ARCHITECTURAL METALS SERIES

L. WILLIAM ZAHNER

STEEL SURFACES

A GUIDE TO ALLOYS, FINISHES, FABRICATION, AND MAINTENANCE IN ARCHITECTURE AND ART

WILEY

Steel Surfaces

ZAHNER'S ARCHITECTURAL METALS SERIES

Zahner's Architectural Metals Series offers in-depth coverage of metals used in architecture and art today. Metals in architecture are selected for their durability, strength, and resistance to weather. The metals covered in this series are used extensively in the built environments that make up our world and are also finding appeal and fascination to the artist. These heavily illustrated guides offer comprehensive coverage of how each metal is used in creating surfaces for building exteriors, interiors, and art sculpture. This series provides architects, metal fabricators and developers, design professionals, and students in architecture and design programs with a logical framework for the selection and use of metallic building materials. Forthcoming books in *Zahner's Architectural Metals Series* will include Copper, Brass, and Bronze; Steel; and Zinc surfaces.

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Steel Surfaces: A Guide to Alloys, Finishes, Fabrication and Maintenance in Architecture and Art

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A Guide to Alloys, Finishes, Fabrication, and Maintenance in Architecture and Art

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This book is in honor of David Norris. A friend and mentor.

Contents

Preface

"Know your own value."

Hank Rearden of Rearden Steel

Atlas Shrugged by Ayn Rand

Steel was one of the first metals I became acquainted with early in my career. It was different than the shiny copper the shop had stacked in a neat pile or the lightweight aluminum stored in racks up off the ground. Steel was heavy, thicker than most other sheet metals, and often possessed the intricate spangle of zinc crystals on the surface from the hot-dip galvanizing process.

Steel was treated rougher. Stored in open stacks. Often coated in a layer of slick oil. It had a smell to it—the smell of machinery, the smell of industry. Steel lacked the care and concern the other metals seemed to be regarded. It was the metal used for making patterns,[1] before the shapes would be cut in copper, aluminum, or steel's royal cousin, stainless steel. After which, they would be relegated to the scrap bin to be recycled. We used to recycle all the metals, and on occasion I would take a massive load of steel scrap to the recycling yard, only to receive less than 20 dollars. It hardly seemed worth it, but we were a company that had worked with metals through the hard times of the Depression, and you wasted nothing. Every steel packaging band was collected and recycled.

The first major projects I was involved with out of college had steel siding panels for cladding the walls of large coal-powered electrical generating plants that dotted the Missouri River. These heavy panels were roll-formed from 18-gauge cold-rolled steel sheet made by INRYCO, short for the Inland Ryerson Company, a once massively large steel producer in the United States. Inland Steel Company, founded in 1893, was one of the last integrated steel companies that turned ore into steel and into semifabricated wrought materials. Its subsidiary, Inland Building Systems, merged with Ryerson and later became INRYCO, but eventually felt the impact of foreign sources of steel and modernization and efficiencies of the mini-mills.

These steel-clad powerplants have stood for over 40 years. The paint coatings used on the steel structure and on the steel panels I worked with was of very high quality and today show little signs of deterioration—some fading with time and ultraviolet exposure, but generally the surfaces are in excellent condition.

[1] Up until the early 1980s, patterns were made from paper blueprints. There were no CAD–CAM files. Steel patterns would be cut to for later use to make elbows or roof jacks. The patterns were hung from hooks on the wall, and when similar items were made, the patterns would be used on the layout benches. A bit archaic in light of the technology of today.

Over time, my experience moved away from the mild carbon steels of siding and metal decking. Aluminum became the base metal for high-quality paint systems. Stainless steel, copper alloys, and later zinc were the metals for design of exposed, uncoated surfaces.

But there was this other interesting steel, a paradox of metal. It was called Corten.

Here was this strange steel that you wanted the surface to corrode. It would stain everything below it while it formed the initial rust, yet it was supposed to last as long as the stainless steels.

The company built its first major building in 1982, and the designer wanted a natural appearance. He chose Corten siding for the plant portion and alclad aluminum for the office. The siding was roll-formed by INRYCO as one of the last gasps of steel production, as INRYCO was to close its doors in 1986. The architect described his design as the new growing from the old – the old being the rusty metal surface of Corten. It is interesting that over the last 40 years, it is the Corten, the weathering steel, that has embraced the future and still appears sturdy and strong while aluminum is looking fragile and antiquated.

