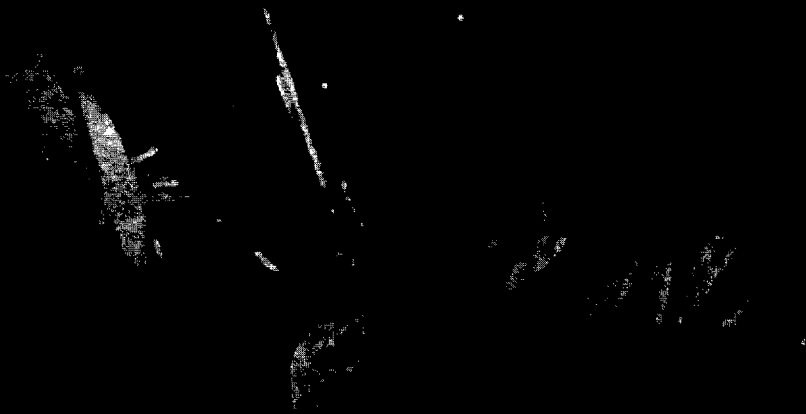




American Welding Society

The Practical Reference Guide to

Welding Metallurgy



Key Concepts for Weldability

THE PRACTICAL REFERENCE GUIDE to WELDING METALLURGY— Key Concepts for Weldability

Compiled/edited/written by

Ted V. Weber

Weber & Associates

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American Welding Society

550 N.W. LeJeune Road, Miami, Florida 33126



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AUTHOR'S NOTES

For many, the metallurgical aspects of welding are not well understood and many of the books and technical articles dealing with the subject are sometimes difficult to master because the lay person does not have the technical background necessary to digest them. Generally, what welding personnel need is a basic understanding of the metallurgy of welding that is sufficient to aid in solving many of the day-to-day problems of fabrication or repair welding.

To that end, I have approached the subject less stringently than most, and have offered some basics that will aid the non-metallurgist in understanding why problems occur, and how to avoid them. While it is necessary to touch on the science in several areas, I have endeavored to limit it to the minimum needed for a practical understanding. I cover the effects of the various elements that make up our alloys, specifically from the weldability standpoint. The effects of cooling rates and the resulting structures are also covered from the mass effect and hardenability standpoints—a perspective I feel will be very helpful in understanding and solving many of the common welding problems.

I hope this Guide will be helpful to all, especially those non-metallurgists who have a need to avoid welding problems so often caused by overlooking the metallurgical considerations.

Ted V. Weber
Hendersonville, Tennessee

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Introduction

Knowledge of welding metallurgy can be beneficial to almost every aspect of fabrication, inspection, and failure analysis. Too often, problems occur repeatedly because the metallurgical aspects are not sufficiently understood (note Figure 1), and as the old saying goes, *"When you continue the exact same practices, why should you expect different results?"*

While the subject of metallurgy, and its subset welding metallurgy, encompasses a very large technical base, there are several basic issues that can be studied and implemented to aid in avoiding problems associated with fabrication and repair welding. These basic issues will be discussed in simple terms and hopefully with an approach that will enable a non-metallurgist to grasp and apply them in order to avoid common welding problems.

Since carbon and low-alloy steels are used predominantly in many industries, these alloys form the basis for much of this metallurgical review. An understanding of the steel basics can then lead to other alloy groups including austenitic stainless steels, copper and aluminum alloys, and the high alloys that include the nickel alloy groups. These families of alloys will also be discussed, but to a much lesser degree.

Definitions

A discussion of metals requires the first step to be a review of several basic definitions. Many definitions used in this guide are from Webster's. A metal is defined as *"Any of a class of chemical elements generally characterized by ductility, malleability, luster, and conductivity of heat and electricity."* Examples of metals include gold, iron, aluminum, and silver. Metals can be found in their natural elemental state, such as the case with gold and silver, or combined with other elements such as oxides, sulfides, sulfates, etc. These combined forms of metals are referred to as *"ores,"* and the elemental metal must be first extracted, or separated from, the other constituents before combining them in desired alloy forms.

An alloy is defined as *"A metal that is a mixture of two or more metals, or of a metal and something else."* The phrase *"something else"* in the definition can refer to the combinations of metals with ceramics, called *"cermets,"* or various other combinations. Some metal alloys occur naturally while others are combined in furnaces by intent to develop particular mechanical or physical properties. Examples of very common alloys include carbon steel, a mixture of primarily iron and carbon, and the austenitic stainless steels that are primarily mixtures of iron, chromium, and nickel. The man-made alloys also contain many other elements that may affect their properties; these will be discussed later.

