon distribution. The homogeneity or heterogeneity of the carbon distribution pattern in iron tools, for example, determines the characteristics of the tools as cast iron, low carbon steel, wrought iron, or crucible steel. Also, specifically cementite (Fe^3C).

Iron-carbon constitutional diagram: "A constitutional diagram each point of which represents the composition of steel or cast iron that is in equilibrium and that contains only iron and carbon." (Shrager 1949, 368). See the Iron Carbon Diagram Appendix for several models.

Iron cored: One of several ancient technique for knife and sword making; steel strips were wrapped and welded around an iron core, then forged into the desired shape. See knife forms.

Iron ingots: Iron ingots are a common form of reprocessed cast iron, often produced in cupola furnaces as the raw material for foundries and other special purpose furnaces. See malleable cast iron and foundry.

Iron mills: The forges that reprocessed the iron ingots derived from blast furnace and bloomery operations for special purpose applications; this term applies to iron production before the era of bulk process steel.

Iron ore: Ore containing any of the iron oxide minerals magnetite (Fe_3O_4), hematite (Fe_2O_3), or siderite ($FeCO_3$), sometimes in various combinations; iron ore also occurs as the hydrated iron oxides goethite and limonite, as in the bog iron deposits of southeastern MA.

Iron road: A famous trading route used from the early Iron Age through the migration period to the late medieval era via which currency bars, smelted in Austria (Styria and Carinthia also called Noricum), were transported by wagon north to the Danube River and then upstream to portages linking Austria and the forges and sword smiths of the Celtiberic lower Rhine region. This latter area was particularly active as the famed Merovingian sword making center of the early Frankish empires of the region (650 – 750 AD). See Celtic metallurgy, Halstadt, La Téne, and spatha.

Iron sand smelting processes: The use of self-fluxing, black sands from the south shore of the Black Sea to produce iron and high nickel steel, c. 1900 BC. This was the first documented industrial production of iron and steel tools, which ironically occurred at the height of the Bronze Age (Wertime 1980). See Chalibean steel and nickel steel.

Iron silicate: Along with ferrite, the principal component of wrought iron; it occurs as glass-like slag and is present in wrought iron in amounts that vary from 1 to 3% by weight. It is distributed in the wrought iron as highly visible threads or fibers, which run in the direction of rolling (mechanical processing). "In well made wrought iron there may be 250,000 or more of these glass-like slag fibers to each cross-sectional square inch. The slag content occupies a considerably greater volume than a percentage by weight would indicate, because the specific gravity of the slag is much lower than that of the iron based metal." (Aston 1939, 2-3). The iron silicate content of wrought iron provides unique qualities, especially resistance to corrosion and to fatigue. The iron silicate content of early forge-welded hand tools explain their resistance to rusting in comparison to modern drop-forged low carbon steel tools, which rust quickly when exposed to moisture.

Iron-fuel contact: A perennial problem in older furnace designs prior to the development of the reverbatory furnace (H. Cort, 1784); iron-fuel contact resulted in the recarburization (oxidation) of the iron being decarburized in finery furnaces. See reverbatory furnace, puddling furnace, ferrosilicate, and oxidation.

Isothermal transformation diagram: Time-temperature transformation (ttt) curves in the form of diagrams that graphically illustrate the changes that occur when steel is cooled at various rates. The diagram for eutectoid steel (Shrager 1949, 143) illustrates the phenomenon that at relative low temperatures (+/- 1000º F) the transformation of austenite into pearlite can take place in a matter of seconds. See the Iron Carbon Diagram Appendix and critical temperature.

Isotropic: Materials having identical properties in all crystallographic formations, i.e. their elastic forms are alike in all directions. See anisotropic.

Japanese swords:

Jominy end quench test: A standard test for determining hardness after quenching.

Kentledge: Hardened blocks of pig iron used as ballast in coasting vessels and then sometimes sold to fineries and foundries for further processing. See iron ingots.

Kill: "To remove dissolved gas in liquid steel so that it will not boil while solidifying." (Gordon 1996, 309). See crucible steel.

Killed steel: Killed steel is held in the crucible until no more gas is emitted, and the surface appears "quiet," a process that prevents blow holes and other structural anomalies. (Spring 1917). When the steel in the crucible solidifies, uneven cooling causes shrinkage that then produces a central pipe in the crucible casting. See pipe and dozzle.

Knife forms: There are five basic forms of knives, as described by Tylecote (1987, 269) (after Pleiner 1969), which are derived from his excavations of central European archeological sites over a period of several decades. These knife forms existed more or less simultaneously in eastern, western, central, and European sites from the beginning of the early Iron Age (Halstadt +/- 700 BC) until the late medieval period (1000-1500 AD). The forms are: the *all iron* knife; knives with *carburized* cutting edges; all (raw or natural) *steel* knife; the *sandwich pattern* knife (the iron components of the knife are folded over the steel cutting edge – the earliest known variation of welded steel construction); and the *pattern welded* knife, where alternating layers of steel and sheet iron are welded together. The last appears to be the most common knife form in archeological sites. See iron cored, history of woodworking tools, and pattern welding.

Knobbler: The bar maker at a finery who made anconies was a knobbler; the name derives from the fact that most anconies had a knob at the end to facilitate ease of movement.

Laminae: With respect to gun smithing, the patterns resulting from the piling and forging of alternating layers of steel and iron strips and plates, which form the composition of the pattern welded gun barrel. See gunsmithing, piling, pattern welding, and gun barrel iron.

Lamellae: With respect to the crystalline structure of steel, lamellae are the plate like structures that characterize pearlite. During the slow cooling of austenite, identical pairs of lamellae are formed by the process of twinning, creating a form of steel, pearlite, with a more distorted crystalline structure than that contained in tempered martensite. See twinning, Neumann bands, laminae, and pearlite.

Lamellar pearlite: "Pearlite crystals covered by a thick layer of cementite." (Shrager 1949)

Laminating: An early Iron Age technique of knife making characterized by pattern welded layers of sheet iron or sheet steel with varying carbon content, as exemplified by Egyptian knives dating from 900 – 800 BC as well as an adz from the same period. See Wertime (1980, 120), knife forms, and pattern welding.

Laminated structure: Alternate layers of different forms of iron, such as the alternating layers of ferrite and cementite that constitute pearlite.

Lap riveting: In boiler making and iron and steel ship building, the riveting of overlapped sheets of iron and steel.

Lap weld: A term pertaining to the welding of pipe; a variation of scarf welding; the skelped pipe edges are beveled, overlapped, and welded together. See scarf weld.

La Téne: La Téne was a village and ritual site on the edge of Lake Neuchâtel in Switzerland; the tools uncovered there reflected both a western movement of Celtiberic metallurgists and the evolution of a more war-like culture than Halstadt; iron axles made their first appearance in Europe in warrior burials at La Téne. See Halstadt, Noricum, and natural steel.

Lattice bending: Lattice bending results from the random application of stress on the lattice structure of metals, producing distortion patterns that lack crystallographic regularity (Barrett 1943, 307). See plastic deformation, cubic structure, and space lattice.

Lattice reorientation: Lattice reorientation of the crystalline structure, of iron for example, occurs by three processes: uniform rotation of the crystals, bending of the lattices between planes of slip, and division of crystals into deformation bands “within which the lattice rotates in different directions.” (Barrett 1943, 347-48). Heating and cooling are the principle causes of rapid lattice reorientation (slip); cold working is the principle cause of slow lattice reorientation (creep). See plastic deformation, slip, and creep.

Lattice structure: The crystalline structure of the unit cells of metals. See allotropic forms of iron, crystallography of ferrous metals, cubic structure, unit cell, lattice reorientation, plastic deformation, and space lattice.

Ledeburite: Cast iron, containing 4.3% carbon in the form of the eutectic mixture of austenite and cementite. The austenite in ledeburite may transform to ferrite and cementite during cooling.

Leg vise: A common tool in many farm workshops; the presence of a leg vise and anvil and basic hand tools such as the ball peen hammer and hand vise suggests that toolmaking activities characterized these workshops from the colonial era until the mid-19th century. Leg vises can be traced back to Roman smithies and are illustrated in Diderot’s encyclopedia ([1751-75] 1959) as well as English pattern books. Most leg vises recovered from New England workshops appear to be domestically produced and are often hand-forged, one-of-a-kind creations of local workshops.

Lime boil: The violent reaction occurring when, during the basic open-hearth process, carbon dioxide gas is released from the limestone on the hearth floor.

Lime as flux: Lime was used extensively to remove phosphorous from iron, especially after 1878 when S. G. Thomas discovered the chemical basis for its usefulness as a slag constituent. See basic steel, limestone, and acid process.

Limestone: Limestone was used as a flux in iron smelting after 1600; the calcium content of limestone greatly reduced the iron content of blast furnace slag, allowing recovery of 90% or more of the iron being smelted. Used specifically as a flux for high phosphorous iron ores after 1878. See lime as flux, acid process, and basic process.

Limonite: Bog iron; also "all forms of hydrous sesqui-oxides of iron." (OED 1975, 1629). "Impure form of goethite containing a variable amount of water." (Gordon 1996, 309). It is mined from bogs and heated for water evaporation; a principal source of iron for bloomeries and blast furnaces in the American colonies, especially in southeastern Massachusetts and the pine barrens of New Jersey. See bog iron and bloomery.

Liquidus: "The upper curve in a constitutional diagram, which is the locus of temperatures at which each alloy starts to solidify." (Shrager 1949, 370). See Barraclough's constitutional diagram in the Iron Carbon Diagrams appendix.

Lost wax process: An ancient method of casting utilizing wax patterns for molds, which are then destroyed by the casting process; particularly useful for precision casting, such as in jewelry making.

Loup: Synonymous with "bloom", as in the bloom or loup of iron produced in the smelting process. See direct process, bloomery, and reduction.

Low carbon cast iron: Produced in air furnaces as white cast iron for the manufacture of malleable cast iron; containing about 20% less carbon than gray cast iron. See cast iron.

Machine steel: A modern form of "low carbon steel," usually with 0.08 - 0.2% carbon content, but without the slag content of malleable iron. Frequently drop-forged in dies to be made into hand tools other than edge tools. Often subject to additional carburization, usually by case hardening. See malleable iron, low carbon steel, carbon content of ferrous materials, and case hardening.

Macro-etching: The treatment of the surface of a sword, for example, by a reagent, for the purpose of determining the quality of metal by analysis of the flow patterns that reveal the structural differences characteristic of the iron and steel used to fabricate (by pattern welding) the sword. See Damascene and reagent.

Magdalenberg: An important early Iron Age metalworking site in Austria, located in Carinthia near Styria and Erzberg (ore mountain), the location of many shaft furnaces and the probable production site of malleable iron and natural steel tools and weapons.

Magnetite: "Magnetic mineral (Fe_3O_4) containing 72% iron; the active ingredient in 'lodestone.'" (Gordon 1996, 310)

Mainspring: Mainsprings replaced weights as a method of powering clocks, first appearing in Germany (1550), becoming widely used in the florescence of German clock making between 1550 and 1634, and then in England and Holland after 1650, after the German industry declined. The search for higher quality steel for mainspring production led Benjamin Huntsman (1742) to readapt crucible steel manufacturing techniques for his Sheffield clock and watch spring business. See cast steel definition 1.

Male die: The upper die, also called a force, made of steel, cast iron, or copper by a drop press in a machine shop, or by a toolmaker, rather than by a die sinker. A heated pattern blank is used to shape the male die by the drop press. The die is then hardened and tempered, making a reproduction of the model.

Malleability: The relative ability of a material to be permanently deformed by rolling, casting, forging, extruding, etc. without fracturing and without developing increased resistance as it is deformed; malleability usually increases when temperature increases. Wrought iron, gold, silver, aluminum, copper, and magnesium are malleable metals. See ductility, plastic deformation, and malleable iron.

Malleable castings: Malleable cast iron having some of the properties of wrought iron; derived from annealed cast iron by a process that involves the cleaning of the cast iron by pickling, followed by its stacking within the annealing oven after being covered with millscale or other forms of iron oxide. Rapid heating is followed by very slow cooling, which produces an iron that is resistant to damage by sudden shock. See malleable cast iron.

Malleable cast iron: The most common and commercially useful form of cast iron – durable, strong, and malleable – its fracture and color expresses its metallurgical composition. Malleable cast iron is made in two forms, whiteheart and blackheart, which are differentiated by the processes used to anneal them and by their chemical composition. White cast iron containing chemically bound graphite is unsuitable for making malleable cast iron until it is melted and annealed to withstand distortion without breaking.

Knight provides this definition "Iron cast from the pig into any desired shape, and afterwards rendered malleable, or partially so, by annealing. A great variety of articles are thus produced in a more economical and correct manner than they could be by forging. Such are bridle-bits, snuffers, parts of locks, various forms of builders' and domestic hardware, some kinds of culinary and other vessels, pokers, tongs, and numerous other things. Many of these are subsequently case hardened and polished. *The art of softening cast iron and working it, and afterward hardening it again*. [italics added] ...The inventor of the process of rendering articles of cast-iron malleable was Samuel Lucas of Sheffield, by whom it was patented in 1804." (Knight 1877, 1376-77). First produced commercially in the United States by Seth Boyden in Newark, NJ, in 1831; with various alloy combinations and heat treatments, malleable cast iron has been used to manufacture an endless variety of hardware and utensils. "Barraclough notes the widespread production of malleable cast iron tools in the 3rd and 4th century BC in China. R. A. F. de Réaumur writing in France in 1722 also describes this process (Barraclough 1984)." (Brack 2007). See gray cast iron, annealing, and temper carbon.