I have worked with weathering steel, the name used as often as the older Corten—or COR-TEN®, as the inventor and trademark holder, US Steel calls it. COR stands for corrosion resistance and TEN stands for tensile strength. Both of these characteristics and more are possessed by this amazing steel.

Nearly 25 years ago we realized the major drawback, from an aesthetic standpoint, was the time it took for the real deep color to appear. People did not want to wait and watch as their building rusted and painted the sidewalks and stonework with a red stain. The idea of preweathering this type of steel seemed to be the answer. Many an artist pushed the metal to achieve this preweathering on their sculpture using acids and wetting the surface. In addition to being hazardous to one's health and safety, this process is impractical for large projects.

After a bit of testing and trials, we came up with a process we now call *Solanum,* the Latin word for eggplant. The color of eggplant is a deep purple brown, similar to what is achieved when weathering steel reaches its point of surface equilibrium. *Solanum* sounded fitting for a metal, in tune with the great Sir Humphrey Davy, who named such metals as potassium, sodium, and, of course, aluminum.

The idea with preweathering is to control the oxide development in an environment specifically controlled for this special steel to corrode slowly and form three rich forms of oxide on the surface, similar to, but much quicker than, the color that formed after years of exposure. The staining would be contained for the most part and collected in our plant.

The weathering steels have a rich color tone that comes across as a material of the earth. Like brick, wood, or patina copper, weathering steel has a very natural, pleasing appearance once the oxidation takes root. Many of the projects shown in this book demonstrate the natural character of this amazing steel.

The steels we sometimes refer to as mild steel or carbon steel are ubiquitous in our everyday environment. Unlike the weathering steels, we do not notice them until they do begin to corrode. Otherwise, they go about their business of protecting us as we drive down the road, or hold our buildings up against the forces of gravity and wind. Once they start to corrode, they get noticed like mold on bread. The carbon steels with their beautifully rugged, dark gray-blue color require some form of protection to hold back rust from developing. It is the material of battleships and tanks, armor to be abused and to withstand abuse, but a little moisture and trouble sets in.

More and more designers are seeing the intrinsic beauty of the carbon steels. Conquering, or at least forestalling, the onset of the feeling of neglect the condition of rust can portray is paramount. Iron, the main element in steel, wants to join up with oxygen – and iron has more ways to join with oxygen than we can count on both hands. There are 16 oxide forms of iron. You want to keep the steel surface dry; water is the catalyst for this coupling with oxygen.

Conversion coatings slow down the marriage with oxygen by introducing other elements such as phosphates, sulfates, and copper selenide coatings that cling to the iron surface and form a barrier of darkened color. At the same time, these coatings can offer a unique appearance while maintaining the intrinsic beauty of steel.

Of all the metals I have written about, steel has been one of the more challenging. From an art and architecture perspective, steel has played a valuable role, but as a bit player, it is an inexpensive alternative. With new techniques of preweathering the high-strength, low-alloy (HSLA) steels, this surface is being recognized as a beautiful, natural material by designers and artists around the world. The darkening, bluing, and variegate finish one can obtain from the mild carbon steels adds an entire new array of possibilities to the design community. Easy to work with, weldable, and now with appealing surface finishing, steel is giving new value to the designer and artist.

L. William Zahner

Steel Surfaces

CHAPTER 1

Introduction

The only way to know how strong you are is to keep testing your limits.

Jor – L to Superman, the man of Steel.

IRON AND STEEL

Iron and steel have a long history with mankind.

The history of contemporary civilization is intermingled with the prowess of iron and steel. Steel is an alloy of iron with a small amount of carbon, usually less than 2%. Iron has been used throughout civilization to make useful tools and armaments. Implements made from iron were harder and could hold an edge better than any other substance known at that time. Even today, hardness and strength are compared to iron.

The atomic symbol for iron is Fe, which is shortened from the Latin word for the metal, *ferrum,* which means "firmness." Iron is element 26 on the periodic chart. See Figure 1.1.

Iron sits between manganese and cobalt and in the same line with ruthenium and osmium, two very dense elements.

Iron is the fourth most abundant element found on the Earth's outer crust behind oxygen, silicon, and aluminum, while the core of the Earth is said to be composed mostly of iron.