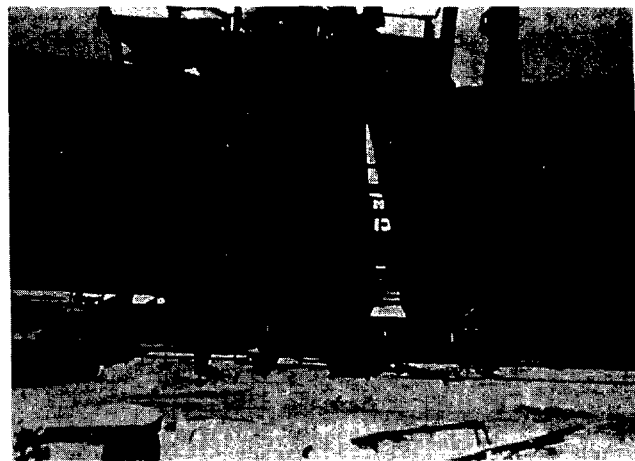


Figure 1. Liberty ship failures from the World War II era: massive hull fractures due to a combination of poor-quality steel, less-than-adequate welding procedures, and low temperatures in the North Sea.

In addition to the iron-based, or ferrous alloys, there are nonferrous groups of alloys of aluminum, copper, and nickel, to name a few of the more common ones. Additionally, many other elements have their own specialized alloy groups, such as cobalt, tungsten, and molybdenum. Alloy development usually occurs due to a need for specialized properties not currently available. Thousands of alloys have been developed to date, and it continues at a rapid pace.

Metallurgy is defined as *"The art or science of separating metals from their ores, and preparing them for use by smelting and refining."* This definition includes both "extractive metallurgy," the separation of metals from their ores, and "physical metallurgy," which prepares them for industrial use. Welding metallurgy is a further extension of physical metallurgy that specifically applies to those metallurgical considerations of the welding operation needed to develop an end product that can be used safely and economically. Figure 2 shows modern fabrication shops.

Metals are very unique materials permitting our industrial world to design and fabricate many very useful items not only for industrial use but for our personal needs as well. Metals vary widely in cost, availability, mechanical and physical properties, heat treatments, corrosion-resistance, weldability, and many other less common attributes. The mechanical, design, or metallurgical engineer has more than 20,000 different and unique alloys to select from for a particular application. Too often, the weldability aspects are not given enough consider-

ation at the start, and when welding difficulties occur, most individuals involved seem surprised. With the vast number of alloys available, and with the majority falling into the category of being readily weldable, one would think that welding problems would disappear. However, the art and science of joining a metal to itself, or joining two dissimilar metals, depends on much more than the initial selection of alloys. Welding a metal successfully and repeatedly requires a great number of welding variables to be considered. These welding variables include:

- Base metal chemistry, thickness, and heat treat condition
- Filler metal chemistry, type, and electrode diameter
- Welding process (choose from over 35 methods)
- Flux system (if required)
- Storage of filler metals and fluxes (heated storage, warm, dry, etc.)
- Cleanliness of base and filler metals
- Joint geometry (V-groove, U-groove, Square Butt, etc.)
- Joint accessibility (one or both sides, open root or backup strip)
- Welding heat input (volts, amps, travel speed)
- Interpass temperature limits
- Interpass cleaning

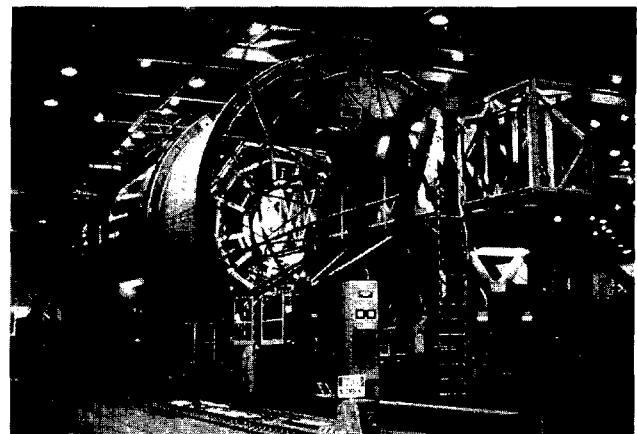


Figure 2. Modern fabrication shops utilizing welding equipment and procedures to avoid fabrication problems.