Malleable iron: A 19th century term for iron having a slightly higher carbon content (0.08 - 0.5% carbon) than wrought iron (< 0.08% carbon content), now commonly referred to as “low carbon steel”. Unlike low carbon steel, malleable iron also contains trace amounts of silicon, manganese, phosphorous, and sulfur, the first three of which can confer beneficial qualities in tools being produced from malleable iron. Silicon enhances the ductility and durability of malleable iron, manganese enhances strength, phosphorous in small quantities increases hardness and has a useful role in nail making. Sulfur has no useful function in any metallurgical context. Malleable iron will harden slightly when suddenly cooled. Modern bulk process low carbon steel (Bessemer steel > 1870) is cleansed of all such contaminants and is also called "machine steel" or "carbon steel." Alloys such as manganese, nickel and other additives are frequently added to bulk process low carbon steel to confer specific properties on the steel being produced. Siliceous slag bearing malleable iron was produced as a "bloom" or "loup" in direct process bloomeries; iron with low slag content was produced in indirect process puddling furnaces from pig iron. Malleable iron containing significant levels of silicon is not suitable for production of tool steel alloys. The silicon content of malleable iron played an important, but unrecognized, role in the forge welding of hand tools in the era preceding bulk process steel and machine drop forging. The confusion between very low carbon wrought iron and relatively low carbon, malleable iron continues, the latter being frequently referred to as wrought iron, while having the same carbon content as modern "low carbon steel." See carbon content of iron, Bessemer process, mild steel, and low carbon steel.

Malleableizing: The annealing of white cast iron for the purpose of changing chemically combined carbon to temper carbon, creating malleable cast iron that is less brittle, more durable and more machinable than gray or white cast irons. See malleable cast iron and temper carbon.

Manganese: An important constituent in steel alloys (+/- 0.2%); it dissolves in ferrite, hardens and toughens it, serves as a deoxidizer, and causes carbon to stay in combined forms as hardened steel. Manganese neutralizes phosphorous and also makes iron non-magnetic. Manganese makes tool steel easier to hot roll or forge and increases the penetration of hardness during quenching. Water quenching of manganese alloy steels tends to make them too brittle for most applications. Historically, the manganese content of iron ore played an important role in natural steel production by lowering the melting temperature of slag and thus facilitating carbon uptake in a bloom of iron. The manganese would become part of the flux, preferentially combining with contaminants such as sulfur and phosphorous, which were removed when the slag was drained off of the bloom. Manganese is thus an important deoxidizing and desulfurizing agent. Manganese, as a constituent of cast iron, played a similar role in the production of German steel; when the cast iron was fined, the manganese preferentially absorbed the sulfur, which was removed as slag. Uniformity of carbon distribution was facilitated, but only in fined cast iron containing the manganese. In the 19th century, the chemical basis of the role of manganese became known; the addition of ferromanganese to the smelting process was the key to the success of Bessemer steel. Siderite is the only naturally occurring iron ore containing manganese; notable siderite deposits of historical importance were located in the Erzberg (Iron Mountain) section of Austria (Noricum) and in the Weald (Sussex) and Weardale sections of England. See German steel, Noricum, and Weald.

Manganese oxide: An important replacement for iron oxide during the fining (decarburization) of cast iron into steel, as in the puddling furnace. Manganese oxide has a lower melting temperature than iron oxide as a slag constituent, and facilitates uniform carbon distribution during steel production. (Barraclough, 1984B, 91-106). See manganese and puddling furnace.

Manganese steel: In its modern form, an alloy steel containing 11 to 14% manganese and 1.0% carbon. It is used for safes, steam shovels, and other uses requiring high wear resistance. It cannot be machined nor softened by annealing, but is made somewhat softer and less brittle by quenching, the very reverse of the usual steel treatment process. See alloy steel, spathic ore, and Spiegeleisen.

Manganiferous: Iron ores containing manganese.

Martempering: Quenching in molten salt at temperature slightly above the critical temperature to produce a fully martensitic structure in a uniform nearly stress free manner.

Martensite: “Martensite is considered to be a super saturated solid solution of carbon in ferrite; it is the hardest, strongest, and least ductile form of steel.” (Shrager 1949, 141). Hard, brittle steel with various distorted microstructures determined by the range of carbon content and distribution, martensite is formed by rapid displacive transformation rather than slower diffusive transformations. The microstructures are lath-like in low carbon steels, and plate-like in high carbon steels. Derived from the rapid cooling (quenching) of austenite, tempering will alleviate brittleness and restore ductility and therefore usefulness in edge tool production. Martensite forms at lower temperatures than pearlite, which is prevented from forming by the rapid cooling of austenite. Martensite has an unstable body centered tetragonal structure differing from austenite and ferrite only in its axial ratio, which is determined by carbon content. Martensite is formed rapidly (0.002 seconds) when austenite is cooled below 240˚ centigrade, and has a needle-like crystallographic structure, with no diffusion into particles of cementite. During the tempering of martensite, carbon is diffused into finely dispersed particles of cementite by a decrease in its axial ratio. Martensite can be considered an intermediate step in the transformation of austenite to ferrite (Barrett 1943, 478). See microstructure, quenching, tempering, austenite, and cementite.

Matchlock: The earliest form of a handgun, matchlocks were unwieldy and unreliable and required a source of fire such as a lit match, which would reveal the position of the gunner to his adversaries prior to the firing of the weapon. Nearly useless during rainstorms and inclement weather, the matchlock was always made of folded and forged strips of wrought iron. The battle of Saco, Maine, 1607, is a landmark event in American history where Micmac Indians, supplied by French traders, made first use of firearms in the form of matchlocks in a pitched battle in America, defeating the Abenaki community during the fur trade wars. See The Davistown Museum publication *Norumbega Reconsidered*, Appendices D and E. See Arquebus, flintlock, wheellock, gun barrel iron, and gunsmithing.

Maximum permissible forging temperature (MPFT): Ranging from 1300° C for low carbon wrought iron, the MPFT declines with increasing carbon content, reaching approximately 1100° C for steel containing 1.2% carbon. Steel containing more than 1.5% carbon is "virtually unforgeable." (Barraclough 1984a, 5). See forging, steeling, and quenching threshold.

Mechanical properties of metals: Properties that determine the ability of a metal to withstand force without tearing or fracturing. See compressive strength, tensile strength, toughness, brittleness, malleability, ductility, impact strength, fatigue, elastic limit, and creep.

Mechanical working: The shaping of metal by hammering, rolling, pressing, punching, bending or drawing to change its form; these processes may also change its physical properties, i.e. its crystallographic structure. The fabrication of armor by a combination of cold hammering and heat treatment is the classic example of medieval era mechanical working of iron and steel. See lattice structure, coal forging, and cold working.

Merchant bar: High quality wrought iron bar stock made by re-processing (piling and re-rolling) bloomery and puddling furnace derived muck bar. See muck bar, anconies, chafery, finery, and bloomery.

Merovingian swords: Produced by Celtic metallurgists for the Frankish kingdoms preceding the reign of Charlemagne, Merovingian pattern welded swords were famed for the quality of their steel and their artistic beauty. Predecessors of the later Viking all steel swords, Merovingian swords represent the high point of Celtic metallurgy utilizing the natural steel produced in Noricum and transported down the Iron Road to the Danube River and then upstream to the metal smithing centers of the lower Rhine.

Metalloids: Non-ferrous constituents of cast iron and steel up to 25% in volume, e.g. carbon in cast iron in the range of 2.2%–5.0%; also silicon, sulfur, phosphorous, manganese, etc. Metalloid alloys in cast iron and tool steel, such as manganese, chromium, nickel, and other metals, radically change the microstructure and thus the appropriate function of the cast iron or tool steel being produced. See alloy steel, silicon, manganese, Chalibean steel, and cast iron.

Metallurgy: “The art and science of extracting metals from their ores and other metal-bearing products and adapting these metals for human utilization.” (Shrager 1949, 371)

Microstructures: In ferrous metallurgy, an almost infinite variety of the morphologies of the crystalline structures in the various phases of the carbon iron system, resulting from the thermal and mechanical treatment of steel and iron. Microstructures can be observed by both micron and electron microscopes; microstructure determines the forms and properties, and ultimately, the uses of iron and steel. See lattice structure, austenite, martensite, annealing, and edge tools. See unit cell and crystalline structure.

Mild steel: Another name for low carbon steel. In ax making before the era of the cast steel ax, a steel bit was welded between a folded piece of mild steel to form the ax. Before the era of bulk process steel (1870), malleable iron, characterized by the same carbon content as mild or “low carbon steel,” but including salacious slag as a micro-constituent, served the same industrial functions (e.g. toolmaking) as "modern" mild steel. See low carbon steel and carbon content of iron and steel.

Mill forging: The action of rollers in modern mills, which create directional grain structure in steel by the use of great pressure.

Millscale: The oxidizing agent, iron oxide, millscale is initially formed from the hammering and rolling of heated iron, the surface of which is oxidized to form magnetic iron oxide. Millscale is often used as a flux in smelting, and, as an oxidizing agent, greatly increases the efficiency of puddling furnaces. See oxidation, reduction, and flux.

Minimum quenching temperature: The temperature below which rapid quenching will not result in hardening; also called the critical point. See quenching, austenite, and martensite.

Moiré Métallique: The intentional use of patterns formed by crystal formation to produce decorative effects on metals; invented by Allard in 1814, etched tinned iron plate was covered with a lacquer to produce lacquered tinware.

Mokumé: The disclosure of the structural and chemical properties of pickled iron and steel in the form of wood grain patterns for the purpose of decorating Japanese iron sword guards (tsuba). Described and illustrated by Cyril Smith in his chapter on Japanese swords (Smith 1960, 57-62). See the Appendix for excerpts from this chapter.

Mold: The form that contains the cavity for the casting of metal objects utilizing molten metals.

Molded malleable cast iron: Malleable cast iron, which, after annealing, is suddenly chilled in iron molds, producing a steely cast iron with a very smooth surface, as in Bailey plane bodies c. 1855.

Molder: In the operation of the blast furnace, the molder was in charge of making sand patterns out of wooden flasks, which formed the pattern of the cast iron object being manufactured, and then supervising the pouring of the melted cast iron in the mold. See patternmaker, hollowware, and blast furnace.

Molder's finishing tools: Slicks, corner slicks, trowels, and lifters – steel hand tools used for shaping, smoothing, and finishing the surfaces of sand molds.

Mountain ore: The term used by Peter Oliver to refer to iron ore being imported from away (probably Pennsylvania) to be used as a substitute for the rapidly disappearing bog iron deposits of the Middleboro, MA, area. Oliver's Forge on the Nemasket River in Middleboro was then producing mortars, cannon, and howitzers for the Crown. In a letter dated March 21, 1756, Oliver, a Tory, noted the superiority of "mountain ore" over bog ore for heavy ordnance. (Weston 1906)

Moxon: Joseph Moxon's *Mechanick Exercises or the Doctrine of Handy-Works* [1703 (1989)] is the most comprehensive survey of blacksmithing, toolmaking, and crafts such as joinery, house carpentry, turning, bricklaying, and mechanical drawing available at the end of the 17th century, and contains important illustrations of basic tools, some of which, such as the frame saw, bow saw, scribe, bevel, keyhole saw, and chisels and gouges, are still found in old tool chests and collections, linking contemporary tool forms to English prototypes used in the early colonial period.

Muck bar: A 19th century American term for unprocessed wrought iron produced by a single passage through a rolling machine. Muck bar was usually subject to further refinement by additional shingling, rolling, or faggoting and piling into higher quality wrought iron.

Multiple hearths: While early colonial forges and bloomeries may have had only one hearth, most post 1750 iron working facilities, including bloomeries, had multiple hearths, occasionally as many as twenty or thirty. Ancony hearths, chaferies, blacksmith forges, and anchor forges are examples of special use hearths used at integrated ironworks or colonial forge complexes.

Mumbra: An ancient African tribe that made cast iron using horn and quartz as flux. (Wertime, 1962)

Music wire: Fine steel wire used as strings in musical instruments as well as for precision measurement functions; produced by drawing annealed steel wire through a draw plate. See draw plate.

Natural steel: "Steel made in a bloomery directly from iron ore. It contained slag particles since it was a carburized form of wrought iron." (Gordon 1996, 310). Natural steel production was dependent on higher than normal fuel to ore ratio, rapid air flow to prevent high furnace temperatures, high silica and manganese, and low phosphorous ore content (Barraclough 1984a, 17) and was the most common steel producing strategy before the blast furnace and the "age of steel." See bloomery, direct process, ferrosilicate, and manganese.

Natural steel edge tools: Tools that are forge-welded (hammered, quenched, and tempered) by the blacksmith directly from the bloom of unrefined smelted iron with a carbon content above 0.2%. Knowledgeable blacksmiths could make high quality edge tools using this method, but only one tool at a time. The best natural steel tools were made from manganese-bearing spathic ores, first at Halstadt (Austria), then by the Romans (Noricum steel, also Austria), in Spain in the medieval period, and especially in south Germany after 1400 AD. Natural steel edge tools were also produced, but probably with greater difficulty, by American blacksmiths with non-manganese-bearing ores before or when weld (blister) steel was not available. Natural steel was the most common constituent of forge welded edge tools from the early Iron Age until the late medieval period. See forging, bloomery, direct process, and natural steel.

Neumann bands: Bands observed in the microstructure of steel resulting from mechanical treatments such as hammering at room temperature and slow deformation at lower temperatures.

These bands are formed by twinning, i.e. the grouping of identical lamellae in patterns characteristic of the crystalline structure of a specific allotropic form of an iron carbon alloy, e.g. pearlite. See Widmanstäten structure, plastic deformation, lamellae, lattice structure, and pearlite.