Iron is one of the few substances that demonstrate magnetism. *Ferromagnetism* is a term given to describe a phenomenon of a few materials to show magnetic attraction. Iron is chief among these; nickel and cobalt are two other elements that exhibit this trait. Ferromagnetism occurs in the rare earth element gadolinium and a few other compounds. Neodymium, rare earth magnets, are alloys of neodymium, iron, and boron. These exhibit a strong magnetic field.

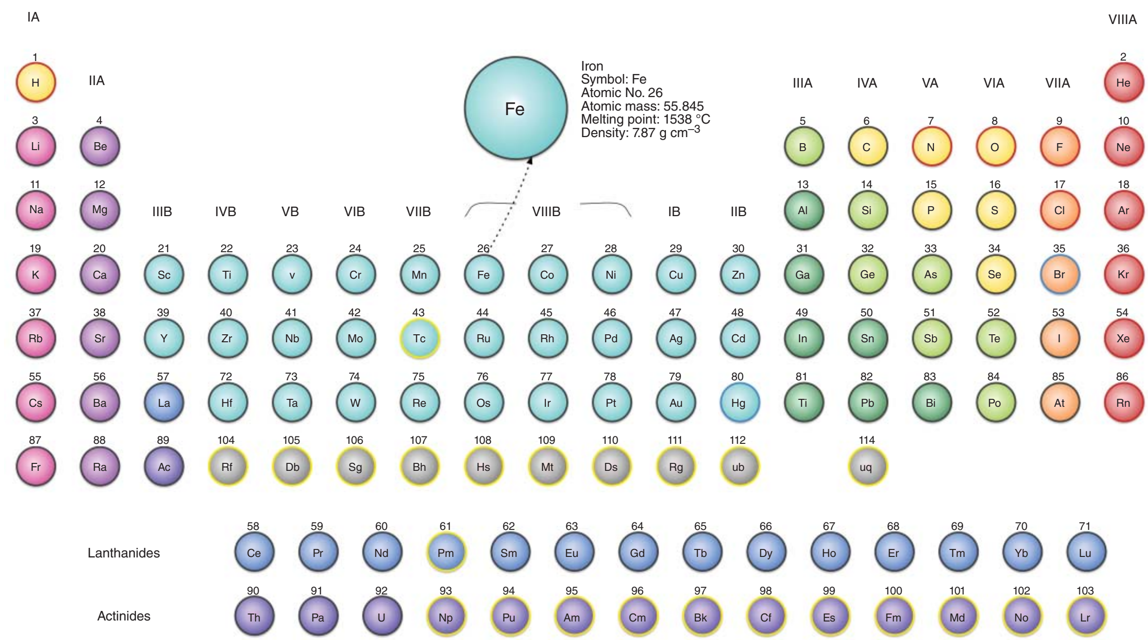

FIGURE 1.1 Periodic table of the elements.

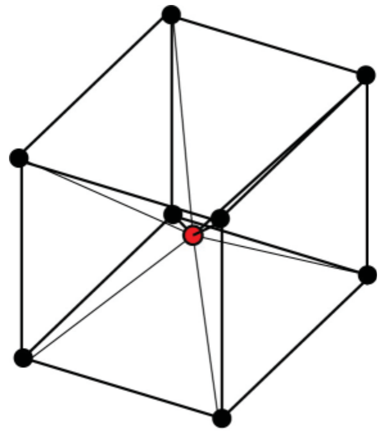

FIGURE 1.2 Body centered cubic structure of iron crystal.

One of irons chief ores, magnetite, sometimes called the *lodestone,* was known to early man as a special material that, when attached to a thread, always aligned in a given direction. This was the first compass, and the term *lodestone* means “leading stone,” for it would point the way.

There is a mystery surrounding the ability of magnetite to become magnetic. Not all magnetite is magnetic, and to make it into a lodestone some strong magnetic field has to be applied. It is suggested that lightning strikes near ore deposits caused some of the magnetite to become strongly magnetized because the electrical current associated with lightning possesses a strong magnetic field and this magnetized the magnetite nearby.