- Weather conditions (sun, rain, snow)
- Ambient temperature (January in Alaska or July in Houston)
- Humidity (Gulf Coast or Arizona desert)
- Preheat temperature
- Cooling rate
- Shielding gases (if required)
- Purging gases (if required)
- Post weld heat treatment (if required)
- Others

The length of the list should not cause dismay. Seldom, if ever, do all the listed variables come into play for a particular weld project, but often, several of them must be considered jointly when developing welding procedures. While the study of scientific principles can assist in developing a welding procedure, experience is also an important factor in that development. Neither source of information can, or should, be ignored in solving welding problems since both can lead to a solution. The trial and error process played an important role in early welding development, and is still a very useful tool for solving day-to-day welding problems. A phrase that supports this process is *"One test can be worth a thousand expert opinions."* Often, a welding test specimen must be prepared to confirm a welding procedure and this approach is still used in most code requirements. The compatibility of the base metal, filler metal, and welding process are still best determined through actually joining the metal by welding a specimen and testing the result.

Metal Structures

Metals have been in use for centuries, and the early metal artisans had little or no understanding of the science of metals. However, even without that scientific understanding, items made of metals found in archaeological sites confirm that metals have been worked into useful shapes for particular tasks for centuries. As shown in Figure 3, representing the early welding days, most metal working and welding was done by the blacksmith, and it relied heavily on trial and error and past experiences. Knowledge was passed on from generation to generation by word of mouth and on-the-job training. Only more recently, within the past 100 years or so,



Figure 3. Early welding was based on trial and error, and most of the time was done in the blacksmith's shop with carefully guarded procedures handed down within the family from one generation to the next.

have metals been studied in a manner to determine their detailed physical, mechanical, and chemical properties.

Initially, the metal workers used the trial-and-error process to develop alloys and the optimum heat treatments for making various products. This worked extremely well for many applications, and included the use of several alloys, including bronze and steel. The early artisans were very secretive with their metal-working knowledge in an effort to avoid competition. The early welding equipment was quite unsophisticated as shown in Figure 4. Today, results of various alloy and welding research studies are published throughout the world.

In today's world, once the metals have been extracted and refined by the extractive metallurgists, the physical metallurgists and welding engineers must have an extensive understanding of the metals' physical and chemical properties to best develop them for end uses. Instruments to accurately measure alloy chemistry have been developed and their use has dramatically increased our knowledge of the metals' chemical properties. We can now also measure the coefficients of thermal expansion, heat conductivity, electrical conductivity and all the other physical properties necessary to further our understanding of metals. Mechanical tests have been developed to determine the mechanical



Figure 4. Early acetylene welding equipment.

properties so necessary for aiding the selection of alloys to perform a particular task. And lab instruments have been developed so the metals' internal structure can be studied to increase our understanding of their behavior. The metallurgical microscope and the scanning electron microscope (SEM) have contributed significantly to our basic understanding of the metal structures.

Metals are composed of many crystals or grains, with grain boundaries between the adjoining individual grains. These grains are usually quite small and require polishing and etching of the metal surface to be seen on a microscope at high magnifications. Within each grain, an ordered structure exists and is comprised of millions of unit cells, each following a natural physical order. At the junction of adjoining grains, there is a mismatch of each grain's ordered structure since each grain is uniquely different, and this boundary of mismatch delineates each individual grain. Figure 5 represents a 200X–400X magnification of a metal structure showing portions of three grains and their adjoining boundaries. Note the specific order within each grain that is unique to that grain alone.

The ordered structure of unit cells within a metal grain can be represented by Figure 6, which represents a three-dimensional metal structure using a "unit cell" approach. This natural order is comprised of metal atoms forming the unit cells. A unit cell is defined as *"The minimum number of atoms that fully describe each of the unique structure orientations."* The sketched representation is only that; remember that the atoms are actually in motion with electrons encircling a core nucleus, and each element has a