Newcastle: The principle steel-producing center of England between 1700 and 1775, Newcastle in the far northeast of England predated Sheffield's emergence as England's late 18th and 19th century center of steel production. Newcastle emerged as an important steel-producing center after iron and steel production activities ended in the Forest of Dean and the Weald of Sussex. See Forest of Dean, Weald, and Weardale.

Nickel-Silver: 50% copper, 25% zinc, 25% nickel; also called German silver; strong, hard, and corrosion-resistant. See Chalibean steel, German steel, and alloy steels.

Nickel steel: An alloy steel containing nickel; nonmagnetic with high tensile strength. Nickel "increases strength by strengthening ferrite without decreasing ductility." (Shrager 1949, 187). A typical nickel alloy is 3.5% nickel and 0.5% carbon and has several thousand pounds per square inch more strength than pure steel. Steels with more than 22% nickel are nearly corrosion resistant, those with 25% to 46% nickel are used specifically for watch parts and measuring instruments due to their failure to expand and contract. Meteor iron often contains about 10% nickel, which greatly strengthens it. Chalybean nickel steel has historically been misinterpreted as meteor derived (Piaskowski 1982). See Chalybean steel and German steel.

Niello: A black alloy of silver, lead and sulphur used for filling in engraved designs in silver and other metals. See alloy and chasing.

Nodular cast iron: Also called ductile cast iron, nodular cast iron is made from iron with a low sulfur content, with various alloys such as sodium, magnesium, and cerium, in which carbon is present in spherical nodules. A versatile modern form of cast iron available in a variety of chemical configurations, characterized by high tensile strength and a significant capacity for elongation, nodular cast iron is representative of the wide variety of iron carbon alloy combinations developed in the 20th century. See cast iron.

Noric steel: Steel produced by Celtic metallurgists from the siderite ores of the Mount Erzberg region of Austria and supplied to both the Roman republic and the Roman Empire for weapons production. Noricum was a Roman province, hence the name of the natural steel produced there from the manganese-rich spathic ores. See natural steel, German steel, Erzberg, Styrian steel, Celtic metallurgy, spathas, and iron road.

Normalizing: A heat treatment for steel, normalizing is the slow cooling of iron based alloys from temperatures above the critical point in an environment of still air and normal temperatures.

Norwegian steel: Forged and laminated steel made out of high carbon hard tempered steel and soft iron; having a Rockwell hardness of 63 – 64, used by knife makers, and capable of being bent in a vise (Latham 1973).

Oakum: A shredded rope or hemp fiber often used for ship caulking, thus requiring the use of caulking irons and mallets, standard tools of the working shipyard.

Oil temper: In the forging of edge tools, the temper obtained by the quenching of tool steel in oil rather than brine or water, oil being the favorite quenching medium of the shipsmith and/or edge tool maker for forging the tools of the shipwright. See tempering, martensite, and brine quenching.

Open-hearth furnace, early forms: The most common form of furnace used in antiquity, the open-hearth furnace had two basic forms, both of which exposed the ore being smelted to the direct impact of the oxidizing flame of the burning fuel. The shaft furnace, which dates to the early Iron Age in central Europe, later developed into the high shaft German Stuckofen, the predecessor of the blast furnace. The second form was the bowl furnace, which later evolved into the Catalan furnace, used in southern Europe until the early 20th century. Both were used for direct process production of iron blooms, and both forms occur as both slag pit furnaces and slag tapped furnaces. The most primitive slag pit type furnaces were characterized by the accumulation of slag in pits underlying the furnace, which required the movement of the furnace to adjacent slag free locations. More practical and productive were furnaces designed with adjacent pits for slag tapping, the residue of which was more easily moved to rubble piles in the form of slag heaps. See shaft furnace, bowl furnace, slag pit furnace, slag tapped furnace, bloomery, and direct process.

Open-hearth furnace, modern forms: The open-hearth furnace is another name for two modern (after 1865) forms of the blast furnace, the Siemens process and the Siemens-Martin process. Both use waste gases to preheat the air blast, and are considered superior to the Bessemer blast furnace because they allow better quality control of alloy steel production. The open-hearth furnace process is also less wasteful than the Bessemer furnace, utilizing all ores and scrap, which were more slowly heated to higher temperatures by indirect radiated heat from a regenerative gas furnace. Modern open-hearth furnaces use gas, coke oven gas, natural gas, oil, and powdered coals as possible fuels. In the original Siemens open-hearth process, "molten pig iron is run onto a hearth or bedcover, which gas flames play to maintain the heat and to burn up carbon and other defects. This process took some eight hours, and in the result, was able to produce an even nature throughout. Shortly after came the Siemens-Martin process which with the use of a basic lining for the hearths had by 1877 got rid of most of the sulfur and phosphorous." (Abell 1948, 148). See basic process, acid process, Siemens-Martin process, and the Siemens regenerative gas furnace.

Optical microscope: William Sorby's use of the optical microscope to investigate the space lattice structure of ferrous metals inaugurated the science of metallography, the study of the microstructure of metals.

Ordnance: In 16th century England and Europe, ordnance, in the form of bronze and cast iron cannons and artillery, were the most important product of foundries and ironworks. The casting of cannon for the coastal defenses of England, for example, was the most important destination for the products of the blast furnaces of the Weald. The demand for ordnance, gun iron, shipsmith's ironware, and edge tools resulted in the expansion of the English iron industry from the Forest of Dean and the Weald north to the midlands, Newcastle, and Sheffield after 1600.

Ore boil: The violent frothing that occurs in the open-hearth process as a result of the interaction between the iron ore and iron oxides in the slag and the carbon in pig iron; the carbon monoxide thus formed causes the frothing.

Oriental crucible steel: Produced in high temperature resistent refractory clay crucibles in small quantities (+/- 3 kilograms) in central Asia (+/- 1000 AD) and probably much earlier in China and Japan. Also apparently a trade item which may have reached the Levant in the first millennium; probably used by the Vikings in sword production. Damascus steel is one variation of Oriental crucible steel; when Benjamin Huntsman "discovered" crucible steel, he was readapting an already known but obscure and difficult steelmaking process for his watch spring manufacturing business. See cast steel, Wootz steel, and Venetian steel.

Over coating: A modern method of ax making; over coating was the overlaying of a piece of high carbon steel (the ax bit) upon a folded iron or low carbon steel ax body prior to welding. (Kaufman, 1972, Klenman 1998). See ax making.

Osmund: A form of malleable iron or natural steel imported from Sweden and Spain during the Medieval period and used for knitting chain mail, also used to make arrowheads and fishhooks. (Gardner 1892)

Overheating: Overheating results in the surface decarburization of iron, which begins occurring at a temperature of 1200º C; surface carbon is removed and the iron is oxidized into an iron oxide scale. "No useful degree of carburization can be achieved when iron is heated unprotected in a forge fire." (Barraclough 1984a, 31). Overheating in direct process smelting had the ironic effect of promoting carbon uptake in the bloom, facilitating the formation of liquid cast iron. Iron absorbs carbon more rapidly at high temperatures; the increase in the carbon content of the bloom then lowers its melting temperature. See enclosure and bloomery process.

Overseas carrying trade: A term referring to the colonial era transport of masts, spars, planks, and other timber products to English and continental shipyards.

Overshot water wheel: The most efficient form of the water wheel, which utilizes the height and volume of falling water as the power source for the operation of the blacksmith's trip hammer, the up and down mill saw, the grist mill, and belt driven machinery of every description.

Oxidation: The combination of oxygen with an element to form an oxide, or the combination of an oxide with more oxygen to form a higher oxide. (Shrager 1949)

Oxidation-reduction reaction: The simultaneous occurrence of the oxidation and reduction of iron in the smelting process. Intermediate reducing agents remove oxygen from the reductant, e.g. iron oxide, therefore oxidizing it; carbon removes oxygen from iron oxide and then is transformed into carbon monoxide: $FeO + C = Fe + CO$. See oxidation, reduction, smelting, and ferrosilicate.

Oxidizing reaction: In iron smelting, the change in composition that occurs during the making of wrought or malleable iron or steel from pig iron when the carbon in the pig iron separates as a gas. When ferro-manganese and ferro-silicon are added to the steel making charge, they serve to reduce the dissolved gases and the iron oxide in the metal. The manganese and silicon form oxides, which collect as slag, encouraging the uniform distribution of carbon in iron to produce raw steel. See natural steel.

Pack carburization: The case hardening of stacked tools packed in a metal box containing carboniferous material, or in a pit containing charcoal.

Packing: The compacting of fibers of wrought iron or carbon steel by hammering to increase the density and thus the strength of the tool or implement being forged. Packing is done with carbon steel, for example, when the metal is "sunrise red, barely discernable in regular light… if the metal is too hot, it will not pack, if too cold it may crystallize and break." (Bealer 1976a, 168)

Pattern books: Toolmaker's catalogs issued in England by manufacturers such as Wykes (watch making tools), Stubbs (files and hand vises), and Timmins (tools of the trades) and often illustrating tool forms derived from Roman and near eastern sources. Pattern books signal the rise of a market economy in the late 18th century where the gentleman and his tool chest become equal, if not greater, in importance, than the lowly artisan such as the file maker, blacksmith, or shipsmith, all of whom used tools to make other tools. See iconography of tools, Moxon, and Diderot.

Pattern maker: The woodworker who crafts the wooden patterns that form the sand mold for casting bronze, brass, aluminum, cast iron, and steel into the wide variety of tools and equipment made in foundries. See cope, drag, and core box.

Pattern makers' shrink rules: Rules that, by graduated variations in their increments, make allowance for the changing (shrinking) dimensions of metals, which contract at various rates during the cooling process from the freezing temperature of the hot metal to room temperature. Such shrink rules, with as many as 12 variations ranging from 1/12" to 3/8" (Stanley 1984) of allowed shrinkage to the foot, provided for the fabrication of larger patterns necessary to compensate for the tendency of metal to shrink upon cooling.

Pattern welding: The ancient craft of knife and sword production based on welding together strips of natural steel or case hardened steel and strips of wrought iron, which were forge-welded, quenched, and tempered to produce the desired weapon. Used as a sword and knife making technique from the early Iron Age to the modern era; made famous by the Merovingians, Vikings, Muslim, and Japanese sword makers. See Damascene, reagent, and knife making techniques.

Pearlitic malleable cast iron: A cast iron, the manganese content of which allows its pearlite matrix to retain carbon in the form of cementite.

Pearlite: The microstructural constituent of steel derived from the eutectoid transformation of austenite; pearlite has a much higher tensile strength (125,000 lbs/sq inch) than ferrite (50,000 lbs/sq inch). If the lamellar morphology of alternating plates of ferrite and cementite containing 0.83% carbon is cooled below 723º C, it then becomes pearlite (Wayman 2000).

Pewter: An alloy of tin and lead or tin and copper; bismuth and zinc are also sometimes a constituent of pewter. While Roman pewter was high in lead, modern pewter, if intended to be used as an eating utensil, is made without lead.

Phase: The physically and chemically homogeneous alloy constituent characterized by definite bounding surfaces, e.g. austenite, cementite, ferrite, but not pearlite, which has a heterogeneous structure.

Phenomenology of tools: The sum total of all the ways in which we construct and deconstruct our world with tools, i.e. the language of tools, including not only the making and using of tools but the construction of landscapes and cityscapes as an iconography of tools. The phenomenology of tools is, in essence, the writing of history via the wielding of tools, as well as the inscription and incorporation of tools in and as art. In the 18th and 19th centuries, huge areas of North American forest were cleared for timber harvesting, charcoal production, and farming. Later in the 19th century, much of this landscape became towns, then cities with paved roads.

The transition from hand made hand tools to machine made hand tools to a consumer society where all artifacts are machine made characterizes the evolution of industrial society. Implicit in this dynamic of the phenomenology of tools are the lessons of pyrotechnic societies, i.e. the environmental impact of carbon dioxide emissions (Gore, 2005) or biologically significant chemical fallout. What is it in fact that we are constructing or have constructed with our tools? (Brack, 1984)

Phlogiston: A theory popular between the late 17th and late 18th century that combustion was due to the presence of phlogiston in the flammable materials, the phlogiston having no mass, taste, odor, or color and being produced as ash by combustion. It was assumed to occur in all flammable materials and to be released by the combustion process. The discovery of carbon and its role in combustion put an end to the phlogiston theory.

Phosphorus: A naturally occurring contaminant in iron ore; when present in wrought iron (+/- 0.025%), it increases hardness, thus is useful in the context of nail making. If above (+/- 0.05%), it causes brittleness at room temperature. It increases the fluidity of cast iron and thus aids in the casting of hollowware. See cold short.

Pickling: The use of a diluted acid bath to remove oxide scale from iron and steel surfaces prior to mechanical treatments such as cold rolling or wire drawing.

Pig iron: The high carbon iron silicon alloy (2.0 - 5.0% carbon content) produced by the hot temperatures of large shaft furnaces and later, blast furnaces. The hotter the furnace fire, the more rapid the absorption of carbon by the iron being smelted. Originally a waste product of smaller bloomery and shaft furnaces; pig iron is the first stage product of the indirect process of iron and steel making. Because cast iron was produced in a liquid form in the blast furnace, when drained off it was solidified in rows of sows, hence the term "pig" iron was due to its appearance as cooled ingots. "Iron alloyed with carbon and silicon produced in a blast furnace." (Gordon 1996, 310)

Pile: To bundle and reforge iron or steel bar stock.