Artistic adaptions to iron implements involved etching the surface of forged iron using organic acids to selectively remove areas of metal. Inlays of softer metals such as bronze, copper, and even silver could further enhance the iron surface. These softer metals could be hammered into grooves in the much harder iron, keying them into the surface to create contrasting artistic effects. Early manufacturing techniques and use of iron allowed the development of artistic surface treatments that expanded the intricate detailing already underway on the softer metals of bronze and copper.

Iron is enigmatic. With all iron’s strength and hardness, it is quick to give it up. Air and moisture are all that are needed to strip this strength from iron. Those two electrons in the outer shell anxiously combine with oxygen, sulfur, or any number of other elements (Figure 1.3). Iron is never found pure in nature. Iron finds thermodynamic equilibrium when it combines with oxygen and other substances. With iron, unlike other metals such as aluminum and titanium, when it combines with oxygen and water is present, it expands as it forms oxyhydroxide. So, as the surface of iron oxidizes, it takes up more volume, creating cracks and allowing more iron under the surface to be exposed.

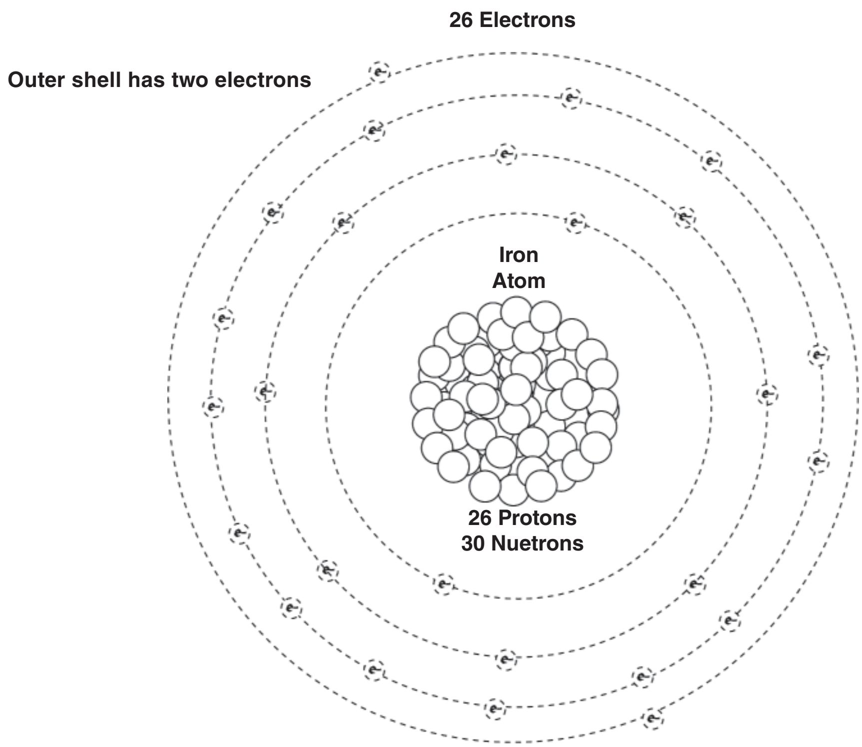

FIGURE 1.3 The iron atom.

Iron Element 26

Atomic Number 26

Crystal structure	Body-centered cube
Main mineral source	Hematite, magnetite, taconite
Color	Gray
Oxide	Black, dark red, brown, yellow
Density	7874 kg/m^3
Specific gravity	7.8
Melting point	1538 °C
Thermal conductivity	83.5 W/m °C
Coefficient of linear expansion	12×10^{-6}/°C
Electrical conductivity	17% IACS
Modulus of elasticity	200 GPa

Iron is the fourth most abundant element on Earth's surface; 6.3% of Earth's crust is composed of iron.

Steel is an alloy of iron. Carbon is the main alloying element introduced into iron to create steel. Other elements are added in small amounts to create specific properties.

Excellent ductility, deep forming ability, superior hardness, machinable. Can be both cold and hot worked.

High fracture toughness

High elasticity – resiliency under shock loading. High vibration resistance.

Hard edge. Can be sharpened and hold an edge.

Nontoxic.

Poor corrosion resistance unless alloyed with specific elements or coated with sacrificial metals.

Finishes:

Mill finish in most applications.

Rarely polished or mechanically finished.

Usually coated.

Organic coatings in the form of polymers and resins are common coatings.

Inorganic coatings in the form of glass, like porcelains, are common coatings.

Metal coatings by hot dipping or by electroplating are common coatings.