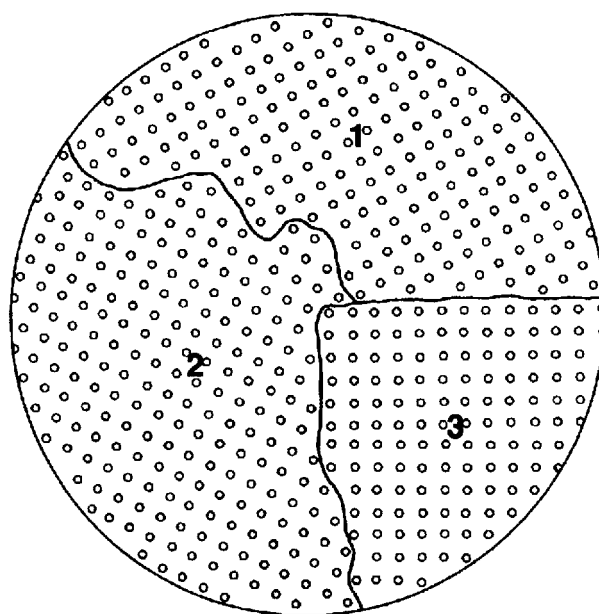


Figure 5. Representation of a metal structure showing portions of three individual grains having an ordered structure within each, and the grain boundaries separating the grains, showing the orientation mismatch.

unique core makeup with varying numbers of electrons encircling the nucleus.

Metals usually fall into one of three types of unit cells or crystal structures: body-centered cubic (bcc), face-centered cubic (fcc), and hexagonal close-

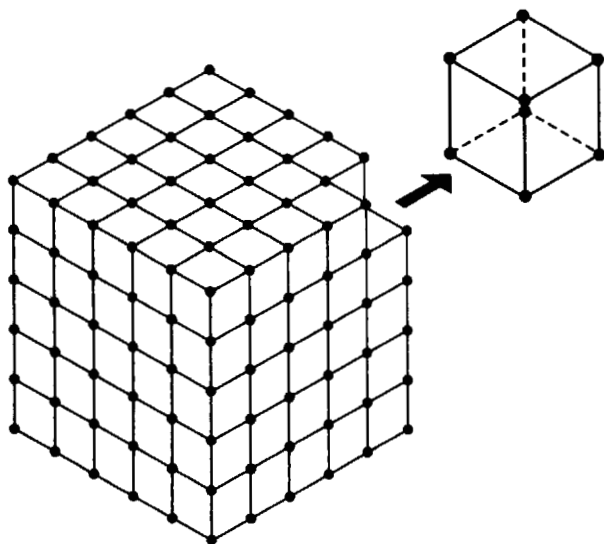


Figure 6. Isometric representation of the ordering of an array of unit cells and one unit cell from the array.

packed (hcp). These three types are shown in Figure 7. Each gets its name from the orientation of the atoms in the unit cell; “cubic” refers to the atoms at the corners forming a cube, with each of its three axes identical in length. The terms “body” or “face” refer to the position of the additional atoms *not* at the corners. For the bcc structure, an additional atom is at the exact center of the cube. For the fcc, additional atoms are positioned on each of the 6 faces, with each face atom being shared with adjoining unit cells. The hcp structure is a bit more complicated, with 6 atoms forming each of the two end faces in a hexagonal shape, while the “close-packed” term refers to the additional three atoms between the two hexagonal end faces.

Metals and alloys can often exist with more than one crystal structure pattern, depending on the metal’s temperature and its rate of cooling to room temperature. There are various phase names attached to these different structures. Steel alloys can have unit cell orientations of bcc (ferrite phase), fcc (austenite phase), and an additional crystal structure known as “body-centered tetragonal” (bct) which is the structure of the martensite phase. The bct unit cell is very similar to bcc but with one axis longer than the other two. The bct unit cell is shown in Figure 8, and it forms on rapid quenching for

many carbon and low-alloy steels. A review of the iron-iron carbide diagram shown in Figure 9 shows the temperatures and carbon contents required for each of the various structures to be in stable forms. As seen in Figure 9, heating a 0.77% carbon steel above about 1333°F causes it to transform quickly from bcc ferrite to fcc austenite. The reverse transformation occurs on slow cooling back to room temperature. Other carbon-percent alloys transform also, but over a temperature range rather than at a discrete temperature. The physical metallurgist takes advantage of these phase and structure transformations to develop quenching and tempering procedures to increase the mechanical strengths of alloys.

Several metals have the fcc structure at room temperature, and these include aluminum, copper, and silver. Metals having the hcp structure as one of their forms include titanium, zirconium, and cobalt. While many metals can transform on heating to alternate phases, thus allowing them to be strengthened by heat treatment, many cannot and these alloys must rely on other techniques for increasing their mechanical strength, such as work hardening or precipitation hardening.