Piled wrought iron: A term for refined wrought iron made by the repeated faggoting of bars or plates of bloomery iron or puddled wrought iron, followed by shingling (hammering) to remove additional carbon and slag constituents and further align the silicon slag content into the fibrous patterns that provide its unique toughness and ductility. The high quality Swedish iron bar stock used in England and America to produce steel was highly refined piled wrought iron, which was essential to the production of the highest quality edge tools. See refined wrought iron, finery, shingling, loup, and whalecrafters.

Piling: A technique used by knife and sword maker in all ages; piling was the bundling then forging of alternate layers of wrought iron and steel. In England, in the age of blister steel (1686 – 1750), piled blister steel was reforged into shear steel; the highest quality steel was known as double shear steel made by re-piling and reforging shear steel yet again (Barraclough 1984a). Shear steel production was gradually replaced by the crucible steel process, the production of steel by a chemical reaction that required fewer steps, less labor and fuel, and offered more quality control of the slag and carbon content of the cast steel being produced. See pattern welding, sword making, and knife forms.

Piling and folding: A process used by sword makers to reduce the heterogeneity of sheet steel and sheet iron during edge tool production. Sheets of steel and iron were forge-welded into a more homogenous mixture by piling and folding.

Pins: Inclusions of unwanted natural steel in wrought iron not fully decarburized, making it useless for many applications - the bane of furnaces making iron shafts and blacksmiths making wrought iron hardware and implements. See natural steel.

Pipe: The shrinkage cavity within a cast steel ingot formed as a result of uneven cooling; in crucible steel making, this cavity is eliminated by the teamer, who has an extra reserve of liquid steel to put in a dozzle (clay cone) to fill the cavity. See dozzle, cast steel, and killed steel.

Piston bellows: Developed in place of accordion bellows after 1750, and used in conjunction with steam engines; their higher efficiency allowed for the construction of larger blast furnaces.

Pit vault molds: Molds set vertically in the ground to receive cast iron or bronze for cannon casting; pit vault molds were Henry the Eighth's principal method of casting cannon in the Weald to protect the south coast of England from French invaders, circa 1520 – 1545. The more advanced 18th century methods of cannon casting are graphically illustrated in Diderot's Encyclopedia ([1751-75] 1959).

Planishing: The hammering of metal to harden and strengthen it, i.e. as in late medieval cold hammered armor.

Plastic deformation: Plastic deformation in metals results from slippage, gliding, twinning, cleavage, or creep and is accompanied by three modes of lattice reorientation. The propensity of the crystalline structure of ferrite, when in the form of wrought iron (<0.08% carbon), for example, to allow slippage, gives wrought iron its soft ductile plasticity. Plastic deformation is the movement of crystal lamellae along slip planes in a particular direction determined by the crystalline structure of the lattice network. See lattice reorientation.

Plasticity: In ferrous metallurgy: the propensity of heated crucible steel to be ductile; i.e. have high workability, to be easily rolled and shaped; no other form of steel has the extreme plasticity of heated crucible steel. The same characterization applies to wrought iron with a carbon content of 0.08% or less; its silicon content enhances its plasticity and workability.

Plating mills: Colonial era ironworks first established in the early 18th century for making sheet iron to produce iron kettles, pans, and utensils as well as hoops for coopers and tin plate for whitesmiths.

Polymetalic societies: Pyrotechnic communities that smelted multiple types of metals, including copper, silver, gold, bronze, and iron; polymetalism is one of the characteristics of industrial society.

Prime mover: The fundamental power source of any tool or machine – human, animal, or water power. The steam engine utilizes heat as a prime mover to do work. See engine and Hunter (1979).

Principio: The largest integrated ironworks in the Mid-Atlantic colonies, Principio (est. 1731) was located at the head of Chesapeake Bay and was a focal point of the growth of the American iron industry in the Pennsylvania/Maryland region after 1720. (Gordon, 1996). Ship fittings produced at Principio and nearby furnaces "ironed" the famous Baltimore clippers constructed in Chesapeake Bay in the century following the establishment of this ironworks.

Privilege: The granting of the right to use the water of a running stream or brook to power a waterwheel for the operation of a trip hammer at a blacksmith forge or for powering saw mills, grist mills or water powered machinery. Individual communities issued privileges from the early colonial period until the middle of the 19^{th} century. See overshot water wheel and trip hammer.

Proeutectiod: The designation for steel, in the form of austenite, formed by ferrite and cementite above the eutectoid temperature of 723º C. When cooled slowly (below 723º C) austenite becomes pearlite, the main microstructural component of cementation steel, with a heterogeneous carbon distribution; if rapidly cooled, martensite is formed. See hypereutectoid steel and hypoeutectoid steel.

Profiler: A machine for cutting complex dies in the die sinking process.

Pressed steel: Steel plate bent or pressed by means of dies into channel or other sectional forms, giving great strength with a minimum weight of metal. (Audel 1948, 419)

Puddled bar: In the decarburization of cast iron, the first bar rolled from a puddled bloom of wrought iron after shingling; also called a muck bar due to entrained impurities. The puddled bar is often subject to further fining and processing. See puddling furnace, muck bar, and finery.

Puddled steel: Puddling is the manufacturing of steel in a puddling furnace by the premature halting of the decarburizing process. "Carbon removal is slowed by adding manganese oxide instead of iron oxide, stopping the boil of the puddled iron. Puddled steel is high in slag content and became an important source of steel in Germany and England between 1855 and 1870." (Barraclough 1984a). Barraclough also notes the oxidation of the carbon was retarded by the "smoky, reducing atmosphere in the furnace during the latter part of the process." Barraclough 1984b, 93-94. Puddled steel to some extent replaced the traditional production of German steel, which was made by decarburizing cast iron in the traditional shaft furnaces. In this sense, puddled steel is “German steel” produced in a refractory (puddling) furnace. Barraclough also notes "it provided for the needs of industry for some time, in default of a better method, and was capable of producing a satisfactory steel from phosphoric pig iron, which is more than could be said for either Bessemer or open-hearth steel up until 1880. It is strange that it has been largely overlooked by almost all of the historians of the iron and steel industry." (Barraclough, 1984b, 94) The extent of production in the United States is unknown, but puddled steel may have been used for small scale edge tool production in New England and elsewhere. Halting the decarburization of cast iron to produce steel instead of wrought iron was very difficult due to the challenge of estimating the carbon content of the steel being produced. It is unknown to what extent individual New England ironmongers mastered this technique and thus supplemented the traditional process of using cementation furnaces to produce blister steel, which then had to be piled and reforged to produce higher quality edge tool steels.

Puddled wrought iron: Made in reverbatory (puddling) furnaces after 1785 by the indirect process from decarburized cast iron, puddled wrought iron contained less siliceous slag than direct process bloomery wrought iron. By 1930, due to the disappearance of both the bloomery and the puddling furnace, wrought iron was no longer produced in any significant quantities in the U.S. See reverbatory furnace, puddled steel, and wrought iron.

Puddling: To decarburize cast iron and to oxidize its slag constituents in a reverbatory furnace.

Puddling furnace: Also called the reverbatory furnace, the puddling furnace was a redesigned version of older refractory furnaces; the first of Henry Cort's puddling furnaces was built in 1784 and was one of the most important advances in iron and steel production during the second stage of the Industrial Revolution. The puddling furnace kept the fuel separated from the ore to avoid recarburization and was used for producing relatively slag free wrought iron from pig iron, using coal or coke as a fuel.

Pyrotechnologic products: The glass, pottery, lime (cement), copper, bronze, iron, steel, and tool steel alloy products produced by polymetalic pyrotechnic societies from the Copper Age to the contemporary era. The characteristic byproduct accompanying polymetalic industrial production is carbon dioxide (CO_2). See phenomenology of tools.

Pyrotechnology: The use of fire to make glass, terra cotta (pottery), cement (lime), iron, and other metals; the primordial industrial basis for civilized society. Given the environmental consequences of pyrotechnic societies including climate change, after five millennia of carbon dioxide emitting industries, industrial civilization may be sailing close to the wind. (Gore, 2006)

Quench hardening: The art of making steel more homogenous by sudden cooling for the purpose of hardening. Hardened steel edge tools were tempered (reheated to less than the forging temperature and slowly cooled to relieve brittleness). See austenite, martensite, tempering, and quenching.

Quenching: The rapid cooling of steel to increase its strength and hardness; quenching also results in extreme brittleness of steel requiring further heat treatment (tempering). For austenized steel, brine, cold water, and oil are the fastest quenching mediums, respectively. Ancient quenching techniques included urine and other assorted odd combinations. See martensite, tempering, carbon content of iron and steel, and quenching threshold.

Quenching method: Choice of quenching methods determines hardness as a function of the rate of cooling; brine, water, oil, and air are the most common quenching mediums.

Quenching temperature: Higher carbon content steel requires a lower temperature for efficient quenching; lower carbon content steel requires a higher temperature.

Quenching threshold: Iron containing less than 0.5% carbon cannot be significantly hardened by quenching and therefore cannot be made into tool steel or quality edge tools. A large percentage of modern steel is low carbon steel (0.2 - 0.5% cc), which can only be slightly hardened by quenching.

Rabble: The tool used by the iron puddler in a reverbatory furnace to stir, form, and remove the loup of wrought iron in the furnace.

Reagent: With respect to Damascus steel, the reagent is the acidic medium, such as lemon juice, used to reveal the particular crystalline structure that results from the forge welding of the sword or gun barrel by a particular smith.

Recarburizer: Carbonaceous materials, including pig iron, added to molten steel to increase its carbon content. Analogous to the ancient process of submerging wrought iron in a bath of pig iron to produce steel.

Recalescene: The sudden reappearance of glowing light in metal being cooled, which occurs during the transition of beta iron to alpha iron.

Recovery: Recovery is the loss of lattice dislocation through the elimination by diffusion of strain hardening from thermal stress, and the subsequent re-crystallization of the lattice structure of a metal.

Re-crystallization: Re-crystallization results from the use of heat treatment to form new crystalline lattice structures in deformed metals.

Red brass: 85% copper, 5% tin, 5% lead, 5% zinc.

Red ocher: A mineral iron oxide and the most valuable of all iron ores (Fe_2O_3), red ocher is finely ground hematite and is perhaps best known for its ceremonial uses in indigenous Native American burial sites.

Red short: "When impurities, such as sulphur arsenic, render the metal unworkable at a red heat, it is said to be *red short*." (Spring 1917). Its brittleness makes it subject to shattering when hammered or forged.

Reducing: The transformation of an element by the removal of oxygen from a highly oxidized state to a less oxidized state, as n the conversion of iron oxide to iron in a blast furnace.

Reducing slag: Slag that facilitates the removal of oxygen.

Reductant: The reactant, e.g. carbon monoxide, that facilitates the chemical reduction of iron oxide to iron, also producing carbon dioxide, while removing the oxygen.

Reduction: The partial or complete removal of oxygen from an oxide. See oxidation reduction reaction.

Refined iron: An optional intermediate step in the production of fine quality wrought iron in the puddling furnace, pig iron is partially decarburized in a run out (cupola) furnace in which multiple tuyères produce an air blast that removes much of the silicon and carbon in the pig iron. The iron is then cast in iron molds and cooled by water circulating in the hollow walls of the mold. The resulting iron, in the form of plates or ingots, is then broken up and further decarburized in the puddling furnace to produce high quality wrought iron.

Refinery: "Hearth used to remove silicon from pig iron preparatory to fining or puddling, usually fired with coke." (Gordon 1996, 310). Not to be confused with "finery," an open-hearth furnace used since ancient times to refine either bloomery iron or cast iron. The refinery represented an additional step in the industrial process utilized, especially in the 19th century, to prepare the cast iron for subsequent manufacturing processes, such as rolling, slitting, or drop-forging.

Refractories: Another term for the crucibles used in cast steel production, which necessitates special high temperature resistant clays (+/-1500º C). The principal contribution of Benjamin Huntsman's reintroduction of the crucible steel process (1742) was his use of high temperature resistant Stourbridge clays to manufacture his crucibles. The unavailability of such clays in America postponed the advent of cast steel production until the Civil War. In the modern era, any high temperature resistant material used to line furnaces. See Stourbridge clays.

Regenerative gas furnace: This form of furnace was introduced in America in 1857, shortly after it was developed in France by Sir Carl Wilhelm Siemens; it recycled and burned waste blast furnace gases, further increasing blast furnace efficiency.

Regeneration: The use of the waste heat and escaping gases to preheat incoming air in blast and other furnaces.

Rennwerk: The direct process reduction of iron ore to wrought iron in which steel is sometimes a byproduct. In Sweden, circa 1600, this was one of three options for making steel. The other two were fining (decarburizing) cast iron (also called German steel) and carburizing wrought iron in a steel furnace (blister steel). After the last decade of the 17th century, blister steel production replaced the fining of cast iron as the principle method for steel production in England; the decarburization of cast iron to make steel remained the principal steel production strategy in most of continental Europe well into the mid-19th century.

Repoussé: The formation of raised designs by hammering the reverse side of malleable sheet metals being utilized for jewelry (etc.) design and manufacture. Combined with chasing, the two techniques are utilized to create three-dimensional works of art. See chasing.

Retained austenite: The retention of austenite results from adding alloys to carbon steel, which prevent the transformation of austenite to martensite, allowing as much as 35% of the structure of steel to remain as non-magnetic austenite, e.g. stainless steels. Tempering will eliminate retained austenite. (Shrager 1949)

Reverbatory furnace: "Furnace with a brick roof heated by flame. Metal on the hearth is heated by reflection and radiation from the roof and does not come in contact with the fuel." (Gordon 1996, 310). Henry Cort's improved design of the reverbatory furnace (1784) was a key event in the Industrial Revolution, enabling the rapid production of larger quantities of wrought and malleable iron for hand forged hardware and tools. The reverbatory furnace was especially important for the refining of cast iron to nearly pure wrought iron to be used in the production of cementation steel, which was then utilized in producing pure crucible steel (cast steel). Also called refractory furnace. See puddling furnace.