Metal oxide salts are common blackening techniques that provide both appearance and corrosion resistance.

Oxyhydroxide layers that develop on particular steel alloys called *weathering steels* are common surfaces used in art and architecture.

Artificial patina	Blacks and mottled grays. Dark greens and dark reds can be produced on steels.
Dark appearance	Iron absorbs and reflects evenly across the spectrum with slightly more on the shorter wavelengths portion of the spectrum. Alloys alter this reflection. Weathering steels have greater emission around the yellow wavelengths and the red end of the visible spectrum.

(*continued*)

(*continued*)

Reflectance

of Ultraviolet	Very good
of Infrared	Poor. Copper absorbs infrared wavelengths.

Relative cost	Low
Strengthening	Cold working, alloying, and tempering are methods used to adjust the strength of steels.
Recyclability	Easily recycled. Higher melting point and coatings on the steel make the scrap value very low.
Welding and joining	Can be welded, brazed, and soldered.
Casting	Steel is frequently cast using all cast methodologies.
Plating	Commonly electroplated with zinc, nickel, and chrome.
Etching and milling	Can be etched and chemically milled.

HISTORY

Iron artifacts, as old as 3500 BCE, have survived to this day. Nickel was found mixed with many of these artifacts, indicating the source of the metal was meteorites collected from the ground rather than mined. [1]

The earliest uses of iron occurred in various regions around the world. Anatonia, India, Egypt, Greece, Babylon, Japan, China, and much of northern Africa, where rich iron ore concentrations are still mined today, were some of the first regions to create iron implements for use in everyday life, warfare, and art.

Iron usage followed that of bronze, the latter being easier to refine and cast. Additionally, copper-bearing minerals were more easily identifiable due to the colorful mineral forms.

It was most likely mankind's aggressive and assertive behavior that drove the early growth and discovery of working with iron. Once mankind figured out how to cast and shape this metal, it soon supplanted copper and the copper alloy, bronze, as the material of war. The alchemist used the symbol of a diagonal arrow or the symbol for man – which is also the symbol for Mars, the god of war. See Figure 1.4.

The Hittites are said to have been one of the first civilizations to mine and work the metal by smelting ore. The Hittite civilization, also referred to as the *Kingdom of Hatti,* controlled the region around Anatolia back in 1700 BCE. They were rivals to the Egyptians. Their use of iron predates other civilizations, and because they were often at war, one can only presuppose the advantage of

[1] Giauque, G., 'The history of carbon steels', *The Book of Steel*, Lavoisier Publishing, 1997, p. 4.

FIGURE 1.4 Symbol of iron used by the early alchemists.

this harder and stronger material presented to the Hittites. The Chalybes were a tribe subject to the Hittites. They lived along the shores of the Black Sea. This tribe is credited with being some of the first to work with iron.

There are sites in Africa that could be even older; however, controversy surrounds their exact date. Thus, iron, entering the realm of man, is most often attributed to the central Asian region. In India, where casting and working with iron was a refined art, excavations in the Middle Ganga Valley show iron working began as early as 2800 BCE. The Mughal Empire of this era was prolific in the exploitation of iron and the early understanding of casting this metal. The metal workers of the Mughal period were experts and were some of the first to work with the lost wax technique of casting. They were known for casting near-perfect iron spheres with no seams.

It has been well established that people of this region exhibited significant prowess in the production of iron and later steel as early as 300 BCE. For the next 500 years, high-quality steel was being produced by the people of this region. They used a method referred today as the *crucible technique* to produce this high-quality steel. The steel produced was of such great quality that King Porus of India offered 15 kg of iron to Alexander the Great as a gift.

The crucible technique involved heating high-purity wrought iron mixed with charcoal and glass. The silicon in the glass would attach to impurities in the wrought iron and float to the top, while some of the carbon would be absorbed into the iron to create steel. This steel was known by the Arabs as *fülåd,* and in Europe it was called *wootz.*

The people of this region traded with the Greeks and Romans, as well as the eastern cultures. The exchange of the science of metallurgy slowly percolated out of this region to other parts of the known world.

The knowledge and ability to temper steel was well known to the metal workers of ancient India. They were known for making incredible swords and blades superior to anything at the time. Even today, some of the art of creating these special blades has yet to be uncovered.