As a quick review before continuing, metals are crystalline structures formed by atoms in ordered patterns. This ordered pattern or arrangement is known as a phase and is described by a unit cell. Metals solidify from many locations at once, initiating at the molten metal’s outer periphery, and growing toward the center of the molten puddle in preferred directions to form grains or crystals. The junction between individual grains is referred to as a grain boundary. The grain size will dictate the amount of grain boundary area present in a metal, which in turn determines to a certain degree the mechanical properties of the metal.

Metal Forms

As noted above, different metals can have different atomic structures, and a single metal can exist in more than one atomic structure. Metals also have various additional forms referred to as “cast,” “wrought,” or “forged.” A common form for metals is the cast form; the metal is heated to above its melting point, poured into a mold, and allowed to solidify into the shape of the mold. If the casting mold is quite large and open-topped, considerable surface oxidation will occur, and significant metal

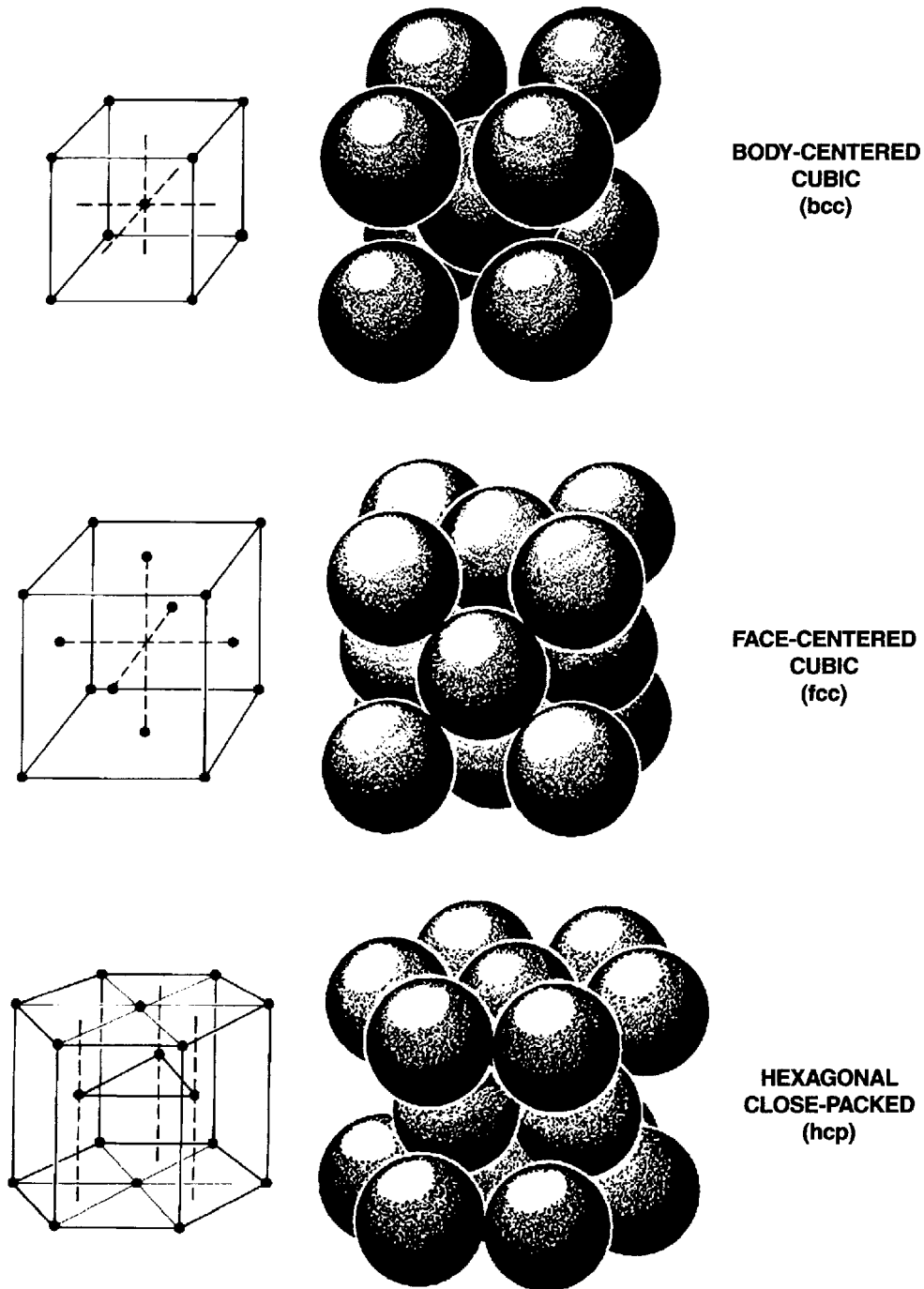


Figure 7. Representations of three common crystal structures, bcc, fcc, and hcp, showing position of individual atoms to form unit cells.

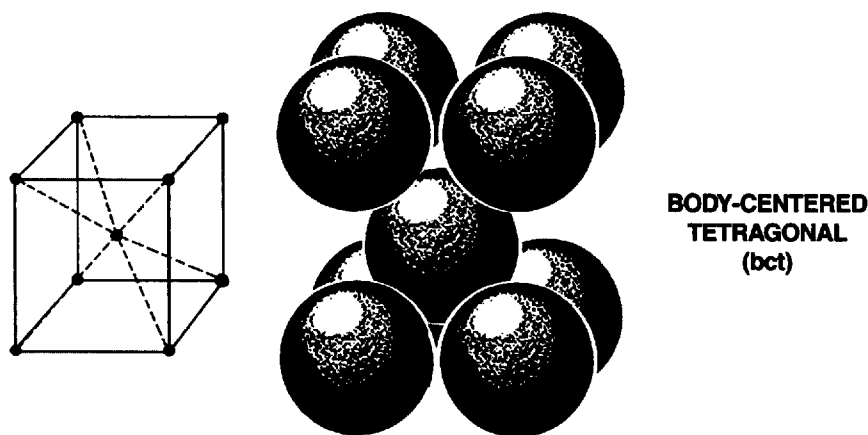


Figure 8. Unit cell of body-centered tetragonal (bct) structure showing position of individual atoms. Note the bct structure is quite similar to bcc except that one axis (the vertical axis in the sketch) is longer than the other two and therefore it is no longer cubic but rather tetragonal.

shrinkage occurs during solidification leading to a depression in the top center of the ingot. This depression is referred to as “pipe” by metallurgists. Often, this pipe is removed prior to forming the ingot into other shapes to remove its degraded quality from the final product.