Riddle: A foundry sieve usually made of brass or galvanized iron cloth for removing solid materials from molding sand.

R.M.S.: A forerunner of high speed steel, Robert Mushet's special self hardening steel, R.M.S., introduced in 1868, contained 7% tungsten and increased metal cutting speeds by 50% (Tweedale 1986). Later it was discovered that manganese rather than tungsten was responsible for its increased efficiency. See Taylor-White steels.

Roasting ovens: Roasting ovens were commonly used before 1850 to preheat and dry iron ore before smelting in either a bloomery or blast furnace. The roasting process was a variation of the ore dressing process, which could also be done by manual crushing with a sledge and air drying; the objective of these processes was to make the surface of the iron ore more porous and thus susceptible to the effects of reducing gases in smelting processes.

Rockwell hardener test: "A method of determining the hardness of metals by indenting them with a hard steel ball or a diamond cone under a specified load, measuring the depth of penetration, and subtracting the latter from an arbitrary constant. Rockwell hardness numbers are based on the difference between the depths of penetration at major and minor load; the greater this difference, the less the hardness number." (Shrager 1949)

Rod mill: A mill utilized for rolling billets into semi-finished hot-rolled rods used for wire drawing.

Rolling direction: Rolling direction determines grain direction in steel or iron bar stock; for knife and edge toolmakers cutting curves or patterns across the grain, reforging the grain direction is necessary before a new directional pattern to the lattice structure of the steel or forged iron tool can be implemented.

Rolling mill: After the decarburization of cast iron in a finery and further refinement of the anconies produced in a chafery, rolling mills were used to shape malleable iron into useable forms such as nail and wire rods, bar stock, and sheet metal for forging into nails, tools, and utensils by a blacksmith or small foundry, or later, into rails (>1830) and I-beams (1870). Rolling removed impurities and further strengthened the iron or steel being rolled. In 1784, Henry Cort designed the basic form of the modern rolling mill, adding groove rollers to rapidly shape the puddled iron produced by his recently redesigned puddling furnace into a multiplicity of forms suitable for manufacturing iron wares of every description.

Ruff, Drawn, Gadd, and Slick (steel): Early 18th century English terminology pertaining to cementation steel and its faggotted and welded enhancements: spring, single shear, and double shear. German immigrants living in or near Newcastle (1680 through 1730) were instrumental in introducing continental steel finishing strategies and applying them to the production of improved varieties of cementation steel.

Round hearth: Introduced in America in 1832, this innovative hearth design increased the efficiency of blast and bloomery furnaces.

Russian iron: Sheet iron with a very hard and highly polished surface, made in Russia by a secret process and used for steam engine boilers, etc., also known as planished iron due to its smooth surface.

Sagger: Metal pot used to hold castings to be malleableized by annealing.

Salamander: Slabs or bears of solidified cast iron produced by high shaft direct process bloomery furnaces as unwanted waste products during the bloom smelting process. In central Europe, they may have been the basis for recognizing the possibility of decarburizing cast iron to produce German steel by altering the fuel to ore ratio in the smelting process. See direct process.

Salt bath: Baths of molten chemical salts utilized for hardening and tempering a metal; they provide uniformity of heat treatment as well as protection from oxidation.

Sand molds: First used by Abraham Darby at his Bristol iron foundry in the early 17th century, sand molds were made with wooden patterns and allowed precise shaping of cast iron products. Sand molds replaced the earlier technique of molding with hay, clay and loam and could be utilized for multiple castings. Wooden patterns and sand molds paved the way for the production of Newcomen steam engine cylinders by Abraham Darby II (c. 1722-1733). See molding, foundry, and cast iron.

Sandwich technique: One of several ancient strategies for making knives; sheet iron is wrapped around a steel core, which is then ground away to expose the cutting edge. See Pleiner (1962).

Sap: Sap is the traditional term for the characteristic appearance of the fracture of blister steel produced in cementation furnaces. Changes in the appearance of sap express the changes in the crystalline structure of iron in its conversion from malleable iron to steel. See fracture, Sheffield classification of blister steel, and cementation furnace.

Scarf weld: An ancient technique for making knives and swords, steel is laid on cold iron, wired, heated, and welded to create a steeled edge tool. Also see Bealer (1976) for a contemporary description of the blacksmith's art of scarf welding, the hammering and welding of two overlapped pieces of metal. See forging.

Secondary hardness: The phenomenon of a second hardening occurs during the tempering of high alloy steel (only), after the initial quench hardening.

Self-hard: The first commercial alloy steel, invented by R. F. Mushet in 1868.

Self-hardening steel: High carbon alloy steels, which harden at room temperature without oil or water quenching; their alloy content slows the transformation of austenite to pearlite.

Semi-steel: High-grade gray cast iron, which is made stronger by the addition of steel scrap in the charge, contains lower silicon, phosphorous, and total carbon content than gray cast irons (3.2% versus 3.4% for gray cast iron and 3.45% for soft gray cast iron). In contrast, the carbon content of white cast iron and annealed malleable cast iron is 2.75%. See cast iron and carbon content of iron and steel.

Shaft furnace: Along with the bowl furnace, the shaft furnace was the most common form of open-hearth furnace for smelting iron; shaft furnaces evolved into blast furnaces as the length of the shaft grew in size. Early Iron Age shaft furnaces were difficult to control and often produced iron with a heterogeneous carbon content, ranging from liquid cast iron and natural steel to malleable iron, though low carbon wrought iron might have been the goal of the smelt. The high shaft bloomery "Stuckofen" furnace of south Germany was the final stage in direct process iron production (circa 1500 AD); the larger shaft furnaces which followed were true blast furnaces producing cast iron that needed refinement into wrought iron and/or steel. See bowl furnace, open hearth furnace, slag pit furnace, slag tapped furnace, and bloomery.

Shaft hole vs. Socket hole: The two alternative methods of securing handles to adzes, axes, and hammers. In Neolithic Europe, socket hole tool design was "the traditional method of hafting the head to a knee-shaped, cleft handle. In the course of time, the shape of the head was drastically modified, yet even when casting was adopted they still kept to the old way of lashing the head to the shaft." (Goodman, 1964, 14) In the early Iron Age in Europe, some socket holes were of square design; "It was about this time, between 500 and 200 B.C., that this traditional method was finally abandoned, and the axe assumed the form familiar to us today, a heavy wedge-shaped forging, with the shaft-hole, usually elliptical in cross-section, made by folding a rectangular billet of iron in the middle, leaving the eye parallel to the cutting edge." (Goodman, 1964, 20). Goodman illustrates shaft hole axes and adzes dating as early as 2900 BC, including Mesopotamian tools utilizing this modern form. It is one of the mysteries of history why the primitive socket hole tool forms continued to be used in Cis-Alpine Europe. . . "One of the most curious blind allies in the whole checkered history of human progress." (Goodman, 1964, 14). See Goodman (1964) *History of Woodworking Tools*; Childe (1925), and *Steel and Tool Making Strategies and Techniques before 1870*, Brack (2007).

Shear steel: The reworking of blister steel to increase purity and homogeneity by taking cut bars of blister steel and piling, reheating, re-welding, re-hammering, and/or re-rolling them. The mechanical working of bundled bars of blister steel more evenly distributed its carbon content. It is called shear steel "because blades for shears for cropping woolen cloth were always made this way." (Spring 1917, 117). Prior to the production of crucible steel, shear or "sheaf" steel was the highest quality steel available; implements marked "shear" or "sheaf" were usually manufactured before 1784, after which the designation "cast steel" became more commonplace. Also called "spring" steel. Many a shipwright's tool was made from shear steel by New England's edge toolmakers.

Shear stress: The stress threshold for crystal flow (slip and creep), shear stress in the lattice (crystalline) structure of metals is temperature dependent, decreasing with increasing temperature and reaching zero at the melting point.

Sheet iron: Produced by plating mills beginning in the early 18th century for use by coopers for hoops and tin plate for whitesmiths.

Sheffield classification of blister steel:

Temper Number	Mean Carbon Content %	Name	Fracture Appearance
1	0.60-0.70	Spring Heat	80% sap
2	0.75-0.85	Cutlery Heat	60% sap
3	0.90-1.00	Shear Heat	40% sap
4	1.05-1.15	Double Shear Heat	20% sap
5	1.20-1.35	Steel Through Heat	Fine crystals throughout
6	1.40-1.60	Melting Heat	Coarse crystals throughout
7	1.70-2.00	Glazed Heat	Very coarse crystals throughout

(Barraclough 1984a)

Sheffield plate: Developed in the late 18th century as imitation silver by Thomas Boulsover, Sheffield plate is fused copper and silver (Tweedale 1987).

Shingler: The manipulator of the puddled ball being hammered at a puddling furnace.

Shingling the loup: This was the first step in manufacturing wrought iron bar stock. The forge master hammered the hot metal bloom of wrought iron to expel the impurities, shape the bloom, and align the silicon fibers remaining in the bloom to enhance the tensile strength of the metal. Shingling preceded the fining (reheating, re-hammering) of the wrought iron or malleable iron, which was then shaped into bars called anconies. See rolling direction, refined iron, puddled iron, merchant bar, and piled wrought iron.

Shipsmith: In England and northwestern Europe in early modern times, the shipsmith was the ironmonger who made both the iron fittings and the edge tools needed to construct a sailing ship; in many cases he also made the anchors. In colonial New England, shipsmiths initially made many of the shipwrights' tools; both the North River and the Taunton River in the bog iron country of southeastern Massachusetts were the location of the forges of numerous shipsmiths working between 1650 and 1750. After 1800, trade specialization resulted in the shipsmith and the edge tool makers being regarded as separate trades, as illustrated in the 1856 *Maine Business Directory*, which lists both as separate trades; all so listed lived in coastal shipbuilding communities or nearby upstream towns with water power for trip hammers and easy access to the Maine coast by river. See adz, slick, and broad ax.

Siemens-Martin process: In 1865, the Martin brothers utilized the regenerative gas furnace designed by Siemens to develop one of the first bulk steel making technologies, which was later perfected in 1877 with the introduction of basic hearth linings. The Siemens-Martin process enabled the melting of any combination of cast and wrought iron to make steel. This process combined the melting of pig iron in open-hearth furnaces by the Siemens process with the addition of molten pig iron to the charge utilized by the Martin process, which originated in France. After 1877, the basic open-hearth process produced more tonnage of iron than the acid open-hearth process, which could not utilize iron ores or pig iron high in phosphorous. See open hearth furnace.

Siemens regenerative gas furnace: Developed in 1857, the gas furnace was quickly adapted for open hearth furnaces as well as for more efficient crucible steel production, both in England and America.

Siliceous slag: The slag or iron silicate content in wrought iron (1.0 - 3.0%); its content depends on the type and extent of mechanical treatment of iron by the smith with hammer and anvil, water-powered trip hammers, or with rolling mills. Most siliceous slag is removed by the blast furnace in indirect iron and steel production; most siliceous slag remains in wrought iron after direct process bloomery smelting. After bloomery smelted wrought iron is refined in a finery furnace, trace amounts of slag remain in the iron, which may play a role as micro-constituents in edge tool production. Trace quantities of silicon of silicon may also be added to cast steel as the result of chemical reactions in the walls of the clay crucibles, which shed tiny amounts of silicon-bearing material back into the crucible steel. The role of silicon as a micro-constituent in the production of fine edge tools has not been determined. See silicon as a softener.

Silicon: Silicon softens cast iron and increases its fluidity; strengthens ferrites, decomposes other carbides and enhances graphite formation. It may also soften edge tools, increasing their ductility.

Silicon as a softener: Silicon helps precipitate chemically combined carbon into free graphitic flakes; the higher the silicon content, the more combined carbon becomes graphite. Silicon greatly increases the machinability of cast iron, for example, iron valves and hollowware. Silicon may also play a role in making those old cast steel plane blades and edge tools from Sheffield and Pittsburg superior to the tools produced from steel made in the modern electric furnace; their silicon content produces a softer more congenial cutting edge traditionally preferred by shipwrights, timber framers, and case furniture makers. The silicon content of edge tools may also increase durability by increasing the tensile strength of the cutting edge, relieving the brittleness characteristic of many modern edge tools. See siliceous slag.

Silicon steel: An alloy steel containing silicon. If containing 1 to 2% silicon it is very tough and suitable for automobile springs. With 3 to 5% silicon it has improved magnetic properties and is often used in electrical appliances. Its role in woodworking edge tool production remains undocumented.

Silver steel: Noted by Cyril Smith as "the first alloy steel to become – undeservedly – popular." It was utilized by Stodart and Faraday during their attempts to duplicated Damascus steel. (Smith 1960, 141) "A soft and ductile steel with a low carbon content. It is supplied ground to a bright finish in small-diameter rods. It is useful for model makers and in laboratories. It cannot be hardened owing to its low carbon content." (Salaman 1975, 247)

Skelp: Strips of mill steel used to produce lap-welded and/or butt-welded steel tubes by drawing the strips through a bell-shaped pattern at welding temperature.

Slack quenching: A quenching rate too slow to produce martensite; the austenite being slowly cooled instead forms pearlite, lamellae of ferrite and cementite arranged by twinning into

Neumann bands. Cyril Smith notes that slack quenching "worked best on a relatively low carbon material. Damascus swords were quenched slowly in oil, or by a current of air." (Smith 1960, Footnote 24). See ferrosilicate, flux, acid process, basic process, and manganese.