One specialized process was the production of the *Damascus sword*, also called damascene. *Damascene* stands for the decorative process of producing wavy lines in metal by inlaying other metals or by etching the surface of metals. Figure 1.5 shows what damascene steel looked like. The Damascus sword was made from steel produced this way.

The damascene steel techniques were believed to be first developed in India. Decorative etching and metal inlay methods were perfected in India in the first millennia BCE. Romans traded with India to obtain swords and cutlery made from their specialized ironworks.

FIGURE 1.5 Damascene Steel The damascene sword techniques were believed to be first developed in India. Decorative etching and metal inlay methods were perfected in India in the first millennia BC.
Source: L. William Zahner

This early steel was known as wootz steel for the carbon content. Developed in southern India around the sixth century BCE, wootz is a steel created using this early crucible melting process. Used in India, then Damascus and the region around Toledo, Spain, this early process used sand, glass, and other substances as a flux to aid in melting iron. The resulting steel was of very high quality. Wootz is high in carbon and contained bands of pearlite, martensite, and ferrite. To make wootz, ore would be cooked inside a sealed clay crucible over a charcoal fire. Early crucible steel would use the high winds from storms to force air into the charcoal in order to achieve the necessary heat.

Little remains of early iron articles due to the propensity of iron articles to corrode when exposed to moisture and oxygen. Once corrosion would start, it was difficult to stop. There simply were no good means of inhibiting iron from wanting to combine with oxygen and form iron oxide or rust.

Most certainly, much of the early iron was collected from meteorites. This fact can be deduced from the language of the regions. The Greek word for iron is *sideros,* translated to mean, "from the stars." The Egyptian word for iron is *baaenepe,* or "gift from heaven." To melt iron, however, requires a blast furnace to achieve the temperatures needed.

Eventually, it was determined that if iron were heated for long periods of time in a crude furnace, a furnace set so that air would rush through the burning mass of charcoal and ore, a spongy lump of metal would form. This malleable iron could be hammered and flattened. Reheating would soften it or, if left for long periods of time in hot charcoal, the outer surface would harden as carbon was absorbed – processes today called *annealing* and *case hardening*.

Cast iron techniques developed out of the casting of bronze work as higher temperatures were achieved as casting processes improved. With the inclusion of small quantities of carbon, say 2–4%, the melting point of iron is reduced. Many diverse ancient cultures practiced and improved the art of casting metals. The Chinese made various small farming utensils as far back as 500 BCE, while in India exceptional casting techniques had been in development centuries earlier. Indian techniques were accepted and adopted by the Persians and the Romans as superior sources of iron products; both cast and wrought could be produced.

An example of the prowess of the Indian metallurgy is the Iron Pillar of Delhi. See Figure 1.6. This amazing structure is 8 m tall and weighs 7 tons. It was cast during the Chandragupta II reign sometime around the fourth century CE. To this day, this 1600-year-old, high-purity iron form shows little signs of corrosion.

FIGURE 1.6 Iron Pillar of Delhi, India Early Architectural Uses In 1849, the designer James Bogardus, created the first self-supporting glass and iron curtainwalls
Source: By Shutterstock

EARLY ARCHITECTURAL USES

In 1849, the designer James Bogardus created the first self-supporting glass and iron curtainwalls. These curtainwalls of iron, cast in sand molds, would stack and bolt together into multistory building fronts. The iron curtainwall proliferated in the new modern cities of eastern seaboard. In 1853, the grand Crystal Palace was erected using this new bolt-up technique of iron supporting glass walls. These intricately detailed curtainwalls of iron and glass were more economical and quicker to construct. They provided both an aesthetic appearance and a fire-resistant front to many buildings in the second half of the nineteenth century. Several major iron-casting companies sprang up across America and Europe to take advantage of the designs that could be developed using cast iron. Examples of cast iron structural columns and cast iron curtainwall are shown in Figure 1.7.

Iron is distinguished from steel in that iron is an element where steel is an alloy of iron. Iron is rarely used in its pure form. Usually, a small amount of carbon is present. Iron used in art comes in several forms, the predominate being cast and wrought. Cast is any iron that has been poured into a mold to create its form or shape, whereas wrought iron is iron that has been heated and shaped with tooling.

Figure 1.8 shows examples of early wrought iron. The upper left is a decorative sculptural form, the lower left a grille made from wrought iron, and the right image is an early clock mechanism made from wrought iron.