Foundries have been forming metals into intricate cast shapes for many centuries since casting was one of the earliest methods for creating a particular shape. In fact, one alloy was used so extensively it became a common alloy family name, *cast iron*. The early uses of cast irons were very crude with resulting poor mechanical properties, but today’s usage can be very refined using many of the recently developed casting alloys. For years, the inexpensive, wear-resistant, intricate castings with complex internal structures needed for automobile engines were made from cast iron and this application continues. Today, however, with automobile weight a major factor in efficiency, many lighter metals, including aluminum and magnesium alloys, are being used for automobile engines.

The “wrought” form of alloys refers to those forms wrought, or *worked*, into other shapes after being poured into the original cast ingot form. Steel plate begins its life as a cast ingot and through subsequent reduction and rolling operations becomes worked into the desired thickness, width, length, and mechanical properties. Tubing can be wrought,

or drawn, by piercing an ingot to make a hole and drawing it through successive dies to obtain the desired diameters and wall thicknesses. Tubing can also be fabricated from thin sheet by forming it into a tubular shape followed by seam welding of its length, usually without the addition of filler metals (autogenous welding). See Figure 10. Shapes such as I-beams and channels are formed by “extrusion,” another form of working the cast ingot into the desired shape. “Forging” refers to the working of cast ingots or bar stock material by forcing, or forging, them into the final desired shape, often at elevated temperatures. Forged-shapes are often more complex than those shapes achieved by rolling or extrusion. Improved mechanical properties can often be achieved during these working operations.

Additional terms applied to working an alloy include “hot working” and “cold working.” Hot working is done above the metal’s recrystallization temperature; cold working is done below the metal’s recrystallization temperature but *not* at temperatures normally referred to as cold. Cold working of steel may be done at temperatures of 600–800°F or higher, and often the cold working itself increases the metal temperature significantly. The high nickel alloy heating coils shown in Figure 11 were formed well above room temperature to reduce the alloy’s mechanical strength to aid the bending operation.