Slag: The non-metallic waste product of bloomery and blast furnaces, usually a silicate of calcium, magnesium, and aluminum, which covers the molten metal in the smelting process. The slag of small bloomery and open-hearth furnaces contains more wasted iron (oxide) than the slag of more efficient blast furnaces, especially if limestone was used as the flux. The slag is usually skimmed off of the molten metal prior to tapping or pouring.

Slag heap: The tell-tale evidence of smelting activities; the siliceous slag-bearing waste products of bloomeries and blast furnaces.

Slick (slice): A long chisel for smoothing or stripping the planking of a wooden vessel, also called a slice by many a Down East shipwright.

Slickers: The hand tools used by molders in a foundry to smooth and finish a sand cast prior to the casting process. See molder, core, drag, foundry, hollowware, and sand pattern.

Slip: Grain displacement that occurs within the crystalline lattice structure of metals during deformation. See plastic deformation, unit cell, space lattice, and stress fields.

Slip interference: The collision of crystals within the lattice structure of metals during slip events, causing internal stress and hardening of the metal. See work hardening, stress fields.

Slip lines: The bands observed on stressed metals due to the deformation of their crystalline structure after cold working by any mechanical process. See slip interference.

Slip plane: That component of the crystallographic plane of the lattice structure of a metal that undergoes plastic deformation during mechanical or thermal treatments.

Slitting mill: A mill with machinery used to cut iron bar stock into rods for use in nail making or wire drawing. Often associated with the chafery in integrated ironworks, slitting is a further step in the refining of wrought iron. Slitting mills were first established in New England in the late 17^{th} century.

Smelting: The reduction of a metal ore, e.g. iron, by a chemical reaction in a high temperature furnace. In the smelting of iron ore, the melted or partially melted product is either cast iron produced in the indirect process after cooling/solidification, or a semi-pasty bloom of either wrought iron or malleable iron produced by direct process reduction with variable carbon content, usually lower than 0.5%. "Any metallurgical operation in which the metal sought is separated in a state of fusion from the impurities with which it may be chemically combined or physically mixed. (Shrager 1949, 377). See blast furnace, bloomery, furnace types, and reduction.

Smelting furnace: A furnace used to reduce iron and other metals from their chemically combined state, e.g. iron oxide, to a metallic state by dissolution (reduction) of the chemical bonds of the iron oxides or other iron ores. In the smelting process, carbon atoms in the furnace fuel remove oxygen atoms from the iron ore, producing iron with a range of carbon content. The most common product of the smelting furnace is wrought iron with a carbon content below 0.08% carbon and ranging as low as 0.02% carbon. The lower the carbon content of the iron produced by the smelting furnace, the more malleable and ductile the wrought iron being produced. In the smelting furnace the iron bloom coalesces at 730º C as a plastic mass that is easy to shape by hammering. If the smelting furnace reaches a temperature of 1150º C to 1200º C, the iron absorbs carbon; at 3.5% carbon content, the eutectic point, liquid cast iron is produced due to the lower melting temperature of iron with a high carbon content. Wertime notes the difficulty of controlling the smelting process in early shaft and bowl furnaces: "The small furnaces to be found in ancient China, medieval Europe or modern Africa posses the capability to yield high-carbon cast iron. Any effort to avoid this result and to produce low carbon wrought iron or steel, by means of a process involving only a single step, became a matter of exquisite human and technical restraint." (Wertime 1962, 44)

Smithy: A blacksmith's workshop for light duty forge-welding, in contrast to a larger forge equipped with a trip hammer for heavy duty work. See trip hammer and water powered drop hammer.

Solder: A combination of tin and lead used by tinsmiths for joining tin plate since the mid 16^{th} century; now commonly found in contemporary workshops and recently the subject of concern due to the health threat from lead poisoning. Also, an alloy of two or more metals used for joining other metals by surface adhesion. See alloy.

Solidification range: The range of temperatures that culminate in the freezing or solidification of a metal. See solidus and liquidus.

Solid solution: The dissolved composition of two metals within each other in their solid state.

Solidus: The lower curve in a constitutional diagram, which is the locus of temperatures at which each alloy has completed solidification. See Barraclough's constitutional diagram in the Iron Carbon Diagrams appendix.

Space Lattice: "The orderly geometric form into which atoms tend to arrange themselves during the process of crystallization." (Shrager 1949) "Every point of a space lattice has identical surroundings… There are 14 space lattices. No more than 14 ways can be found in which points can be arranged in space so that each point has identical surroundings." (Barrett 1943, 2-3). Space lattices are expressed through their system of axis, each of which possesses specific characteristics, i.e. equality of angles and links. The basic unit of a space lattice is the unit cell, which in metallurgy has three common forms: body centered cubic (bcc), face centered cubic (fcc), and close packed hexagonal (cph). While there are a limited number of forms of the space lattice, there is an unlimited number of crystalline structure patterns that can exist within those forms. When in the form of low carbon ferrite, iron is characterized by the body-centered cubic form of the space lattice of its crystalline structure, which provides strength in comparison to the face-centered cubic form of ductile metals such as copper and gold. When heated beyond the temperature of 910º C, the allotropic form, and thus the space lattice structure, changes to the face centered cubic form (austenite). Metals that lack plasticity, such as cobalt and titanium,

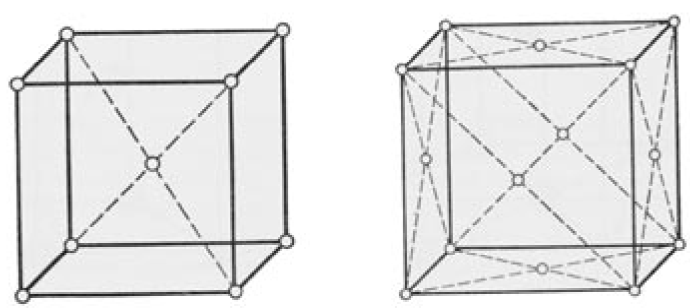

Figure 2. Body-centered cubic unit cell.   Figure 3. Face-centered cubic unit cell.

Figure 1. Space lattice (Shrager 1961, 5).

have a close packed hexagonal crystalline structure. See Shrager (1949), Barrett (1943), plastic deformation, unit cell, and lattice reorientation.

Spalling: The surface cracking and flaking of metals resulting in the creation of small particles of loose metal.

Spangle: The surface patterns on watered steel swords, derived from the crystalline structure of the steel. See Damascus steel, Damascened steel, and especially Cyril Smith (1960).

Spathas: Doubled edged pattern welded broad swords used by the Goths to defeat the Romans at the battle of Adrianople (400 AD). In 53 BC, the Romans had defeated the Gauls with the help of their superior swords, made by Celtic metallurgists (sword smiths) in Noricum, who now made the Spathas for the Goths to use against the Romans (Gardner 1892). See Noricum, pattern welding, Styrian steel, iron road, and Celtic metallurgy.

Spathic ore: Another name for the manganese rich iron ores from the Styrian and Carinthian section of Austria. See German steel, manganese, Noricum, Spiegeleisen, Styrian ore.

Spheroidizing: The softening of high carbon steels by the freeing of ferrite from cementite, therefore causing the cementite to assume a globular crystalline structure, facilitating machinability. Spheroidizing occurs after initial heating just above the transformation temperature, followed by lengthy heating just below the critical point, i.e. another form of heat treatment.

Spiegeleisen: In its modern form, a pig iron containing 15 - 30% manganese and 4.5 – 5.0% carbon, added to steel both as a deoxidizing agent and to raise the manganese content of the steel. (Shrager 1949) Spiegeleisen also refers to cast iron derived from ores containing naturally occurring manganese, which was used to produce "German" steel (1400 to 1875 AD). This cast iron was produced in a blast furnace using manganese rich siderite iron ores (+/- 2.0% manganese), resulting in cast iron with a bright, mirror like appearance or “mirror iron,” a brittle fracture, and manganese content of 5.0 - 10.0% in its final form. Manganese as a component of the flux preferentially combined with sulfur and phosphorus; their elimination in and as slag allowed more homogeneous carbon distribution within the austenitic iron after the slag formation (manganese oxidation) process. The resulting steel/iron mix was further refined into bar stock, bundled, reheated, quenched, broken up into fragments, reheated, annealed for +/- 45 minutes, and re-hammered as billets of steel (German steel). German steel was also produced in England after the establishment of the first blast furnaces in the mid 15th century, until the cementation furnace became widely used after the mid 17th century. On September 22, 1857, Robert Mushet patented the modern form of Spiegeleisen as an addition to Bessemer steel to relieve its “burnt out” quality (Fisher 1963) by enhancing its strength, durability, and hardness. The addition of Spiegeleisen was a key step in the successful adaptation of the Bessemer steel process to a wide variety of industrial applications (e.g. steel rails and machinery). The widely varying amounts of manganese in various forms of cast iron produced from 1350 to the present time, as well as its presence in a wide variety of modern tool steels, illustrates its importance as an alloy of iron and steel. See German steel, alloy steel, Styrian steel, Noric steel, and manganese.

Spring steel: Blister or weld steel reheated, re-hammered, and/or re-rolled into bar steel to increase purity and homogeneity. Prior to the era of Sheffield crucible steel production (cast steel), all high quality tool and special purpose steels were manufactured by piling and reforging bars of blister steel that would, in some cases, be tediously but artfully reworked into fine steel tools of equal quality to the later more easily manufactured cast steel tools. See shear steel, cast steel definition 1, blister steel, and piling.

Sprue: Representative test pieces of cast iron, which show by their fracture their approximate composition, i.e. a gray iron fracture indicates a high silicon content.

Spurrier: The smith who forged steel spurs and stirrups in the Medieval era. (Gardner 1892)

Stainless steel: Developed by Harry Brearley in 1913 for cutlery, stainless steel contains 18% chromium and 8% nickel, has high tensile strength and resists abrasion and corrosion. One of the most important steels produced in the modern electric arc furnace.

Stampings: Drop-forged tools or hardware (e.g. gun parts) made by forcing red hot low carbon steel or malleable iron into dies. See drop forging, malleable iron, and low carbon steel.

Steam driven tilting saws: The single most important mechanical device invented to facilitate wooden ship building; the appearance of tilting saws in Bath, Maine area shipyards beginning in 1850 (Baker 1973) signaled an end to millenniums of use of the whip, pit, and frame saws as the mainstays of the work of ships' carpenters.

Steel: A thermodynamically stable alloy of iron containing from 0.2% to 2.0% carbon. In contrast, wrought iron, a silicon slag bearing iron alloy, is defined as containing <0.8% carbon content. Cast iron, which is much more brittle than steel, is an iron alloy containing more than 2.0 - 2.2% carbon; most cast iron products contain 3 - 3.5% carbon. (Note: the upper and lower limits of carbon in steel vary among information sources.) Steel is malleable at high temperatures; its ductility, malleability, and ability to be welded decreases in proportion to its rising carbon content. Thermal and mechanical processing determine its microstructure. Its unique quality, if containing in excess of 0.5% carbon (the quenching threshold of steel) is that it is greatly hardened by sudden cooling (quenching), after which it is very brittle and fractures easily, requiring further heat treatment by tempering or annealing to soften the martinized steel for edge tool production and other uses. Quality edge tool manufacturing is only possible with repeated slow reheating, hammering, and slow re-cooling (annealing, also called tempering) of the steel cutting surface of the edge tool. The advent of the modern open-hearth electric furnace process allowed a wide variety of alloy steel types to be manufactured, therefore opening up the floodgates for tool and machinery production of every description, i.e. the classic period of the Industrial Revolution. The magic of steel is its range of properties. The most remarkable quality of steel is its capability of being tempered to many degrees of hardness, allowing the production of a wide variety of tools and weapons from ancient to modern times. See carbon content of iron and steel, natural steel, German steel, puddled steel, bulk process steel, and low carbon steel.

Steel blooms: Steel produced as semi-solid or solid masses by the following processes: natural, Brescian, German, blister (cementation), and puddling. Liquid steel, in contrast, was produced in crucibles and by modern bulk steel making processes, such as the Bessemer.

Steel furnace: Prior to the introduction of modern forms of steel furnaces, the term “steel furnace” was synonymous with cementation furnace, which were sandstone furnaces that kept the fire separated from the ore being smelted. Cementation furnaces for blister steel production replaced shaft furnaces for producing German steel in England in the mid to late 17th century and began appearing in America after 1720. See furnace types and cementation furnace.

Steel piling: The piled steel sword is the characteristic sword of the Vikings, made from piled sheets or strips of steel, possibly Wootz steel obtained during trading activities; piled steel swords are a variant form of the earlier Merovingian swords +/- 700 AD, made from pattern welded layers of steel and wrought iron. See pattern welding, Viking swords, Wootz steel, and Merovingian swords.

Steel press: "A machine for compressing molten steel in casting, to improve the quality of the product." (Audel, 1942, 544)

Steeling definition 1: The process used by a blacksmith to convert red hot wrought iron to steel. The process includes repeated hammering to remove slag and other impurities, reheating the wrought iron allowing it to absorb sufficient carbon from a carburizing fuel such as charcoal, for example, by case hardening, quenching (rapid cooling) to achieve hardness, and tempering (slow reheating and cooling) for a final softening of the steel. Prior to the era of modern chemical analysis (1885 f.) a blacksmith judged the quality of his steel intuitively and subjectively as well as objectively by considering the following observable properties of his product: appearance, texture, feel, color, fracture, and grain. In essence, the job of a blacksmith was to evaluate the microstructural changes when wrought iron is converted to steel by making visual and tactile evaluations of his product. Did the desired steel product have tears, veins, spots, or fissures indicating impurities? Did the product have the smooth look and feel of steel rather than the gray or white grainy quality of cast iron, or the fibrous ductile quality of wrought iron? In this context, up until the late 19th century the work of the blacksmith was an art, not a science.