In the late 1700s, techniques of casting iron columns were developed and the use of iron as a structural support member proliferated. Cast iron columns provided excellent compressive strength,

FIGURE 1.7 Cast iron columns and curtainwall.
Source: L. William Zahner

FIGURE 1.8 Early wrought iron work.
Source: L. William Zahner

and designers used iron to create thin supporting storefronts, balcony supports, and even interior column supports. They were more resistant to fire than conventional wood columns and took up less space than stone supports, providing better viewing into shops with their smaller cross section. Iron columns could be cast with decorative features and could be bolted quickly into ornamental assemblies. These cast iron facades provided the needed compressive strength, stiffness, and hardness. They could not be forged or shaped because of their inherent brittleness, and catastrophe followed if they were subjected to bending and tension stresses.

Early uses of iron were of the wrought iron form. Wrought iron was in predominant use early because it did not require fully melting the ore. To fully melt the ore would require very high temperatures, so instead a hot mass of iron and other substances, usually carbon from charcoal used in the oven and slag materials from the heat, would be hammered apart to reveal small globules of iron. These globules would be collected and reheated, and then forged together by further hammering. The ability to reheat and hammer these globules of iron together to form larger elements was key to the success of iron in antiquity. Objects could be shaped this way with blows from a hammer, essentially “welding” the pieces together. The iron would join into a larger mass and would be thinned and shaped into all sorts of implements, from swords to farming implements.

Wrought iron has a long, linear grain appearance, as opposed to the regular grains of the cast irons. When broken, the grains have a fibrous or wood-like appearance. Wrought iron has lower carbon than cast iron and has inclusions from slag and oxides that are integrated by the hammering and extending of the metal grains. By integrating the slag, a more fibrous structure can be obtained, which improves flexibility.

Some telltale signs used to distinguish the difference between cast iron and wrought iron artifacts are, first, that cast iron usually is the more detailed of the two. Additionally, mold lines and detail are the domain of castings. Cast iron assemblies are bolted, whereas wrought iron assembles are riveted or heat forged together.

Wrought iron has better strength characteristics than cast iron. Wrought iron is older than cast iron because it could be created from the spongy bloom of iron in the old charcoal furnaces. These old furnaces could not reach the temperatures needed to smelt iron complete from the ore. Instead they would arrive at a carbon rich porous lump of iron mixed with various other substances. This lump would be hammered repeatedly to remove physical impurities. The larger physical impurities would spall away as the lump became thinner. Iron-rich prills could be extracted from the mass as the outer shell of glassy oxides are broken away. The prills were of rich in iron and would be hammered and folded into a larger, workable mass of wrought iron. As hammering and folding continued, the iron grains would stretch and elongate creating more strength while allowing good ductility without the brittleness of a cast iron. Wrought iron has inclusions of slag and other substances that give it a distinctive surface appearance. This grain-like structure runs through wrought iron and is created by stretching and extending these fibers through the iron as it is hammered and folded. Wrought iron has good strength, corrosion resistance and the carbon content are less. As with cast iron, today most wrought iron is actually a steel alloy, generally a low-carbon form of mild steel. Steel replaced wrought iron in the nineteenth century as new processes were introduced in the manufacture of ferrous goods.

Improvements in the manufacturing of steel started in the early 1800s. Most iron was smelted by the crucible method. This method of steel production used charcoal and later coke to produce steel from pig iron.

By the second half of the nineteenth century, the need for steel increased, and a new process, called the Bessemer process, was developed. Henry Bessemer in England and William Kelly in the United States developed a method of blasting air to change pig iron into wrought iron. This would remove carbon, but the carbon could be added back in a more controlled manner to make steel. The process is still used, and it carries the name Bessemer, who applied for a patent on the process in 1856. However, Kelly, claimed that he had also developed the process in Kentucky, in 1851. Kelly later filed for a priority claim for the process in the United States and was awarded a patent, essentially for the same process, in 1857. The Bessemer process developed because of the need of massive amounts of consistent railroad track. Prior to that, it was made from cast iron. The Bessemer process revolutionized steel making.

The commercial manufacture of wrought iron is left to small art foundries. The last major commercial foundry ceased making wrought iron in the early 1970s. Today, what we call wrought