Steeling definition 2: The creation of steel cutting edges on iron tools by scarf welding, or folding and welding steel onto the iron tool, e.g. the creation of a welded steel-iron interface. In the case of knives, steeling was also done by folding iron over steel, then quenching it. Salaman provides two examples of how hardness required for edge tools is obtained by a working blacksmith: "(a) carbonization: the edge was heated in a charcoal fire and then rapidly quenched in cold water -- a method known in pre-historic and Roman Britain, or (b) by the equally old method of 'steeling', i.e. thin strips of good quality steel were let into the edge of a wrought-iron blade and joined by forge-welding in the fire." (Salaman 1975, 247)

Stock removal method: A modern knife making technique involving sawing then grinding off excess steel from steel bar stock, in contrast to the forging of the knife blade (Latham 1973).

Stopped off: The covering over of parts of an iron tool, other than its working edge, during the carburization of edge tools that occurs in forge welding. Clay was a common media for enclosure during such procedures; the clay cover protected the iron from the oxidizing impact of burning fuel. See enclosure, forging, and carburization.

Stourbridge: An early steel making center in the Midlands of England, Stourbridge was famous for its fine heat-resisting clay, so important to Benjamin Huntsman's production of crucible cast steel (1742).

Stourbridge clay: The high temperature resistant clays found near the Village of Stourbridge in England and utilized by Benjamin Huntsman to make the crucibles used for the production of the cast steel he needed for his watch spring business. No such high temperature resistant clays were available in the U.S. for production of cast steel until the 1840s. See cast steel definition 1 and crucible.

Strain hardening: The crystalline deformation of the lattice structure of metals, which increases their hardness and yield strength prior to shear stress induced slip; strain hardening decreases with rising temperature. Annealing is the recovery from the strain hardening of the lattice structure of, for example, steel, which is then softened and made less brittle (under less strain) by annealing.

Stress fields: Stress fields surround dislocations on slip planes… "Dislocations may be generated at a flaw and follow each other along a slip plane until they encounter some imperfection or a boundary where they become stuck. The stress field that they set up at this point opposes the approach of additional dislocations and therefore hardens the metal." (Barrett 1943, 338). Stress fields may also build up a super lattice of dislocations, which serve to raise critical shearing stress through the phenomena that similar dislocations repel each other and dissimilar dislocations attract each other, creating a checkerboard of stress fields throughout the crystal. See slip, creep, plastic deformation, and work hardening.

Stress relief: Thermal treatments, such as tempering, that relieve the stresses in the lattice structure of iron and steel alloys caused by cold working and quenching and work-related plastic deformation. See cleavage plane, creep, annealing, and space lattice.

Stuckofen furnace: The high shaft furnace used in Austria and Germany during the Renaissance that evolved out of earlier low shaft furnaces and was the immediate predecessor of modern blast furnace forms. See furnace types.

Styrian ore: Iron ore with 1.0 - 2.0% manganese content found in the ores of the Styrian-Carinthian area of Austria, but otherwise not commonly encountered in the ores of Sweden and the United States. This ore facilitated the direct process production of iron having steel-like qualities (strength, durability, hardness) while still containing significant amounts of siliceous slag inclusions. See German steel, natural steel, Noricum, Spiegeleisen, Weald, Weardale, and Styrian steel.

Styrian process: The continental technique of refining (decarburizing) pig iron containing manganese (Spiegeleisen) by the use of charcoal fuel to produce wrought iron, malleable iron, or German steel.

Styrian steel: Natural steel produced by the reduction of iron ores containing manganese in direct process bloomeries, later produced by fining blast furnace-derived Spiegeleisen. Also called German steel, the Styrian method was the principle steel producing process of Renaissance England and Europe north of the Alps between 1350 and 1650. Carinthia and Styria, in Austria, were the principle sources of manganese-containing iron ores from the early Iron Age until the 19th century, thus the name of the process. See natural steel, German steel, and Noric steel.

Sulfur: A major contaminant in iron and steel production resulting from the introduction of coke as a fuel. Sulfur limited the uses for cast iron unless neutralized by a high lime base slag at high temperatures, producing the phenomena of "hot shortness" during forging, when steel contaminated with sulfur would disintegrate upon impact when hammering. The introduction of steam-driven piston blowers, creating higher temperatures, which helped burn out the sulfur, allowed the successful use of coke as a universal blast furnace fuel in the late 18th century (Tylecote 1976). Sulfur is also neutralized in slag at lower melting temperatures by the presence of manganese in iron ore in the smelting process. See spathic ores and hot short.

Surface carburizing: A difficult, tedious, and infrequent method of steel production requiring protecting the tool being carburized from the combustion gasses, which would simultaneously oxidize (decarburize) the iron or steel surfaces of the tool being forged. See case hardening, enclosure, case carburization, and carburizing.

Surface hardening: To impart to the surface of low carbon steel, by carburizing and austenizing, a wear and abrasive resistant surface while retaining a ductile and tough interior composition. Also called case hardening. See cementation furnace, case hardening, and carburization.

Surface oxidation: The greatest problem of the hot forging of iron implements or tools; exposure to the oxygen in the atmosphere results in the loss of iron and scaling on the surface of the iron tool being worked; the higher the forging temperature, the higher the rate of surface oxidation.

Swage: Used by blacksmiths for rounding bar stock, the swage has two components. The bottom swage fits into the hole in an anvil or swage block; top swages are often handled and are used to pound the metal into the desired shape on the bottom swage.

Swage block: A large block of cast iron or semi-steel with multiple holes and rectangles of various sizes used for shaping hot bar stock by a blacksmith or toolmaker.

Swedish iron: The high quality, low sulfur nearly phosphorus free charcoal-smelted wrought iron smelted in Sweden and exported to England and America. English steelmakers preferred Swedish charcoal-smelted iron to domestically produced mineral-fuel-smelted iron because of its superiority for blister and crucible steel production. The success of the English steel industry (1750-1860) was closely connected to the ready availability of Swedish iron. Despite international trade restrictions, Swedish bar iron was imported to the colonies, and to toolmaking centers such as New Bedford, in the early 19th century, possibly for use in steel furnaces for blister steel, wrought iron, and whaling tool production. See Whalecrafters, blister steel, charcoal, charcoal iron, wrought iron, and finery.

Tap hole: The discharge opening for molten metals in a smelting furnace.

Taylor-White steels: Frederick W. Taylor and Maunsel White discovered, during their investigation of high speed steels, that the key ingredient in Robert Mushet's self hardening steel wasn't the tungsten but its 1.7% manganese content, which when quenched just below the melting point increased cutting efficiency (working capability) two to four times. (Tweedale 1986)

Teeming: The use of a ladle to fill ingots with molten metal.

Temp: The trough, usually made of stone, which transported melted iron from the blast furnace to the molds used for making hollowware.

Temper carbon: The form of carbon found in gray cast iron and malleable cast iron in the form of nodules of large gray flakes of free graphite, also called free carbon. Temper or free iron softens cast iron, weakening its structure, but also increasing its machinability. Annealing of cast iron can restore durability, especially in cast iron containing silicon, manganese, and other alloy micro-constituents. See white cast iron, gray cast iron, free graphite, and combined carbon.

Temperature control: The key to successful forging techniques for the earliest edge tool and edged weapon makers as well as for the most modern knife and edge tool etc. makers; loss of accurate temperature control during the forging process results in an inferior product.

Tempered martensite: In fully tempered steels, the change from the martensite matrix to homogenous distribution of carbon is a result of the uniform distribution of fine particles of cementite within the martensite, stabilizing its lattice structure by relieving its brittleness (i.e. its strain hardening). See tempering, cementite, austenite, and critical point.

Tempering: The process of reheating steel that has been hardened by quenching, to reduce the hardness and especially the brittleness of edge and other tools, usually done at a temperature range of 200º C to 600º C for periods ranging from 30 minutes to hours. The variables of time and temperature determine the microstructure of steel, as with martensite, where tempering precipitates iron carbide (cementite), creating less brittle steel by encouraging the homogenization of its carbon content. "To make steel less brittle and therefore tougher, to relieve internal stress and either to stabilize the retained austenite or to cause it to transform into a dimensionally stable structure." (Shrager 1949, 165). Closely related to annealing.

Tensile strength: The maximum load that a material can withstand without being pulled apart; also known as maximum strength or ultimate strength. Tensile strength is measured in units of force per unit area. The non-metric units are pounds-force per square inch (lbf/in^2 or psi). Soft gray cast iron has the lowest tensile strength at 23,000 lbf/in^2 or psi. Tensile strength is highest in high carbon tool steels used for lathe tools, chisels, files, and saws (steel with a 1.25% carbon content has a tensile strength of 135,000 psi); wrought iron has an intermediate tensile strength of 52,000 psi.

Thermal fluctuations: Changes in temperature that affect the stress fields of the crystal lattice structures of metals and that thus generate lattice dislocation. See tempering, annealing, and lattice reorientation.

Thermal stress: The stresses in the crystal lattice structure of metals caused by temperature change. See thermal fluctuations.

Thermal treatment: The heating and cooling of iron and steel, which produce a range of structures from coarse pearlite to fine martensite. See austenizing and martensite.

Thermit welding: Fusion welding utilizing finely divided aluminum and iron oxide (thermit), principally used for welding rail joints. A mold is constructed on either side of the rails to be welded; superheated (2800° F) ignites the thermit. The reaction spreads throughout the mass; the aluminum unites with the oxygen molecules of the iron oxide producing pure iron in the form of superheated (up to 5000° F) aluminum alloy liquid steel. Discovered in 1896, thermit is produced in refractory lined crucibles; the process requires preheating the rails. Thermit welding is no longer used for rail welding.

Tin plate: Sheet steel covered with a thin layer of molten tin.

Topman: In the operation of the blast furnace, the topman was the person feeding the furnace with ore, charcoal, and flux.

Tool: Any instrument of manual operation. (OED, 1975, Oxford)

Tool steel: Steel with a carbon content of 0.5 – 1.3%; used for the working parts of a tool (Palmer 1937). Other sources define tool steel as having up to a 2.0% carbon content. Tool steels also often contain other alloys, for example silicon (0.25%), manganese (0.25%). Cobalt, vanadium, and chromium are examples of other tool steel alloys used in toolmaking. See alloy steel and carbon content of iron and steel.

Toughness: The ability of a metal to withstand impact without fracture; the opposite of brittleness, commonly used to express resistance to sudden shock. Wrought iron, due to its entrained slag is famous for its tensile strength and toughness. See mechanical properties of metals.

Transcrystalline fracture: Fracture that passes through the lattice structure of metals rather than around the boundaries of crystal structures (intercrystalline fracture). Shrager (1949, 380) notes this kind of fracture as "the normal type of failure observed in metals."

Transformation temperature: Temperature levels at which phase change occurs in iron carbon alloys. See austenized, critical temperature, and iron carbon diagrams.

Transition point: Temperatures at which changes in crystalline structure of metals occur.

Trip hammer: The water-powered trip hammer of the medieval period, also called a drop hammer, represented the first step in more efficient iron production by relieving the smith of much of the work of hammering out the slag from the bloom. Operating initially at 50 – 75 blows per minute, trip hammers increased in size and speed after 1750, when coke powered steam hammers appeared in Europe. In America, coal or coke fired steam hammers allowed forges to be located well away from water power sources, encouraging centralized development of iron production centers. In the 19th century, large trip hammers played a central role in the factory system of mass production of drop-forged low carbon steel tools. The increasingly powerful hydraulic press has replaced most trip hammers since 1875. See overshot water wheel, shingling, and drop-forging.

Trompe: A water blowing engine run by air compressed by falling water. Pipes carry air and water to a receiver where the air is forced into a blast pipe connected to the tuyère, providing the air for the smelting process.

Tungsten steel: Tungsten steel is an alloy containing 5 to 7% tungsten. It is used for manufacturing magnets and in tool steel to facilitate cutting (milling).

Tuyere (tuyère): The opening at the base of Catalan and open-hearth forges for the admission of the nozzle of a leather bellows; the forced air or air draught needed for the smelting process would enter this opening and follow the tuyère tunnel to the charcoal fuel being burned. The use of the tuyère was the first of the improvements in furnace design and iron smelting of the early Iron Age; also the openings for air blast in any furnace. See blowing devices.

Twinning: Twinning is the reorientation of the lattice structure during plastic deformation of metals. Along with slip, twinning is one of the principle forms of crystal deformation. Twinning is one of the results when "a lamella within a crystal takes up a new orientation related to the rest of the crystal in a definite symmetrical fashion. The lattice within the twinned portion is a mirror image of the rest; the plane of symmetry relating one portion to the other is called the twinning plane." (Barrett 1943, 307) In many cases twinning involves rapid slip or sheer along the glide plane rather than rotation of the planes, and is the characteristic deformation process that occurs during annealing. Barrett also defines twinning as the symmetrical reorientation of exactly duplicate lattice structures occurring rapidly during slip events by the "…shearing movements of the atomic planes over one another" (Barrett 1943, 308) "…twinning brings slip planes into position for further deformation." (Barrett 1943, 316). See Neumann bands and lattice structure.

Uniform transformation: The production of high alloy steels with minimal internal stresses by slow transformation processes such as normalizing in still air. "Oil quenching produces less rapid change of volume and consequently less distortion than does water quenching." (Shrager 1949, 157). Hence its preferred use in the edge tool forging process. See quenching and normalizing.

Unit cell: Unit cell is the basic unit of the space lattice of the crystalline structure of metals that expresses their allotropic forms. Iron has two forms of temperature-dependent unit cells: the body-centered cubic structure (BCC) up to 910° C (1670° F), and the face-centered cubic structure (FCC) from 1670° F (910° C) to 2552° F (1400° C). Above 1552° F, iron reverts to the FCC unit cell structure. A third form of the unit cell is the close-packed-hexagonal (CPH) space lattice structure, characteristic of non-ferrous metals such as cobalt, magnesium and titanium. See allotropic forms, body-centered cubic structure, close-packed hexagonal structure, and space lattice.

Upsetting: Upsetting is to make a piece of iron rod thicker and shorter by hammering. See Bealer, 1976.

Venetian steel: Noted by Moxon in 1677 as the highest quality of all the steels available in the 17th century, it is not currently known what techniques or combinations of techniques the Venetians used to produce their famed steel. Natural steel from Noricum had been brought down through Alpine passes to Italy during both the Roman Republic and Roman Empire. Brescian steel was ubiquitous during the Italian Renaissance and Wootz steel, the smelting techniques of which were closely related to those used to produce Brescian steel, would have been easily accessible to Venetian mariners. See Moxon, Brescian, and Wootz steel.

Viking swords: Pattern-welded steel and iron sword blades similar in metallurgical structure to the pattern-welded Merovingian blades of central Europe (+/-750 AD); the earliest sword of this type was found in a Roman site in Britain in the 2nd century. The principle weapon of the Vikings, and probably locally made, Cyril Smith notes their sudden disappearance in the 10th century. It is unknown whether the well-traveled Vikings obtained some of the metal working skills from Muslim countries making Wootz steel. (Smith 1960)

Walloon process: The production of low sulfur iron in open-hearth furnaces using charcoal was the fundamental process for producing high quality iron from blast furnace pig iron from the late 14th century to 1784, when Henry Cort perfected the puddling furnace. Charcoal protected the bloom of iron from being oxidized prior to its removal for forging. The Walloon process furnace was used to produce Swedish iron as well as to fine the pig iron at the Saugus, MA, Ironworks c. 1646 (Gordon 1996). The Walloon furnace produced not only very low carbon wrought iron (0.02 - 0.08% carbon content) but also a wide range of malleable iron with a carbon content below that of quenchable steel (0.5% carbon content). This malleable iron was often made directly into hoes, shovels, and other hand tools by a blacksmith, as for example, the one whose forge was next to the integrated ironworks at Saugus. See malleable iron, wrought iron, muck bar, and carbon content of iron and steel.

Water bellows: Japanese fan bellows run by a horizontal water wheel, later used in Korea and China; the main source of power for most Japanese forges in antiquity. See Wertime (1962).

Watered steel: Etched steel, displaying the pattern derived from the metallurgical composition of the steel and the welding techniques of the smith, including both his mechanical (hammering) and thermal (forging) treatment of the sword, knife, or gun barrel being constructed. The metal surface of the artifact being forged is then watered, i.e. treated by pickling, submerging, or covering its surface with such acidic substances as lemon juice, ferric sulfate, or "acidulated water." (Breant 1823) See, in particular chapters 2-5, Cyril Stanley Smith's (1960) classic, *A History of Metallography*. See Damascene steel, pattern welding, and Japanese swords.

Water-hardened steels: Low carbon and low alloy steels that can only be hardened by quenching in water.

Water powered drop hammer: Another term for a trip hammer, the drop hammer became the hydraulic helve hammer of the later 15th century. See trip hammer.

Water quenching: Water quenching is the one quenching method of sufficient speed to give full hardness to low carbon (0.5% carbon content) steels.

Weald: The area in Sussex to the southeast of London that was, along with the Forest of Dean, an important iron and steel producing area of Tudor England during the age of the merchant adventurers. See Cleere (1985), forest of Dean, manganese, and ordnance.

Weardale: An important source of iron ore in the late 17th and early 18th centuries for the brief florescence of the iron and steel industries in Newcastle and the Derwent Valley in northeast England, 1685 – 1750. Along with the Weald, a second location of manganese-bearing iron ores, Weardale ore was "…not greatly dissimilar from the Carinthian ores. From the pig iron smelted from such ores it would have been possible to produce 'natural steel' by the continental method and it should be noted that there was a blast furnace operating on these ores at Allensford, nearby, from about 1670." (Barraclough 1984a, 64). Barraclough notes that shortly thereafter (1703) the Hollow Sword Blade Company was, along with most other forges in England, producing blister steel in a cementation furnace. See Weald, German steel, and shear steel.

Welding: The joining two pieces of low carbon steel and/or malleable iron at temperatures just above their melting point. See scarf.

Welding heat: The individual welding temperatures necessary for a blacksmith to bring wrought iron and/or malleable iron and blister steel to their individual welding heats to facilitate "steeling", as in the forge welding of edge tools. The welding heat for wrought iron lies between 2500 – 2700 F; after reaching that temperature, wrought iron will give off sparks and droplets of melted metal. With increasing carbon content, the welding heat of steel drops; cast steel being the most difficult to weld. Steel containing carbon content in excess of 1.5% cannot be welded.

Weld steel: In the manufacturing of axes and other edge tools not made of cast crucible steel, a welded steel cutting edge (bit) was fused (welded) with the iron components of the tool, hence the name weld steel. Weld steel was produced in ancient times as natural steel and after the advent of blast furnaces as German steel (fined cast iron). The most common form of weld steel bar stock, used between 1700 and 1900, was blister steel derived from the carburization of bar stock in the cementation furnace. Cast steel produced by the crucible steel process after 1750 may also have been used as weld steel. Most edge tools utilizing cast steel as weld steel are usually marked either "cast steel" or "warranted cast steel." Blacksmiths working before the development of the cementation furnace (1650) may have spotted nodules of natural steel accidentally produced in the iron smelting process, extracted these fragments of steel from the bloom, and welded them onto iron sockets and ax handles. The British Museum has an excellent example of a Roman period weld steel socket chisel found at Camerton, England, in which nodules of natural steel appeared to have been utilized for a primitive weld steel cutting edge. See blister steel, cementation furnace, cast steel, forge welding, scarf welding, steeling definition 2, and bit.

Whalecrafters: Whalecrafters were the New Bedford community of tool makers who specialized in making harpoons as well as edge tools for the whaling communities of southern New England. (Lytle 1984). The impost records of the New Bedford Customs District, made available by the New Bedford Whaling Museum, indicate large quantities of Swedish iron were imported between 1816 and the 1830s to New Bedford. If not used to make the ductile wrought iron shafts of harpoons, Swedish bar iron was carburized in as yet undocumented steel (cementation) furnaces to make blister and shear steel for local edge toolmakers, and for whalecrafters who also made steeled edge tools. After 150 years of making blister steel in England, and a century of use in America, small steel furnaces were a likely component of the ironworks of many whalecrafters and edge toolmakers.

Wheel cutting engine: A hand operated machine for cutting teeth and gears; first used in England c. 1670.

Wheellock: A variation of the matchlock gun first produced in 1515 in Nuremburg; the wheellock was characterized by a flash hole with pyrites. The expensive-to-produce wheellock was particularly popular with the gentry in Elizabethan England, who used it for hunting in preference to the unwieldy matchlock arquebus. The advantage of the costly wheellock was that it could be fired with one hand. See flintlock, Arquebus, gun barrel iron, gunsmithing, matchlock.

White cast iron: "Cast iron having cementite as its principal constituent." (Gordon 1996, 311) Cementite is iron chemically combined with graphite; it therefore contains little or no free graphite and has very limited commercial applications unless it is melted and annealed into more useful gray cast iron. White cast iron is low in silicon and thus easier to convert to wrought iron than gray cast iron; it was the preferred iron used in the puddling furnace for conversion into wrought iron. It is produced by rapid cooling in an iron rather than sand mold, and can then be annealed by heating to a cherry red heat for 60 hours to allow crystalline graphite to become free carbon, thereby producing malleable cast iron. See malleable cast iron, gray cast iron, silicon, and cast iron.

White heart: Malleable cast iron in which all the free carbon is converted to chemically combined carbon during the annealing process.

White metal: Metal alloys with a significant tin content, which promotes elasticity and assists the even distribution of stress loads.

Whitworth steel: A form of fluid, compressed steel that Sir Joseph Whitworth (c. 1862) adapted from Huntsman's technique of producing cast steel in crucibles; its brand name was Wheatsheaf, and was preferred for making shotgun barrels. Whitworth steel was later made by the Siemens-Martin (c. 1870) process. See cast steel.

Whitworth thread: The standard screw thread used in England and continental Europe; has a 55° angle. Named after its inventor, Sir Joseph Whitworth, (1792-1871). See the discussion of

Whitworth's role as an Industrial Revolutionary in *Hand Tools in History: Steel and Tool Making Strategies and Techniques before 1870* at: www.davistownmuseum.org/TDMtool.htm.

Widmanstäten structure: The patterns formed by alternating areas of pearlite and ferrite after rapid cooling of low carbon steel containing large austenite grains. Alois von Widmanstäten first noted this crystalline structure in 1808 on meteorites in the royal mineral collection in Vienna; the term now refers to artificial structures in annealed steels. (Smith 1960, 150). See Neumann bands.

Wire annealing: The softening of cold hardened or drawn wire by slow heating.

Wootz steel: Another name for Damascus steel, it originated in India in ancient times and was used for edge tools, swords, and sitar wire (Craddock 1998). An early form of crucible steel, it was made in +/- 3 kg batches in crucibles, especially in Muslim communities since at least the early Christian era. Bealer (1976A) suggests Wootz steel was made with molten cast iron in a manner similar to the Brescian method, and was composed of a mixture of granules of soft iron and carbon steel. Moxon (1975) notes Wootz steel as one of the principle forms of steel available to toolmakers in the late 17^{th} century. C. S. Smith indicates Wootz steel was made in cakes, which were not fully melted, "but sometimes consisted of an aggregate of unmelted iron granules or little plates cemented together by once molten cast iron. Such a structure would result from the standard Indian process of steel making if the temperature were insufficient to melt the alloy completely. The crucible charge was an iron sponge, sometimes roughly forged into plates, together with wood for carbonization." (Smith 1960, 21). See Damascus steel, Moxon, crucible steel, Venetian steel, and Viking swords.

Work hardening: Hardening of iron and steel by deformation that occurs during hammering, rolling, drawing, punching, and/or bending of metals at temperatures below the critical point. See stress fields and slip interference.

Wrought iron: Slag bearing malleable iron with low carbon content (0.08% or less), wrought iron does not harden when cooled suddenly (quenching). Its two principal components are high purity iron (ferrite) and iron silicate, a glass-like slag with a high silicon content. Due to its malleability and ductility, it is easily shaped, threaded, machined, hammered, or stretched when hot. Its primary slag constituent after removal of unwanted impurities is silicon (siliceous slag), which gives it its unique characteristics, particularly its resistance to stress concentration (toughness and tensile strength) as well as its corrosion resistance. Produced in larger quantities with better quality control after the invention of the puddling (reverbatory) furnace (1784), the purer wrought iron thus produced was the key ingredient in producing higher quality cementation and crucible steel. The slag inclusions in wrought iron aid its corrosion resistance, making it especially useful in stressful environments where moisture would quickly corrode steel. When forged across the grain instead of along the grain, loss of strength occurs. Knight provides this description of the refining of high quality wrought iron: "Iron sufficiently pure to be drawn out into bars and welded. . . The iron obtained from [simple furnaces] was a spongy mass, which was drawn out at intervals by tongs, hammered gently and cautiously, and then more energetically, to press the particles of iron into contact and squeeze out the intermixed slag. The mass thus obtained was cut up into smaller pieces, which were repeatedly heated and hammered till a sound bar of nearly pure iron was obtained." (Knight 1875, 1377). The irony of the Knight definition is that the “nearly pure iron” may have been wrought iron with a carbon content of less than 0.08%, but in fact most iron being produced from both the bloomery and the puddling furnace had a slightly higher carbon content, ranging above 0.08% cc to 0.2% carbon content. This “malleable” iron still contained significant trace amounts of siliceous slag, but because of its slightly higher carbon content, was much more suitable for forging common tools such as shovels, hoes, tongs, augers, and early wagon wrenches than softer and more ductile wrought iron, which was more easily deformed. See malleable iron, silicon, muck bar, puddling furnace, bloomery, direct process, and iron silicate.

Wrought Steel: A superior type of wrought iron later replaced by Bessemer and Siemens-Martin's open-hearth low carbon steel, i.e. a malleable iron with a higher carbon content than wrought iron (below 0.8%); wrought steel was forged out of solid iron bar stock.

Yield point: The load per unit area at which deformation or elongation occurs without further increase in stress.

Zelechovice furnace: Slavic bloomery furnaces were used in the late 8th and early 9th centuries in the Moravian section of Eastern Europe. Of particular interest with respect to the issue of direct process natural steel production, these primitive, bowl type furnaces were built into the ground and were characterized by a unique bowl cavity at the bottom of the furnace in which the bloom of iron was protected from the oxidizing effect of burning charcoal, while at the same time being covered by the charcoal. Heterogeneous blooms of natural steel were produced by leaving the bloom of iron within the bowl cavity at the bottom of the furnace adjacent to both the tuyère and the burning charcoal. See Pleiner (1969) page 461, for an illustration of the basic design of this early furnace, also reproduced in volume 6 of the Hand Tools in History series: *Steel and Tool Making Strategies and Techniques before 1870*.